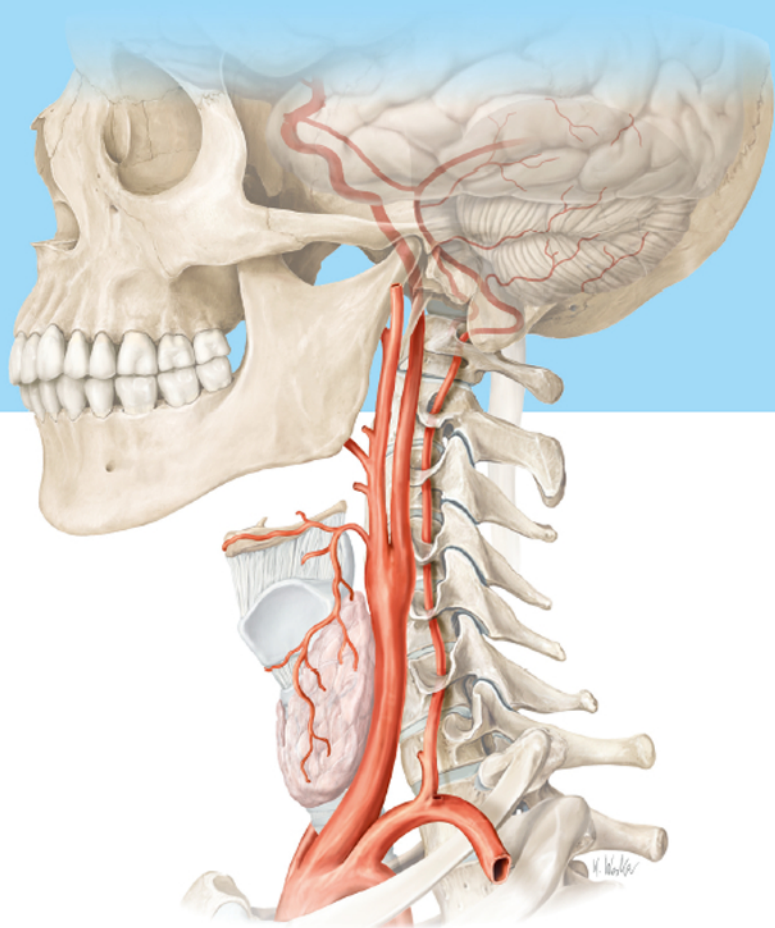


# Neurosurgery Fundamentals

Nitin Agarwal



Thieme









# Neurosurgery Fundamentals

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To my family for the unconditional support.  
To my fellow residents for helping me carry the message.  
To my mentors for educating me in the art of neurosurgery.  
To my patients for teaching me on a daily basis.



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## Foreword

When Nitin Agarwal asked me to write this foreword, I was happy to learn that he put together his experiences, reflections, and advice in this *Neurosurgery Fundamentals*. The process of collecting important bits of knowledge and insight is so critical and I am happy to see a young writer already making his contributions. I know from my own writings that brevity is essential to be relevant for medical students and residents, and this handbook distills the basics of history, neurological examination, anatomy, radiology, and the operating room. This handbook also summarizes key concepts in trauma, vascular, tumor, spine, functional, and pediatric neurosurgery, which are the clinical problems most likely to be encountered in patients in the early stages of the aspiring neurosurgeon's career or when on call in the middle of the night. The accompanying figures and illustrations are well done and complement the text. I particularly enjoyed the roadmaps to academic careers and the advice from masters. Getting leaders in our specialty to share their insights on

succeeding in neurosurgery is invaluable and rarely done, and this book captures the advice of key leaders. I congratulate the editors and authors of this handbook. I expect that it will soon become a classic for aspiring neurosurgeons who want to get off on the right foot, and that we will be seeing this handbook in the coat pockets of many neurosurgical subinterns and residents on the wards.

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## Preface

Neurological surgery is a complex and highly selective specialty. As such, excellent texts are available to educate medical students, advanced practice providers, and residents engaged in the field. Given the magnitude of neurosurgical information to absorb, many of the existing references may be overwhelming. *Neurosurgery Fundamentals* offers a portable reference for neurosurgical providers in training to quickly digest the essentials of neurosurgical care. Its content enables quick preparation for medical student sub-internships or neurosurgical residency. Chapters include questions to aid retention of knowledge. The text also features

a roadmap for matching into residency as well as advice from prominent academic neurosurgeons. Lastly, this handbook features a comprehensive collection of resources including textbooks, electronic resources, conferences, grants and awards, select peer-reviewed journals, organized neurosurgical membership, and board review references. High yield resources are highlighted to help in reader identification. Overall, this text is a unique and succinct guide for any aspiring neurosurgical provider.

*Nitin Agarwal, MD*

---

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I would like to say thanks to all my colleagues who contributed to this handbook to augment the training of future neurosurgical providers. I am very grateful to all the Thieme editors, especially Timothy Y. Hiscock, Gaurav Prabhuzantye, and Sarah

E. Landis, for guiding me through this opportunity to enhance medical student, advanced practice provider, and resident education in Neurological Surgery.

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# 1 Roadmap to a Career in Neurosurgery

Ahmed Kashkoush, David T Fernandes Cabral, Robert M Friedlander

## 1.1 Introduction

Neurological surgery is the field of medicine dedicated to surgical treatment of nervous system pathology within the brain, spine, and in the periphery. The American Board of Neurological Surgery (ABNS) is responsible for selecting the training requirements for Neurosurgery residents.<sup>1</sup> Neurosurgery residency is 7 years (84 months) in duration, which consists of 54 months of core clinical neurosurgery and 30 months of electives. The aim of this chapter is to lay down a framework for preparing for the neurosurgery residency application.

## 1.2 Applications

### 1.2.1 Match Data

For the 2017–2018 academic year, there were 110 Neurosurgery residency programs accredited by the Accreditation Council for Graduate Medical Education (ACGME).<sup>2</sup> Generally, Neurosurgery programs accept 1 to 3 incoming residents every year, with the larger programs accepting 4 residents per year. Neurological surgery was among the most competitive specialties in the 2018 Match. According to the National Resident Matching Program (NRMP), there were a total of 310 applicants who preferred the specialty for 225 positions (1.38 applicants/positions).<sup>3</sup> Note: All NRMP statistics in this chapter are calculated for applicants that preferred Neurological Surgery (n = 310) and not those that ranked Neurological Surgery programs (n = 325).<sup>3,4</sup> The match rate for U.S. allopathic seniors into

Neurosurgery was 86%; for comparison, the match rate for all specialties combined was approximately 94%. For 43 total international medical graduate (IMG) applicants in 2018, the match rate was 23%.<sup>5</sup>



Given the limited spots open for incoming residents, it is important to prepare early in medical school for the application process in order to have the best chance for success.

In a survey of 28 out of 104 residency directors (27% response rate) for Neurological Surgery conducted in March 2018, responders were asked to cite factors in interviewing and ranking applicants. Of all factors, most program directors cited the following as important factors for selecting applicants to interview<sup>6</sup>:

- Letters of recommendation (100%).
- United States Medical Licensing Examination (USMLE) Step 1/Comprehensive Osteopathic Medical Licensing Examination (COMLEX) Level 1 scores (100%).
- Performing a neurosurgery rotation in that department (88%).
- Alpha Omega Alpha membership (88%).
- Evidence of professionalism and ethics (84%).

When asked about important factors in ranking applicants, residency directors most frequently cited<sup>6</sup>:

- Interactions with faculty during interview and visit (96%).
- Interpersonal skills (88%).
- Interactions with house staff (88%).
- Letters of recommendation (84%).
- USMLE/COMLEX Step 1 Score (84%).

Results from the NRMP suggest that academic achievements are most important in selecting applicants to interview, but personality and interactions with others are most influential in ranking applicants. It is important to note that the relative importance of each of these factors vary with program.

1.2.2 Qualifications

USMLE Step 1 scores are important screening factors to assess one's candidacy for neurosurgical residency programs. As noted earlier, 100% of residency directors utilize Step 1 scores to select applicants for an interview.<sup>6</sup> For those who matched in Neurosurgery as their preferred specialty, the mean Step 1 score for 2018 was 245 among 188 matched United States (US) allopathic seniors according to 2018 NRMP

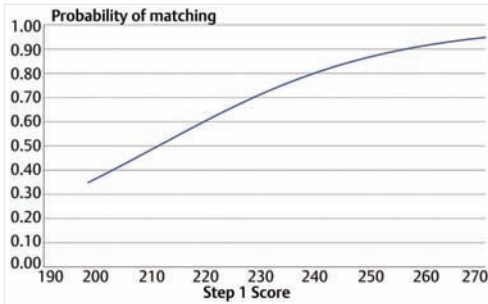
data (►Table 1.1).<sup>3</sup> For those 28 US seniors who preferred Neurosurgery but did not match in the specialty, the mean score was 234. Utilizing probabilities calculated with 2016–2018 data, the likelihood of matching in Neurosurgery as their preferred specialty with a score of 250 or higher is approximately 85 to 95%. For scores within the ranges of 220 to 230, 230 to 240, and 240 to 250, the probabilities of matching are approximately 50 to 60%, 70 to 80%, and 80 to 85%, respectively (►Fig. 1.1). For IMGs, the mean scores for matched and unmatched applicants are similar to those of US allopathic seniors.<sup>5</sup> However, a notable difference is that even with an extremely high score (> 260), the probability of matching in Neurosurgery as a preferred specialty for IMGs is still about 45% according to 2016–2018 NRMP data (►Fig. 1.2). As such,

**Table 1.1** Summary statistics on United States allopathic seniors that preferred neurological surgery\*

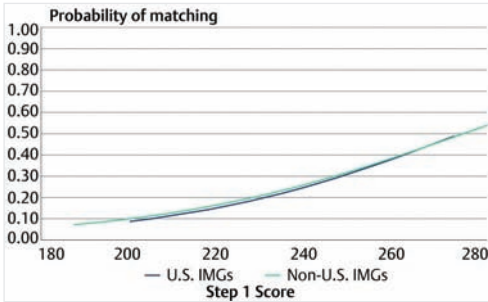
| Measure                                                                                       | Matched<br>(n = 188) | Unmatched<br>(n = 28) |
|-----------------------------------------------------------------------------------------------|----------------------|-----------------------|
| Mean number of contiguous ranks                                                               | 16.4                 | 8.5                   |
| Mean number of distinct specialties ranked                                                    | 1                    | 1.3                   |
| Mean USMLE Step 1 score                                                                       | 245                  | 234                   |
| Mean USMLE Step 2 score                                                                       | 249                  | 238                   |
| Mean number of research experiences                                                           | 5.2                  | 4.4                   |
| Mean number of abstracts, presentations, and publications                                     | 18.4                 | 8.9                   |
| Mean number of work experiences                                                               | 3.2                  | 2.5                   |
| Mean number of volunteer experiences                                                          | 7                    | 6.9                   |
| Percentage who are AOA members                                                                | 31.9                 | 21.4                  |
| Percentage who graduated from one of the 40 US medical schools with the highest NIH funding** | 43.6                 | 10.7                  |
| Percentage who have PhD degree                                                                | 13.6                 | 3.8                   |
| Percentage who have another graduate degree                                                   | 20                   | 28                    |

\*Used with permissions from NRMP.<sup>3</sup>

\*\*Top 40 US medical schools with the highest NIH funding is from the NIH website. Abbreviations: AOA, Alpha Omega Alpha; NIH, National Institutes of Health; US, United States; USMLE, United States Medical Licensing Examination.



**Fig. 1.1** Probability of United States allopathic seniors matching into neurology by United States Medical Licensing Examination (USMLE) Step 1 score. (Reproduced with permission from National Resident Matching Program [NRMP].)<sup>3</sup>



**Fig. 1.2** Probability of international medical graduates matching into neurology by United States Medical Licensing Examination (USMLE) Step 1 score. (Reproduced with permission from National Resident Matching Program [NRMP].)<sup>5</sup>

IMG applicants may benefit from getting involved in research at a Neurosurgery department and building relationships with the faculty at that institution.

While Alpha Omega Alpha (AOA) membership is not necessary for Neurosurgery residency, top-tier programs may have a preference for selecting AOA members.<sup>7</sup> Performance during clinical rotations is evaluated with grades, which are based on performance on shelf examinations, enthusiasm for the subject matter, and ability to assist other members of the healthcare team. Performance on clinical rotations is largely subjective and if residents or preceptors detect arrogance or disinterest, it may be reflected as a low grade for the course. Given the competition for Neurosurgery residency positions, applicants should strive for high grades in all of their rotations (High pass to Honors).<sup>7</sup>

### 1.2.3 Research

Research is very important part of the Neurosurgery application as producing peer-reviewed publications demonstrates an ability to bring tasks to a conclusion.

In the 2018 Match, the mean number of abstracts, presentations, and publications for US allopathic seniors who matched was 18.4 whereas that for unmatched applicants was 8.9.<sup>3</sup> The importance of research is especially true for candidates targeting highly ranked academic centers and for IMG applicants. One study suggested that student h-index was an independent predictor of matriculation into top-tier research institutions,<sup>8</sup> thus emphasizing the role of actively contributing impactful

papers to the neurosurgical literature. Recognizing faculty that have a proven track record of working with students is a key aspect to identifying potential mentors in the field. Looking at past years' match lists may help to evaluate which prior students of the group were successful in matriculating into programs of interest. Other very important factors to consider in a faculty mentor are seniority, personality, projected timeline of the project, funding availability for conferences, impact of the research produced, and availability. Also remember, pairing up with residents who are active in research may open up connections with other more senior faculty members of the institution. Additionally, getting involved with the institution's student interest group can open up networking opportunities, and has also been shown to increase publication count and institutional match rate into Neurosurgery.<sup>9</sup>

Given the short time frame for completing publications, prospective Neurosurgery candidates should begin early, preferably in their first or second year of medical school. Early involvement in research is important because students are expected to attend to a higher load of clinical duties during rotations; there are many funding opportunities available specifically for medical students during the summer after first year (see section 20.4 Grants and Awards).<sup>10,11,12</sup> Opportunities to augment one's research portfolio exist via dedicating a year to protected research time during medical school with graduation in 5 years instead of 4 years. However, delaying graduation for dedicated research time is not necessary. Additionally, an individual must be highly productive must strive to complete several publications to account for this extra time. Again, there are many funding opportunities that are available specifically for medical students, such as the Howard Hughes Medical Institute Medical Research Fellowship and the National Institutes of Health (NIH) Medical Research Scholars Program.<sup>13,14</sup>

### 1.2.4 Research for IMGs

The importance of research for IMG applicants cannot be stressed enough. In 2018, the mean number of abstracts, presentations, and publications for IMG applicants who preferred and matched in Neurosurgery was 46.6.<sup>5</sup> For those who have already finished medical school and do not have research experience, the best next step is to find a research position in a US academic Neurosurgery department. In this case, doximity.com is a very useful website for assessing the research output of different programs. Institutional websites can be utilized to assess research options within the department and contact information for lab directors. Students should contact various labs and not feel frustrated if emails go unanswered. Faculty members are extremely busy and often involuntarily forget to reply to emails. Persistence is key. Applying to several laboratories as well as making an effort (if feasible) to meet *in-person* will increase the chances of success.

IMGs must take into consideration the diverse types of research positions offered by the lab. For instance, some laboratories are very open to receive people for volunteer or unpaid research, which could dramatically impact entry into the US. Students who are not US citizens or green card holders will need to apply for a visa to start the research job.



Please be aware that tourist visas are not allowed for research positions.

Most labs will offer a J1 visa, which in most cases has a 2-year rule and a limit of 7 years. Visit the Department of State website for details regarding 2-year home-country physical presence requirements and eligibility for a waiver.<sup>15</sup> In order to

apply for a J1 visa for a volunteer research position, the student will need to prove to the US Government that the student or a sponsor (most likely your family) has the equivalent of \$30,000 or more. Another factor to consider is that volunteering positions will not come with health insurance. The bottom line is that IMG students will need a significant amount of funds to apply for volunteering positions, which unfortunately are the most common.

The second option, which would be the best-case scenario, is to get a postdoctoral research fellow position. This case offers employment at the university, which comes with a salary, health insurance, and in some cases, different benefits offered by the university. Again, a visa is required, which in this case could be a J1 or an H1B. Please refer to the Department of State for detailed explanation regarding visa issues.<sup>15</sup>

During this time, students will spend a month with the Neurosurgery service and develop the basic foundations of neurosurgical knowledge and techniques. Here, both the faculty and house staff will have the opportunity to evaluate if a student has the caliber for the field of Neurosurgery. By the end of the rotation, candidates should be in a position to request a letter of recommendation from the residency director or chairman of the department. To stand out as a valuable member of the team during the Neurosurgery clerkship, students will need to build on and utilize many of the skills learned in their prior rotations.



The 3 A's (Affability, Availability, and Accountability) and "How to Swim with Sharks" have been frequently cited as guidelines for medical students.<sup>16</sup>

### 1.2.5 Away Rotations

As a candidate chooses where to do away rotations, it is important to define what the student's priorities are. It is critical to evaluate the culture and training available at each program. From a clinical stand, it is important to evaluate the case volume. A useful metric is to compare the ratio of total case volume divided by the number of residents in the program. Low volume translates into lower operative exposure throughout residency. On the research side, perform a literature search on the entire faculty to understand the true academic commitment and faculty accomplishments. If the applicant is interested in research, search to determine the number of clinical neurosurgeons who are principal investigators of NIH or Department of Defense-funded projects. This will provide a measure of the role models available at the specific program.

Performance on a sub-internship is perhaps the most important aspect of a candidate's profile at that particular institution.

Many others cite "Message to Garcia" as a guide for an exceptional performance on the neurosurgery sub-internship:

*"The world bestows its big prizes, both in money and in honors, for but one thing. And that is Initiative. What is Initiative? I'll tell you: it is doing the right thing without being told. But next to doing the thing without being told is to do it when you are told once. That is to say, carry the Message to Garcia: those who can carry a message get high honors, but their pay is not always in proportion. Next, there are those who never do a thing until they are told twice; such get no honors and small pay. Next, there are those who do the right thing only when necessity kicks them from behind, and these get indifference instead of honors, and a pittance for pay. This kind spends most of its time polishing a bench with a hard-luck story. Then, still lower down in the scale than this, we have fellow who will not do the right*

*thing even when someone goes along to show him how and stays to see that he does it; he is always out of job, and receives the contempt he deserves, unless he happens to have a rich Pa, in which case Destiny patiently awaits around a corner with a stuffed club. To which class do you belong?"<sup>17</sup>*

### 1.2.6 Recommendations

Three letters of recommendation are required to apply for Neurosurgery. The Electronic Residency Application Service (ERAS®) allows up to four letters to be submitted. One of these letters should be from the department chair and/or the program director at the home institution. While on away rotations, try to obtain a strong letter from the chairman or program directors at those institutions. These letters will largely be based on input from residents and other faculty observing your performance.

Letters from non-neurosurgeons are not encouraged as these may have a lower impact, given individuals outside of the field may have limited ability to comment on the qualities necessary for Neurosurgery.<sup>7</sup>

The seniority of the letter-writer may also affect the impact of the letter. Neurosurgeon research mentors may have a unique ability to comment on candidate qualifications as they have likely overseen their work and long-term maturation. Students should also keep in mind that they can submit different letters to different programs. For instance, if a student knows that a certain letter-writer has connections at a program of interest, that letter may be more strategic than others. In addition to letters, mentors may offer to call programs to advocate for the student.

### 1.2.7 Interviewing

Interview season is an expensive and stressful process. One study reported that the average cost incurred during Neurosurgery residency interviews was approximately \$7,180 ± 3,880 (mean ± standard deviation).<sup>18</sup> Despite these costs, in-person interviews are important for learning about the culture of each institution, touring the facilities, and meeting potential colleagues and mentors. Know that once an interview has been obtained, the applicant pool has become significantly narrowed down. Most successful applicants aim to attend 10 or more interviews to optimize their chances given that a greater number of contiguous ranks yields a higher probability of matching.<sup>7</sup> The interview day itself will be hectic. Most applicants will have an introduction by the chairman, a walking tour of the hospital, and some time to spend with the residents. Arrive at the interview with a handful of prepared questions. Ask about key faculty projections and transitions, operating room experience, program for team building and social activities, variety of clinical experience from hospitals within the healthcare system, enfolded fellowships, research opportunities and support, resident matriculation into academic centers, any other areas of interest. During interview sessions, candidates should strive for a bidirectional conversation. Be a good story-teller and emphasize key strengths of the application. Candidates will likely be asked about their specific interests and long-term goals in neurosurgery as well as their research. Conveying background knowledge, roles, and key findings of research projects will be expected of interviewees. After the interview, consider sending thank you notes to each program. Generic communications sound like generic communications. Write about something specific and meaningful about the program and visit. Email is an acceptable form of post-interview



communication and follow-up inquiries. If an applicant is still undecided about how to rank programs, a second look is always an opportunity to re-evaluate a program and demonstrate interest. In some cases, programs may offer the applicant another interview with key faculty and residents at the second look.

### 1.2.8 Ranking

Much of ranking is based on the applicant's feeling for the program on interview day. There are many aspects of a program that an applicant should consider when ranking and these vary based on personal preference. If an applicant genuinely disliked a program and would not be happy working there for 7 years, then it might be best not to rank it highly regardless of perceived prestige. It is vital that applicants build an intimate understanding of the matching algorithm. In brief, the match algorithm is "applicant proposing," which means that preference is given to applicant over program rank.<sup>19</sup> The algorithm thus encourages students to rank programs in order of preference rather than in order of candidacy at each program. In essence, the order of the rank list does not influence the chance of matching into Neurosurgery. Applicants should not rank lower-tier programs higher because they believe it will increase their chances of matching. On the contrary, it only increases the chances of matching at a less preferable institution.

## 1.3 Profiles

### Robert M Friedlander, MD, MA

Chairman and Professor

Walter E Dandy Chair

Head of Cerebrovascular Neurosurgery

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University of Pittsburgh Medical Center

"On my surgery rotation, I really liked taking care of an acute patient and fixing

things. Sometimes, we were breaking things, but hopefully not too many times. The problems with surgery, however, were several in my mind. I did not think it was a field that was conducive to laboratory research. Residents were on-call every other night for 5 years, which to me at that point felt like too much. I then remember talking to the Surgery clerkship director about the dilemma that I was in. I liked surgery but it seemed really hard and a lot of work. He said 'Robert, you can be a dermatologist or a surgeon. If you like dermatology, then God bless you. In dermatology, residency is going to be much shorter, there will be fewer hours, your career will be more or less 9 to 5, and you will not have weekend emergencies. But if you dislike what you do, you are going to wake up miserable, go to work miserable, go home miserable, and not be happy. Surgery, sure, you wake up early, you work hard, you may have to take call every other night, but it's 5 years. It's a long time, but it's a limited amount of time, and you have the next 30 years to practice something that you love. You are going to love waking up, you are going to be excited to go to work, you are going to love doing surgery, you are going to go home and be happy with your family. But it really depends if you like it or not.' So that conversation at least opened my eyes to a surgical career and was a very transitional conversation for me. It was my good friend in medical school who put the neurosurgical bug in my head. He was doing research and always so excited about neurosurgery that I decided to do a rotation in neurosurgery. And I loved it. I remember the first time that I saw a neurosurgical operation. It was a cerebellar met. I remember just seeing the cerebellum pulsate and to me it was really cool and exciting, just seeing the brain, opening the fissure, and seeing the blood vessels. To me, it was just phenomenal. So, at that point, I decided to do neurosurgery, about midway through third year of medical

school. To me, having the privilege of opening someone's head and fixing it, being able to use my hands, and being able to teach residents—to me, it is too fulfilling. To have the ability to do research, which I love; surgery, which I love; and teaching, which I love; and now, to be able to administer and have a vision, to not only impact what I do but to mentor a large number of faculty and residents, and to establish a neurosurgical legacy in a leading neurosurgical department, to me is a privilege, an honor, and a great responsibility.”

### **L Dade Lunsford, MD, FACS**

Lars Leksell Distinguished Professor  
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Chair, Technology and Innovative  
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Pittsburgh, Pennsylvania

#### *Path to neurosurgery*

“My interests in neuroscience probably began in college. At the University of Virginia, I got to participate in a master's level undergraduate program, where I spent 2 years working on neuroscience research. At that time, we were working on the transfer of learning information in a rat model and doing things like corpus callosum resections and using a technique called “spreading depression” to functionally inactivate brain function and study memory function in one hemisphere of the rat. That stimulated my interests in neuroscience. I already knew that I wanted to go to medical school, so during that same time, I completed my pre-med requirements. I had lived in the state of Virginia for 21 years and made the decision that it was probably a good idea to go somewhere else for a period of time for medical school. So I ended up going to Columbia University and started working for a neurologist who was

focused on epilepsy, before my first year of medical school. Over the course of time, my clinical interests in neuroscience centered on neurosurgery. I spent time on the neurosurgical service at Columbia Presbyterian Hospital and did rotations at a couple other places during my third and fourth years. I decided to go back to University of Virginia to do my internship for a year, but after a year, I decided I wanted to go to Pittsburgh to do my neurosurgical training. I came here in 1975. At the time that I came, the first major breakthrough in brain imaging came with the development of the computed tomography (CT) scan, which showed up on the same day I started my residency. It became clear to me immediately that the world was going to change in a big way. So I worked on combining imaging with guiding technology. At the time, that was not actually done in brain surgery since movement disorder surgery had died during that era after the development of L-dopa. To precisely reach areas in the brain, I developed, as a resident here, a stereotactic guiding device that was CT-compatible. I became further interested in deep brain types of surgery. I had an opportunity to spend a few months in Europe in 1979, trying to decide where I wanted to do a fellowship after I finished training in neurosurgery here. I applied for an American Association of Neurological Surgeons (AANS) supported William P. Van Wagenen fellowship, which is given once a year. This allowed me to spend a year in Sweden doing training in stereotactic surgery and functional neurosurgery. I came back to Pittsburgh in 1981, and joined the faculty and, in essence, I have been here ever since. My interests have still remained in minimally invasive surgical techniques to be able to avoid the risks and complications of more aggressive brain surgery, while finding ways to minimize collateral damage in brain surgery. One of the techniques that we developed was the first dedicated stereotactic operating room

with a CT scanner, which was put in 1981 here at UPMC. In 1987, we brought in the first 201 source gamma knife (fifth unit ever built) for brain surgery. Over the last 30 years, we have updated the various gamma knife devices five times and now radiosurgery has become a major component of what is done in neurosurgery, both in the brain and spine. Currently in our program, which is probably one of the busiest in the US, we do about 9,000 operations per year. Radiosurgery techniques, using things like gamma knife and spine radiosurgery devices, accounts for somewhere around 12% of the total neurosurgery practice. It has become a major component of what the field is and it is a major component of what current residents in training need to learn while they are in training. My other interests have been related to proving that new technology has value. One of the crazy things about US healthcare is that sometimes industry develops tools that are expensive but are not always shown to have sustained value over the course of time. What we have done in working with tools like gamma knife is to maintain comprehensive patient databases that allow us to do long-term outcomes research. We have published somewhere around 650 peer-reviewed articles in the scientific literature plus 12 books related to technology, a large number of them related to gamma knife. Patient care, teaching, and academic publishing in clinical research is what I have been doing for 40 years or so that I have been in practice."

#### *Mentorship*

"When I was in childhood and through high school, I studied piano for many years, and I had a 90-year-old piano teacher who was a concert pianist. She had a significant impact on me in terms of the need to study and apply myself. I was a never a natural talent in piano, but I was someone who was able to work hard to meet her demanding nature. Similarly, I do not think that people

who go into neurosurgery should be rocket scientists in the sense of being 200-level IQs. I think those people are brilliant theoreticians but they cannot deal with the reality of taking care of a patient sitting in the emergency room with a blood clot in their head. You have to be able to focus and apply yourself. Certainly when I decided to come to Pittsburgh for training, Peter Jannetta, who was the first truly academic chair of this department, was a major influence on me because of his somewhat demanding nature, but also his requirement that you provide skillful surgical care of patients. After that, I had experience working with two Swedish neurosurgeons Eric Olof Backlund at the Karolinska institute, and Lars Leksell, who was the originator of Gamma Knife. He was no longer clinically active, but was very much active in terms of his continued research interests and how to do this type of noninvasive surgery."

#### **Nathan Zwagerman, MD**

Assistant Professor  
Department of Neurosurgery  
Medical College of Wisconsin

"I grew up on a small farm in Michigan. My parents are hog farmers and I am the oldest of four boys. In rural west Michigan, the plan was that I would continue the farming line. However, early on, I realized that I did not want to be on a farm. Farming just was not for me. I did not mind the work, but I just did not like it. So I was looking for every opportunity I could get to leave. It was clear from an early age that I enjoyed learning about the biology of the hogs and when I was in high school, I took Advanced Placement biology.

During medical school, I enjoyed anatomy and doing dissections in the cadaver lab. I realized very quickly that I could not sit in class anymore. I was very tired of lectures and lecture halls and all the lectures were available online at twice the speed. To get me out of the house, I ended up

going to different grand rounds, depending on what subject we were studying. During neuroanatomy, I interacted with a couple of neurologists in the beginning of my third year and they told me about neurosurgery grand rounds.

I was leaning towards surgery at that point. I went to neurosurgery grand rounds midway through my third year. They were presenting at Morbidity and mortality (M&M), it was an aneurysm case, which was initially nonruptured. The video was up and as they were about to clip the aneurysm and the aneurysm ruptured. I remember the intensity of the room changed. The entire atmosphere was something that I had never experienced before. I thought this is something I must know more about. As a result, during my third year, I learned more about it, spent more time going to grand rounds, meeting the residents, picking their brains, just kind of hanging out around the department, while doing my rotations. I did a month of research with Dr. Ding, who also helped guide me further toward neurosurgery. I did a couple of rotations at Wayne State, Northwestern, and the University of Vermont, and was totally secured that neurosurgery was where I wanted to be. That is how I got into neurosurgery, I was a late bloomer, so to speak. Ten years ago, I would have never pictured myself as a skull-based surgeon in Milwaukee, but it is funny how life takes you on a ride."

### **Shelly D Timmons, MD, PhD, FACS, FAANS**

Professor of Neurosurgery  
Vice Chair for Administration  
Director of Neurotrauma  
Department of Neurosurgery  
Penn State University Milton S. Hershey  
Medical Center  
Hershey, Pennsylvania

"From the time I was a little girl, I had a keen interest in all things medical and anatomical, and I knew that I wanted to be a doctor at a very early age. When I was

about 16, I read an article about brain surgery and from that moment on, there was nothing else I ever wanted or planned to do. The brain as the arbiter of our interactions with others and the world had always fascinated me, and the opportunity to work with my hands (as is so prevalent amongst surgeons) was a driving factor, as well as the chance to study and understand the most complicated organ in existence! That interest also led me to pursue my PhD in neurophysiology when the opportunity arose at the end of my residency training."

### **Robert F Heary, MD, FAANS**

Professor  
Department of Neurological Surgery  
Director, Center for Spine Surgery and  
Mobility  
Rutgers New Jersey Medical School  
Newark, New Jersey

"I began my career as a general surgery resident. Midway through my third year of residency, I rotated on the neurosurgery service and had a great time. It became apparent that neurosurgeons had the opportunity to use their minds to think through complex decisions and help many people in the process. The thrill of taking care of debilitated and injured patients was fabulous. After my rotation on neurosurgery was completed, the Chief of the Section of Neurological Surgery (part of the Department of Surgery in those days) asked me to leave General Surgery and become a neurosurgery resident. It took me less than an hour to realize that this was the chance of a lifetime. Between the various spine surgeries and brain operations that I had the good fortune of participating in, I was thoroughly convinced that the correct career path for me was being handed to me and I accepted the position. I then began five more years of residency in neurological surgery and I have never regretted this decision for an instant. Later in my neurosurgical training, I decided to specialize in spinal surgery and I took an offer at a prestigious orthopaedic spine program to become a

spine fellow. Once again, I was very fortunate to make an excellent decision. Having spent the past 2+ decades performing complex surgery, and training a large number of superb neurosurgery residents during this time, has been the best decision I have ever made. I would not trade the career in neurosurgery for any other job in this world. I am also completely confident that our wonderful profession will continue to attract the “best and brightest” to enter into the rapidly expanding field of medicine that enables us to do more positive things for our patients than any other field in medicine.”

### M Sean Grady, MD

Charles Harrison Frazier Professor of  
Neurosurgery  
Chairman, Department of Neurosurgery  
Perelman School of Medicine  
University of Pennsylvania  
Philadelphia, Pennsylvania

“Entering medical school at Georgetown, I was unsure of what specialty I might ultimately choose. I was fascinated by Anatomy and challenged by Neurosciences so felt, upon starting clinical rotations that somewhere in the field of surgery would lie my future. A 2-week rotation on the Neurosurgery service set my career for the next 35 years. Unlike other services, I would enthusiastically spend all day and night taking care of the patients, being in the operating room and reading and learning nonstop. It was phenomenally exciting and I now realize that level of commitment is the hallmark for someone interested in a career in Neurosurgery. It is an enormously rewarding and at the same time incredibly humbling career in which I thought then and know now that I would be an eternal student. In my training at the University of Virginia from 1981 to 1987, I never saw a MRI; there was no endovascular neurosurgery, endoscopic neurosurgery, major spine instrumentation, or deep brain stimulation, to name just a few advances in the field. I am most certain that

much of what our trainees learn today will be abandoned for new approaches or whole new areas will open for surgical intervention. So, if you like continuous learning and change, neurosurgery is the specialty for you. Finally, what we do as neurosurgeons has huge implications for our patients and their families, both positive and negative. There is no higher high nor lower low than the surgical results in Neurosurgery—a neurosurgeon must possess equanimities. Always remember: do no harm.”

### Pearls



- It is important to prepare early during medical school to build a competitive neurosurgery residency application.
- IMG applicants should focus on expanding their research portfolio and developing relationships with senior neurosurgery faculty in order to enhance their chances for matching.
- Sub-interns should always exhibit Affability, Availability, and Accountability towards patients and colleagues.
- USMLE Step 1 scores, research accomplishments, and letters of recommendation will help to secure interviews.
- Letters of recommendation and interpersonal skills influence applicant rank order.

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# 2 History of Neurological Surgery

Edward G Andrews, Chandranath Sen

## 2.1 Introduction

Before the dawn of the 20th century, the tools available to medical practitioners, in particular surgeons, made operating on the central nervous system virtually impossible except in the most rudimentary of applications. Advances developed slowly, with the techniques and instruments changing little from the incipient

civilizations of the Inca and Egyptians to the medical world of 19th-century Europe and United States. It was not until the late 19th century with the advent of anesthesia, antisepsis, and the ability to localize lesions in the brain successfully that neurosurgery could blossom. This chapter provides a historical timeline of advancements in the field of neurological surgery (► Fig. 2.1).

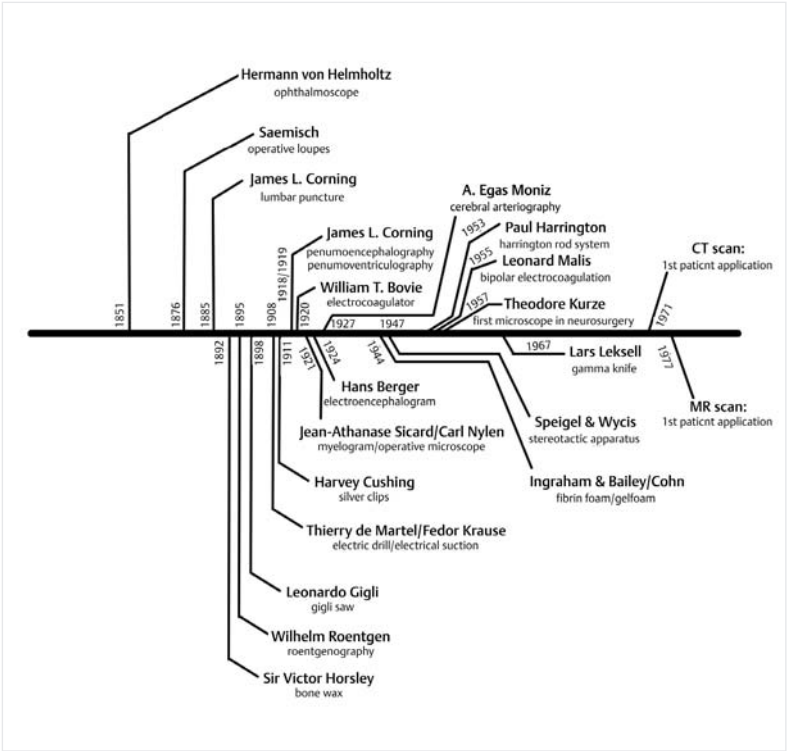


Fig. 2.1 Neurosurgical timeline.

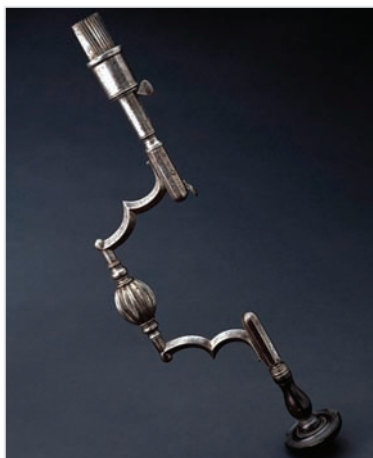
## 2.2 The Pre-Cushing Era

### 2.2.1 Paleolithic

Neolithic skulls with round or ovoid perforations recovered from prehistoric settlements in France date back as early as 8000 BC. These perforations were initially thought to be a product of trauma, but the lack of any classical signs of trauma, such as associated fractures, argued that these they were in fact intentional. There is proof that Neolithic man, inspired by magical or religious beliefs, made postmortem “diskettes” from cadaver skulls to wear as amulets.<sup>1</sup> Nevertheless, there are also data that suggest some of these openings were made while the patient was still living. The scarred margins at the wound edges indicate healing had occurred before the death of the patient, and therefore, the perforations could have indeed been practical attempts at surgical intervention. Regardless of his motivation, Neolithic man made holes in the skull by tedious scraping with flint or obsidian to create a gradual depression or to carve intersecting lines that formed a rudimentary rectangular bone flap.<sup>2</sup>

### 2.2.2 Ancient

Archaeologists have found skulls with craniotomies similar to those of their prehistoric predecessors in burial sites of the ancient Incans and Egyptians as well. The Egyptians in particular documented extensively their medical practices, outlined best in the Edwin Smith papyrus, the world's oldest known surgical treatise dating back to the 17th century BC. Its author, Imhotep, discusses treatments of cranial wounds and fractures with a twist drill wrapped in a bowstring, with the backward and forward motion of the bow spinning the drill.<sup>3</sup> It was not until the age of the Greeks and the arrival of Hippocrates, however, that craniotomy was first codified as a surgical treatment in the Hippocratic works *Corpus Hippocraticum* and *On Wounds in the Head*.



**Fig. 2.2** Surgeon's trephining kit from the mid-1700s. (Image has been provided courtesy of Science Museum, London.)

At this stage, the prehistoric technique of shaving bone evolved into a technique that involved cutting a circular groove and lifting the bone flap off, which then metamorphosed into the more efficient circular crown saw, or “trupanon” drill, referenced by Hippocrates.<sup>1,2</sup> This was the trephining drill in its simplest form (► Fig. 2.2).

### 2.2.3 Classical

While these ancient civilizations all eventually faded into the background, the trephine remained as the prime fixture in the neurosurgical armamentarium. There were modifications made to this design that allowed accessing the intracranial space quicker and more efficient, but little progress beyond this tool occurred over the centuries as this surgical option was often avoided at all costs due to significant rates of infectious complications.<sup>1,4</sup> This changed in the mid-to-late 1800s with the advent of antisepsis and aseptic technique. Trephination was suddenly back in vogue



and, as a result, rapid innovation in neurological surgery would ensue.

## The Pre-Cushing Generation

For neurological surgery to emerge as a specialty in the 20th century, a handful of physicians needed to lay the foundation for its arrival with three important medical discoveries: general anesthesia, antisepsis, and cerebral localization.

- **Anesthesia:** William T.G. Morton, a dentist, introduced ether in 1842 and James Y. Simpson, an obstetrician, introduced chloroform in 1857.
- **Antisepsis:** Ignaz Semmelweis, a Hungarian physician and obstetrician, demonstrated that handwashing with chlorinated lime before delivery reduced postpartum fever in the mother. Joseph Lister, in 1867, designed an antiseptic treatment of wounds that involved carbolic acid.<sup>5</sup>
- **Cerebral localization:** Gustav Fritsch and Eduard Hetszig used electrical stimulation on the precentral gyrus to define function in wounded soldiers with traumatic brain injuries in 1870. Pierre Paul Broca, who was one of the first to trephine for removal of a cerebral abscess, identified the left pars opercularis and pars triangularis in 1861 as the source of expressive aphasia. Carl Wernicke mapped receptive aphasia to the posterior aspect of the left superior temporal gyrus almost a decade later in 1874. Additional notable contributions came from neurologists Hughlings Jackson, David Ferrier, Gowers, and Charcot.

A new era of experimentation and invention dawned once neurosurgery could occur at the leisure of the surgeon with the above perquisites in place. Quickly, the list of “firsts” grew. Sir Victor Horsley was among the preeminent neurosurgeons prior to Cushing. One of his most notable achievements was the successful resection of a spinal cord tumor in 1888 in association

with Sir William Gowers, who himself was known for the successful evacuation of an intracerebral abscess in 1886. Horsley was one of the primary early influences on the treatment of trigeminal neuralgia, for which he achieved pain relief by sectioning the posterior root of the trigeminal nerve. Last but not least of his accomplishments, he was the first to operate on the pituitary gland in 1889, although Schloffer was the first to clearly document the successful removal of a pituitary tumor in 1907.<sup>5,6</sup> William Macewen was a contemporary of Horsley’s based in Glasgow. While he was a latecomer to neurosurgery with his first case recorded in 1876, he was no less impactful as he is among the earliest to document successful removal of a brain tumor (meningioma) in 1879.<sup>1,5,7,8</sup> He was followed by Francesco Durante, who had striking success removing an orbital groove meningioma in 1885. To wit, the patient was still alive 10 years after surgery unlike Macewen’s patient who succumbed to his disease and surgical wounds shortly after his operation. Other notable surgeons of the pre-Cushing era included the following:

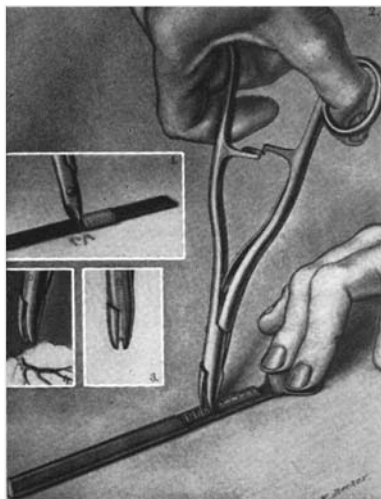
- William Detmold: the first to open the lateral ventricle to evacuate a cerebral abscess in 1850.
- Richman Godlee and Hughes Bennett: first resection of glial neoplasm in 1884. While considered a success, the patient died from intracranial infection 28 days after surgery.<sup>4</sup>
- William W. Keen: Philadelphia-based surgeon who was the first to successfully resect a brain tumor in the United States in 1891.
- Charles Ballance: performed one of the earliest reported cases of acoustic neuroma removal.

## 2.3 The Cushing Era

Harvey Cushing is arguably the most influential neurosurgeon to date, which has earned him the reverent moniker of the

"Father of Neurosurgery." He was famous for his rigorously perfected technique. One of his critical inventions was epoch making by addressing the problem of hemorrhage. Cushing's silver clip, which he introduced in 1911, made hemostasis possible (► Fig. 2.3). Similarly, his solution to increased intracranial pressure during surgery was groundbreaking when he first described the use of lumbar puncture to relax the brain intraoperatively in 1908. Prior to his arrival, the mortality associated with neurosurgery was estimated around 50% or higher despite antisepsis.<sup>9</sup> Cushing's mortality rate, however, was unprecedented: 8.4% for brain tumor surgeries and around 10% for pituitary surgeries, at a time when mortality for the latter was almost 75%.<sup>10</sup>

Some additional examples highlighting his contributions to neurosurgery include



**Fig. 2.3** Cushing's silver clip with applicator kit. (Reproduced, with permission, from Horrax G, Some of Harvey Cushing's contributions to neurologic surgery, *J Neurosurg.* 1981;54(4): 436–447.)

his temporal and suboccipital decompression for relief of high intracranial pressure, which he used for palliation in the event of a nonresectable tumor. After the First World War, he outlined the management of penetrating head trauma based on his experiences as a surgeon for the army. In 1927, Cushing adapted Bovie's electrocoagulator to neurosurgery, initially using it for piecemeal removal of brain tumors (► Fig. 2.4).<sup>10</sup> He removed his first pituitary for acromegaly



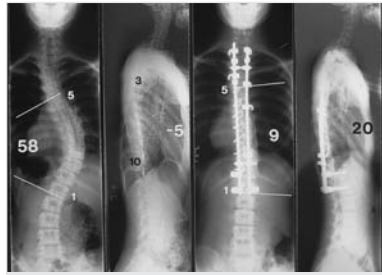
**Fig. 2.4** Bovie electrocoagulator. (Reproduced from Vender J, Effect of hemostasis and electrosurgery on the development and evolution of brain tumor surgery in the late 19th and early 20th centuries, *Neurosurg Focus.* 2005;18(4):1–7.)

in 1909 using Schoffler's transsphenoidal approach. Oscar Hirsch, a Viennese otolaryngologist, subsequently modified this technique in 1910 to the classic and now commonly used endonasal transsphenoidal approach.<sup>5</sup>

Other significant members of the neurosurgical field at this time included Charles Frazier, known for his treatment of trigeminal neuralgia by division of the sensory root instead of entire extirpation of the gasserian ganglion as Cushing proposed, and Emil T. Kocher, a large figure in the operative treatment of epilepsy as well as spinal and cranial trauma.<sup>11</sup> Walter Dandy, a prolific contemporary of Cushing's, is credited with discovering the function of choroid plexus in 1914, the third ventriculostomy in 1920, and the first cerebral aneurysm clipping in 1937.<sup>12</sup>

## 2.4 Spinal Neurosurgery

Similar to its cranial counterpart, spinal surgery was hamstrung by infection until the advent of antisepsis in the closing decades of the 1800s. With effective antisepsis, the neurosurgeons of the pre-Cushing and Cushing eras developed durable solutions to spine pathologies that had been difficult to address previously. Macewen performed the first recorded laminectomy in 1886 and Menard performed the first costotransversectomy in the opening years of the 20th century.<sup>13</sup> Fritz Lang was the first to fix the spine posteriorly in 1909 by tethering celluloid rods with silk thread and steel wires adjacent to the spinous processes. Spinal fixation, however, did not further progress until Paul Harrington developed his eponymous rod system in 1953, which became a means to stabilize the spine in multiple pathologic contexts such as traumatic injury, degenerative disease, and deterioration from neoplastic processes (► Fig. 2.5).<sup>14,15</sup> It was ultimately short-lived, however, due

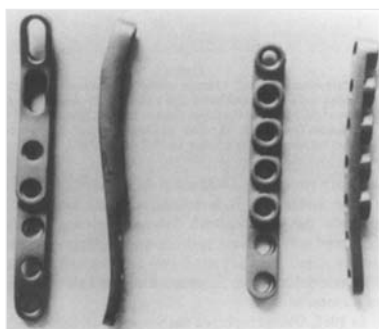


**Fig. 2.5** Harrington's rod system.  
(Reproduced from Vialle L, Berven S, de Kleuver M, AOSpine Master Series, Vol. 9: Pediatric Spinal Deformities, ©2017, Thieme Publishers, New York.)

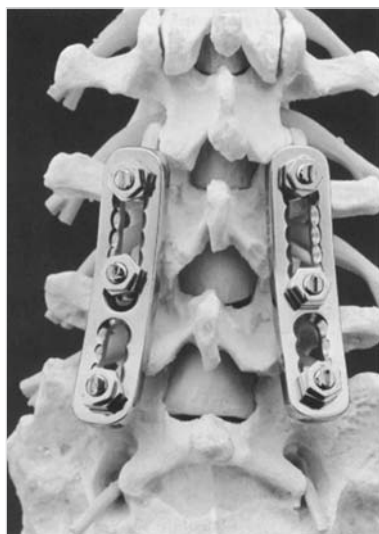
to its myriad complications like dural compromise and need for an concomitant external brace. Eduardo Luque modified Harrington's approach in 1976 with his own Luque rod system, which used long contoured rods affixed with sublaminar wires.<sup>15</sup> This signaled the arrival of three-column fixation with the transpedicular screw, a significant step toward modern techniques. Michele and Krueger first described pedicle screw fixation in 1949, but it was not until the 1960s that this fixation technique established its dominance as the main approach for posterior fixation.<sup>15</sup> The surgeons responsible for its rise in popularity and codification were Roy-Camille in 1970, followed by Arthur D. Steffee in the United States with the development of his variable plating system and the Steffee screw (► Fig. 2.6 and ► Fig. 2.7).<sup>16,17</sup>

## 2.5 Instrumentation

The accomplishments of the above surgeons would not have been possible without the long history of invention not only from their compatriots, but also from the innovative thinking of other pioneers of surgery



**Fig. 2.6** Pedicle screw plate fixation system designed by Roy-Camille made from cobalt-chromium. (Reproduced from Kabins MB, Weinstein JN, The history of vertebral screw and pedicle screw fixation, Iowa Orthop J. 1991;11:127–136.)

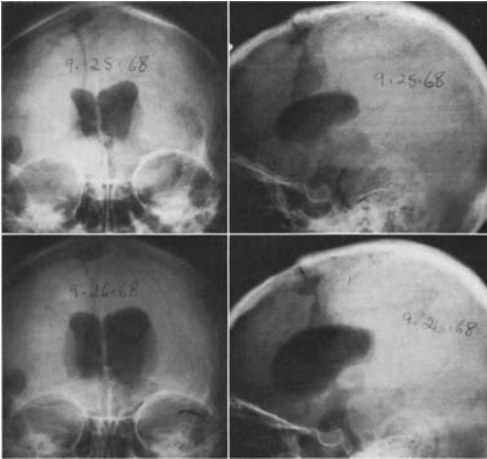


**Fig. 2.7** Steffee, or variable screw placement, system.

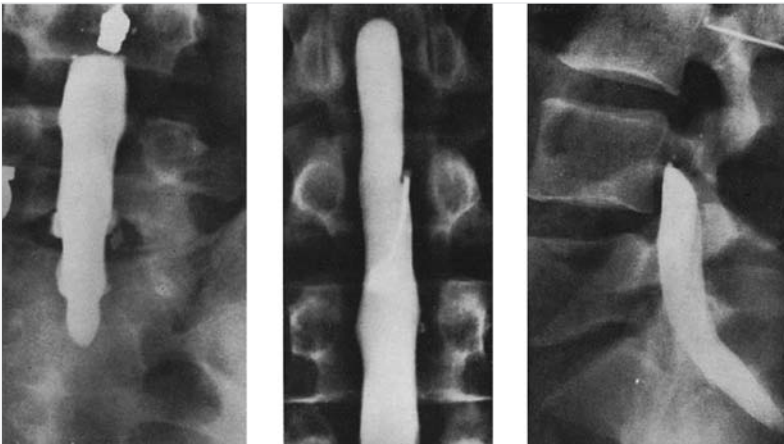
and even visionaries outside of medicine. A summary of these remarkable achievements is catalogued chronologically below.

- 1851: Hermann von Helmholtz invented the ophthalmoscope, introducing the fundoscopic examination and a helpful tool in diagnosing intracranial mass lesions.
- 1876: Saemisch, a German surgeon, was the first to wear loupes while operating.
- 1885: James L. Corning performed the first lumbar puncture, but it was not used in practice as a diagnostic and therapeutic tool until 1891 by Heinrich Quincke.
- 1892: Sir Victor Horsley introduced an antiseptic wax in 1892 to control diploic bleeding and to achieve hemostasis, although there is evidence that Henri Dolbeau, a Parisian surgeon, first used bone wax in 1864 during extirpation of a frontal osteoma.<sup>18</sup>
- 1895: Wilhelm Röntgen invented X-ray-based radiography, which subsequently bears his name (roentgenography). Craniography and spondylography were created once Röntgen's idea was adapted to the needs of neurological surgery.
- 1898: Leonardo Gigli adapted his famous saw for cranial surgery by creating a curved wire that would not damage the dura during formation of the bone flap.<sup>19</sup>
- 1908: The electric drill replaced hand-powered trephining after Thierry de Martel's improvement upon the design of the foot-powered drills that dentists were using. That same year, German neurosurgeon Fedor Krause introduced an electrical suction for use in surgery, which Cushing improved upon in 1920.<sup>20</sup>
- 1911: Cushing introduces silver clips for hemostatic control (► Fig. 2.3).
- 1918: Walter Dandy invented pneumoventriculography, and pneumoencephalography the following year in 1919. In these studies, he injected air into the patient's cerebrospinal fluid (CSF) spaces before shooting a craniograph, outlining the ventricular system and subarachnoid territories (► Fig. 2.8).

- 1920: William T. Bovie, a plant physiologist, invented his famous electrocoagulator, which used electric current to produce focused intense heat. Cushing applied this invention to his surgical practice in 1927 (► Fig. 2.4).<sup>21,22</sup>
- 1921: Jean-Athanase Sicard injected a contrast dye, lipiodol, into the CSF areas as Dandy had done with air, which was then followed by an X-ray. His experiments produced the first myelogram (► Fig. 2.9). Carl Nylén also designed and built the



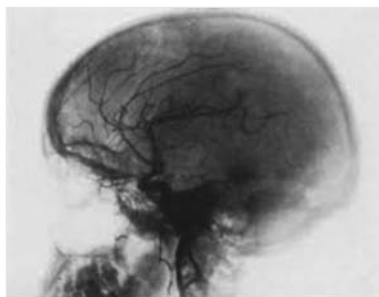
**Fig. 2.8** Pneumoencephalography and pneumoventriculography pioneered by Walter Dandy. (Reproduced, with permission, from Rover RL, et al, Progressive ventricular dilation following pneumoencephalography: a radiological sign of occult hydrocephalus, JNS. 1972;36(1):50-59.)



**Fig. 2.9** X-ray myelography as engineered by Sicard. (Reproduced, with permission from Mason MF, Raaf J, Complications of pantopaque myelography, J Neurosurg. 1962;19:302-311.)

world's first surgical microscope in this year, which he used for the first time for a case of chronic otitis media. It was upgraded from monocular to binocular in 1922 by Gunnar Holmgren, a Swedish otolaryngologist.<sup>23</sup>

- 1924: Hans Berger develops the electroencephalogram (EEG), building on the work of Fritsch and Hetsch. He first used his EEG during a neurosurgical operation on a 17-year-old boy by Nikolai Guleke.<sup>24</sup>
- 1927: A. Egas Moniz adapted the previous two techniques from Dandy and Sicard to intracranial vasculature, thus inventing cerebral arteriography (► Fig. 2.10).
- 1944: Franc Ingraham and Orville Bailey discover the hemostatic utility of fibrin foam, a product prepared by fractionation of human plasma, and the duralike nature of fibrin film. Cohn and colleagues were simultaneously working on a similar product made from fractionated plasma called Gelfoam.<sup>25,26</sup>



**Fig. 2.10** Moniz's cerebral arteriography adapted from Dandy and Sicard's techniques for visualization of cranial and spinal cerebrospinal fluid spaces. (Reproduced, with permission, from Lobo Antunes, J. Egas Moniz and cerebral angiography, *J Neurosurg.* 1974;40:427–32.)

- 1947: Spiegel and Wycis report the first human use of a stereotactic apparatus to target intracranial lesions, laying the foundation for frame-based stereotactic brain biopsies.<sup>27</sup>
- 1951: Lars Leksell coins the term "stereotactic radiosurgery"<sup>28</sup> and thereafter develops the first Gamma Knife in 1967 for the treatment of trigeminal neuralgia.
- 1953: Paul Harrington develops his rod system for posterior spinal fixation and fusion.
- 1955: Leonard Malis develops bipolar coagulation by using fine-tip jeweler's forceps.<sup>29</sup>
- 1957: Theodore Kurze became the first neurosurgeon to use a microscope during surgery.
- 1960s: A revolution was underway in neurosurgery with the microscope at its center. Contributors to its development included R.M.P. Donaghy, Julius Jacobson, Ernesto Suarez, M.G. Yasargil, and Harold Buncke, a plastic surgeon. Jacobson was also the leader in early microsurgical instrumentation, credited with creating the original microneedle holder and microscissors.
- 1970s–1980s: The advent of computed tomography (CT) in the early 1970s and the emergence of magnetic resonance imaging (MRI) in the later 1970s provided the ability to visualize the brain and gave neurosurgeons the opportunity to target tumors or perform functional lesions to restore function. The first CT and first MRI applied to patients were in 1971 and 1977 respectively.<sup>30</sup>
- 1988: L. Dade Lunsford installs the first Gamma Knife in the United States.<sup>31</sup> Gamma Knife offers noninvasive alternative treatment for a variety of intracranial targets.
- 1990s: Ken Winston and Wendell Lutz adapt radiosurgery to linear accelera-



tors, later redesigned and dedicated to radiosurgery and fractionated stereotactic radiotherapy.<sup>32</sup> Mark Carol invents intensity modulation, allowing for three dimensional shaping of radiation.<sup>33</sup>

- 2000s: The rod-lens endoscope is refined and coupled to minimally invasive image-guided approaches to the parasellar region, lowering morbidity and length of hospital stay for tumors previously requiring lengthy transcranial microneurosurgical dissection with significant postoperative morbidities and prolonged hospitalizations.

### Pearls

- Among the titans of neurosurgery before the modern era, Horsley, Macewen, and Cushing are the key contributors to remember.
- Prior to the late 1800s, neurosurgery advanced little and was limited to the simple technique of trephining for cranial access. Spine surgery was almost out of the question, given the rates of infection.

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## 3 Neurological Examination

*Prateek Agarwal, Daniel Y Zhang, M Sean Grady*

### 3.1 Introduction

Historically, the neurological examination was the primary method by which neurosurgeons evaluated a patient's neurologic status, determined anatomic sites of dysfunction, and deduced the underlying pathology. Today, however, outpatients often arrive at the clinic with laboratory testing, electrophysiological studies, imaging, prior evaluation by a neurologist or primary care provider, and even an established diagnosis. Thus, in practice, neurosurgeons use a focused and selective neurological examination to corroborate pathology identified by other diagnostic modalities and assess the functional status of the patient. Similarly, for inpatients, the neurological examination is a rapid and cost-effective first-line assessment for tracking patient progress and assessing acute changes. This chapter summarizes key elements of the neurological examination.

### 3.2 Mental Status

This chapter offers a brief overview of the mental status examination (MSE), which is an important tool in assessing functional and cognitive deficits (►Table 3.1). This can be important in evaluating a patient with dementia; and from a neurosurgical perspective, the MSE may help localize a lesion to cortical regions of the cerebral cortex (frontal, parietal, temporal, and occipital lobes), which are regions of higher cognitive function. Importantly, if level of consciousness (►Table 3.2) and language (►Table 3.3) are not intact, other elements of the MSE cannot be accurately assessed.

### 3.3 Cranial Nerves

The integrity of a cranial nerve (CN) can be determined by quickly assessing its respective function (►Table 3.4).

#### 3.3.1 CN I

CN I is rarely tested in clinical practice, but can be tested by having the patient identify common odors in one nostril at a time (e.g., coffee, vanilla).

#### 3.3.2 CNs II and III

The examiner should have the patient cover one eye at a time while covering his or her own contralateral eye. The examiner should then hold up some fingers in the most peripheral areas of the visual fields and ask the patient to identify how many fingers are held up. Monocular vision loss localizes anterior to the chiasm, bitemporal hemianopia localizes to the crossing fibers of the chiasm, and homonymous hemianopia/quadrantanopia localizes posterior to the chiasm (see ►Fig. 18.1). Acuity can be tested using a hand-held visual acuity card one eye at a time.

### Fundusoscopic Examination

The fundusoscopic examination is performed using an ophthalmoscope in darkness and ideally with the patient's pupil dilated. One should generally observe a red reflex (reddish-orange reflection off retina), the margins and size of the optic disc, retinal vessel abnormalities, and retinal lesions (e.g., hemorrhages, exudates).

**Table 3.1** Mental status examination for neurosurgeons

| Elements                                                                                                                                                   | Assessment                                                                                                         | Descriptors                                                                                                                                                                                                        |
|------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Level of consciousness                                                                                                                                     | GCS, FOUR score                                                                                                    | Alert, attentive, vigilant, drowsy, lethargic, fluctuating, confused, unresponsive, asleep                                                                                                                         |
| Orientation                                                                                                                                                | “What is your full name?”<br>“Where are we?”<br>“What is today’s date?”                                            | Oriented to person, place, and time                                                                                                                                                                                |
| Attention                                                                                                                                                  | Subtracting serial 7s from 100, spell “world” backwards                                                            | Intact/impaired                                                                                                                                                                                                    |
| Language                                                                                                                                                   | Fluency, repetition, naming, comprehension, reading/writing                                                        | Fluency: Quantity, rate, rhythm<br>Repetition: Able to repeat phrases<br>Naming/comprehension: able to name high/low frequency objects, able to follow simple/complex commands<br>Reading/writing: Intact/impaired |
| Perceptual disturbances                                                                                                                                    | Perceptions of environment, perceptions of self                                                                    | Hallucinations, illusions, depersonalization, derealization                                                                                                                                                        |
| Memory and cognition                                                                                                                                       | Immediate, recent, and remote memory (5-min delayed recall of 3 items)<br>MMSE, Mini-Cog, MoCA, clock-drawing test | Intact/impaired                                                                                                                                                                                                    |
| Abbreviations: FOUR, Full Outline of Un Responsiveness; GCS, Glasgow Coma Scale; MMSE, mini mental state examination; MoCA, Montreal Cognitive Assessment. |                                                                                                                    |                                                                                                                                                                                                                    |

**Table 3.2** Glasgow Coma Scale grading scale

| Glasgow Coma Scale | Response                   | Score |
|--------------------|----------------------------|-------|
| Eye opening        | Spontaneous                | 4     |
|                    | Response to verbal command | 3     |
|                    | Response to pain           | 2     |
|                    | No eye opening             | 1     |
| Verbal response    | Oriented                   | 5     |
|                    | Confused                   | 4     |
|                    | Inappropriate words        | 3     |
|                    | Incomprehensible sounds    | 2     |
|                    | No verbal response         | 1     |
| Motor response     | Obeys commands             | 6     |
|                    | Localize to pain           | 5     |
|                    | Withdraw to pain           | 4     |
|                    | Flexion to pain            | 3     |
|                    | Extension to pain          | 2     |
|                    | No motor response          | 1     |

**Table 3.3** Aphasia syndromes and the associated locations of pathology

| Syndrome              | Fluency | Repetition | Compre-<br>hension | Reading | Writing | Localization                                                                                |
|-----------------------|---------|------------|--------------------|---------|---------|---------------------------------------------------------------------------------------------|
| Broca's               | -       | -          | +                  | +       | -       | Broca's area                                                                                |
| Wernicke's            | +       | -          | -                  | -       | -       | Wernicke's area                                                                             |
| Anomic                | +       | +          | +                  | +/-     | +/-     | Temporal, parietal, and occipital regions of the cortex outside of classical language areas |
| Conduction            | +       | -          | +                  | +       | +/-     | Arcuate fasciculus                                                                          |
| Transcortical motor   | -       | +          | +                  | +       | -       | Left mesial frontal, supplementary motor area                                               |
| Transcortical sensory | +       | +          | -                  | -       | -       | Left posterior watershed zone between MCA and PCA territories                               |
| Transcortical mixed   | -       | +          | -                  | -       | -       | Anterior and posterior watershed zones                                                      |
| Global                | -       | -          | -                  | -       | -       | Vast region of the left hemisphere                                                          |
| Pure word deafness    | +       | +          | -                  | +       | +       | Left or bilateral superior temporal gyrus lesion                                            |
| Pure alexia           | +       | +          | +                  | -       | +       | Left occipital lobe with involvement of splenium of corpus callosum                         |
| Aphemia               | -       | +          | +                  | +       | +       | Motor cortex outflow to articulators                                                        |
| Pure agraphia         | +       | +          | +                  | +       | -       | Left inferior frontal region                                                                |

Abbreviations: MCA, middle cerebral artery; PCA, posterior cerebral artery.

**Table 3.4** Cranial nerves and their functions

| Cranial Nerve            | Function                                                                                                                                                           |
|--------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| I (Olfactory)            | Sensory: Olfaction                                                                                                                                                 |
| II (Optic)               | Sensory: Vision                                                                                                                                                    |
| III (Oculomotor)         | Motor: Extraocular muscles, levator palpebrae superioris<br>Parasympathetic: Pupillary constrictor, ciliary muscles                                                |
| IV (Trochlear)           | Motor: Extraocular muscle (superior oblique)                                                                                                                       |
| V (Trigeminal)           | Sensory: Sensation of the face, cornea, nasal and oral cavities, anterior 2/3 of the tongue<br>Motor: Muscles of mastication, tensor tympani                       |
| VI (Abducens)            | Motor: Extraocular muscle (lateral rectus)                                                                                                                         |
| VII (Facial)             | Sensory: Taste of anterior 2/3 of tongue<br>Motor: Muscles of facial expression, stapedius<br>Parasympathetic: Salivary and lacrimal glands                        |
| VIII (Vestibulocochlear) | Sensory: Hearing, vestibular system                                                                                                                                |
| IX (Glossopharyngeal)    | Sensory: Sensory and taste of the posterior 1/3 of tongue, pharynx<br>Motor: Stylopharyngeous<br>Parasympathetic: Salivary glands                                  |
| X (Vagus)                | Sensory: Pharynx, larynx, thoracic, and abdominal viscera<br>Motor: Soft palate, pharynx, larynx<br>Parasympathetic: Cardiovascular, respiratory, gastrointestinal |
| XI (Accessory)           | Motor: Sternocleidomastoid, trapezius                                                                                                                              |
| XII (Hypoglossal)        | Motor: Tongue muscles                                                                                                                                              |

## Pupillary Light Reflex

The pupillary light reflex simultaneously tests CNs II and III, as CN II senses incoming light and parasympathetic fibers running along the outside of CN III stimulates the pupillary constriction both in the ipsilateral eye (direct reflex) and in the contralateral eye (consensual reflex). The examiner should shine light directly onto one eye and observe whether both pupils constrict equally, and then test the other eye in the same manner. If the examiner swings the penlight back and forth between eyes, and one pupil is consistently larger than the other, this

suggests an afferent pupillary defect (APD) whereby CN II of the eye with the larger pupil is not intact.

### 3.3.3 CNs III, IV, and VI

## Eye Movements

The examiner should first observe for any ptosis, eye deviation, and nystagmus (involuntary eye movements) at baseline. Then, the examiner should have the patient follow his or her finger to make an “H” in space and observe if either eye is unable to fully move in a particular direction or if any nystagmus is elicited.

Classic nerve palsies include CN III palsy (“down and out”) in which the affected eye cannot be raised or adducted, CN VI palsy in which the affected eye cannot be abducted, and CN IV palsy in which the affected eye cannot look “in and down” (e.g., going down stairs, reading a book). Another classic finding is an internuclear ophthalmoplegia (INO) as a result of medial longitudinal fasciculus (MLF) damage in which the affected ipsilateral eye cannot adduct when it attempts to gaze contralateral relative to the affected eye.

## Vestibulo-ocular Reflex

The vestibulo-ocular reflex (VOR) assesses the integrity of both CN VIII and two nerves that control extraocular muscles (CNs III and VI) simultaneously because activation of the vestibular system through head movement in one direction produces eye movement in the other direction, thereby enabling the eyes to remain fixed on a target. The VOR can also be elicited via cold-caloric testing, especially during a brain death examination, which mimics head movement away from the ear in which cold water is infused. Intact brainstem function is indicated by eyes moving toward the ipsilateral ear, while intact cortical function is indicated by contralateral horizontal nystagmus. It should be noted that if voluntary eye movement is impaired, but the VOR is intact, this points to a supranuclear gaze palsy stemming from a lesion above the brainstem.

### 3.3.4 CN V

#### Facial Sensation

Facial sensation can initially be tested using light touch or pinprick testing on the

patient’s forehead (V1 ophthalmic division), cheeks (V2 maxillary division), and chin (V3 mandibular division). The examiner should have the patient close both eyes and ask if light touch or pinprick feels the same on both sides and probe for any pain, paresthesias, or numbness in each of the three divisions.

## Muscles of Mastication

To test the muscles of mastication, the examiner should have the patient open the jaw and close the jaw against resistance as well as move the chin laterally on both sides.

### 3.3.5 CN VII

#### Facial Strength

Facial strength can easily be assessed by having the patient shut the eyes tightly, smile, and puff out the cheeks. The examiner can also observe more subtle signs of facial weakness such as mild facial droop, nasolabial fold flattening, drooling, or dysarthria. With regards to CN VII, a central lesion will affect the contralateral lower half of the face but spare the forehead, whereas a peripheral lesion will affect the entire ipsilateral face.

## Blink-to-Threat

Blink-to-threat is generally reserved for the patient with depressed consciousness or aphasia. It simultaneously tests CNs II and VII, as CN II transmits visual information from a threat, whereas CN VII controls blinking. The examiner should flick his or her fingers near the lateral edge of each eye and observe for blinking, being careful not to stimulate the corneal reflex (CNs V and VII) with excessive air movement or actually touching the cornea.

### 3.3.6 CN VIII

#### Vestibular Function

The VOR via head movement and cold-caloric testing can be assessed to evaluate the integrity of CN VIII. The presence of nystagmus that suppresses with visual fixation and is not direction-changing also suggests a peripheral CN VIII lesion that is affecting vestibular function.

#### Hearing Function

The examiner can grossly assess hearing by rubbing his or her fingers together close to the patient's ear while the patient's eyes are closed. The Weber and Rinne tests using a 512 Hz tuning fork may provide a more detailed assessment to distinguish between sensorineural and conductive hearing loss.

### 3.3.7 CN XI

Strength of the sternocleidomastoid is tested by asking the patient to rotate the head against resistance (hand pushing on chin). Strength of the trapezius is tested by asking the patient to shrug the shoulders against resistance (hands pushing on shoulders).

### 3.3.8 CNs IX, X, and XII

#### Palatal Movement

The examiner should instruct the patient to open the mouth and say "ahhh", observing for symmetric upward movement of the palate as well as the absence of uvula deviation. A CN X lesion may result in contralateral uvula deviation.

#### Gag Reflex

If the examiner requires more information, a gag reflex can be performed to simultaneously assess CNs IX and X, whereby the

response to stimulating the oropharynx with a cotton swab on either side is compared.

#### Tongue Movement

The patient should protrude the tongue and move it laterally in both directions as well as superiorly and inferiorly. In addition, the examiner should have the patient push the tongue against the inside of the cheek on both sides with resistance from the examiner pushing on the outside of the cheek. A CN XII lesion may result in ipsilateral tongue deviation.

#### Dysarthria

Lesions of these nerves may result in dysarthria, which is a disorder of speech production rather than language. Verbal articulation may be tested with the following phrases: "no ifs, ands, or buts", "baseball player", and "fifty-fifty."

## 3.4 Motor Examination

### 3.4.1 Bulk

The motor examination should begin with an inspection of muscle bulk, looking for symmetry, atrophy, and fasciculations, which are random, spontaneous, and involuntary muscle twitches.

### 3.4.2 Tone

Muscle tone refers to residual tension in a relaxed muscle, which often manifests as the resistance to passive stretch in a relaxed muscle. In order to accurately assess tone, the patient must relax the muscles and allow the examiner to move them passively.

Hypertonia is further described as spastic or rigid. Spasticity is seen when a

limb is moved quickly, the tone increases and more force is required to move the limb further. This is often tested with passive foot dorsiflexion. In contrast, increased tone in rigidity does not depend on how fast the muscle is moved. Cogwheel rigidity is characterized by rhythmic, jerky increased tone during passive motion, whereas lead-pipe rigidity is characterized by continuous increased tone during passive motion.

### 3.4.3 Strength

When testing muscle movements, the examiner should have the patient resist the examiner as he or she attempts to move a certain limb. It is important that

each movement is performed with the relevant joint stabilized, such that muscles and the nerves that innervate them are tested in isolation (►Table 3.5). If a patient is unable to overcome any resistance, the examiner should have the patient perform the movements without resistance both against gravity and in a plane that eliminates the effect of gravity in order to appropriate grade strength (►Table 3.6).

### Subtle Weakness

#### Drift

In clinical practice, drift can refer to either simple extremity drift or pronator drift. Extremity drift refers to an extremity

**Table 3.5** Major muscles and their associated movements and innervation

|                   | Spinal cord level | Peripheral nerve        | Movement                             | Major muscle(s)                                                                        |
|-------------------|-------------------|-------------------------|--------------------------------------|----------------------------------------------------------------------------------------|
| Upper extremities | C5                | Axillary nerve          | Shoulder abduction                   | Deltoid                                                                                |
|                   | C5–C6             | Musculocutaneous nerve  | Elbow flexion                        | Biceps                                                                                 |
|                   | C7                | Radial nerve            | Elbow extension                      | Triceps                                                                                |
|                   | C7–C8             | Median and ulnar nerves | Wrist flexion                        | Flexor carpi radialis, flexor carpi ulnaris                                            |
|                   | C7                | Radial nerve            | Wrist extension                      | Extensor carpi radialis brevis, extensor carpi radialis longus, extensor carpi ulnaris |
|                   | C7                | Radial nerve            | Finger extension                     | Extensor digitorum                                                                     |
|                   | C8–T1             | Median and ulnar nerve  | Finger flexion                       | Flexor digitorum profundus, flexor digitorum superficialis                             |
|                   | C8–T1             | Median nerve            | Thumb opposition, abduction, flexion | Opponens pollicis, abductor pollicis brevis, flexor pollicis brevis                    |
|                   | C8–T1             | Ulnar nerve             | Finger abduction                     | Dorsal interosseus muscles                                                             |

(Continued)

**Table 3.5** (Continued) Major muscles and their associated movements and innervation

|                   | Spinal cord level | Peripheral nerve   | Movement             | Major muscle(s)                                                     |
|-------------------|-------------------|--------------------|----------------------|---------------------------------------------------------------------|
| Lower extremities | L1–L3             | Nerve to iliopsoas | Hip flexion          | Iliopsoas                                                           |
|                   | L3                | Obturator          | Hip adduction        | Adductor brevis, adductor longus, adductor magnus, adductor minimus |
|                   | L3–L4             | Femoral            | Knee extension       | Quadriceps                                                          |
|                   | L4–L5             | Peroneal           | Ankle dorsiflexion   | Tibialis anterior                                                   |
|                   | L5                | Superior gluteal   | Hip abduction        | Gluteus medius, gluteus minimus                                     |
|                   | L5                | Peroneal           | Big toe extension    | Extensor hallucis longus                                            |
|                   | L5–S1             | Sciatic            | Knee flexion         | Biceps femoris                                                      |
|                   | S1                | Inferior gluteal   | Hip extension        | Gluteus maximus                                                     |
|                   | S1                | Peroneal           | Foot eversion        | Fibularis peroneus brevis, fibularis peroneus longus                |
|                   | S1                | Tibial             | Ankle plantarflexion | Gastrocnemius                                                       |
|                   | S1                | Tibial             | Big toe flexion      | Flexor hallucis longus                                              |

**Table 3.6** Strength grading scale

| Score | Criteria                 |
|-------|--------------------------|
| 5     | Full strength            |
| 4     | Overcome some resistance |
| 3     | Overcome gravity         |
| 2     | Cannot overcome gravity  |
| 1     | Muscle twitching         |
| 0     | No muscle contraction    |

gradually drifting downward after 5–10 seconds when voluntarily raised against gravity. Pronator drift is assessed by having the patient fully extend the arms at shoulder level with the palms facing upwards. The patient should then close the eyes and shake

the head for approximately 10 seconds. Arm pronating and downward drift are signs of an upper motor neuron lesion.

Satelliting

Satelliting is another sign of subtle weakness and is assessed by having the patient rotate the arms around each other. If one arm becomes more stationary after several seconds with the other arm “satelliting” around it, this suggests some degree of weakness in the stationary arm.

3.4.4 Involuntary

There are several involuntary motor movements that the examiner should also note should they be present (► Table 3.7).



## 3.5 Reflex Examination

### 3.5.1 Reflex Grading

There are several deep tendon reflexes that the examiner should assess (► Table 3.8). Deep tendon reflexes are graded on a scale from 0 to 4, where 0 is absent, 1 is reduced, 2 is normal, 3 is increased, and 4 is defined

as myoclonus. As this scale is relatively subjective, comparing right-sided and left-sided reflexes is often more valuable than the grading itself.

### 3.5.2 Babinski's Sign

Babinski's sign is a primitive reflex that occurs in infants and normally disappears by 12 months of age. The examiner assesses for Babinski's sign by stroking the sole of the patient's foot with a blunt instrument along the lateral aspect starting at the heel and then moving in a curve just below the toes. In adults, the normal response is a flexor plantar response (i.e., down-going big toe), whereas the abnormal Babinski's sign is an extensor plantar response (i.e. up-going big toe).

### Hoffman's sign

Hoffman's sign is not a true primitive reflex and can be present in normal adults. The examiner assesses for Hoffman's sign by flicking distal aspect of the middle finger and observing for any flexion of the thumb. The presence of Babinski's and/or Hoffman's sign can suggest an upper motor neuron (UMN) lesion.

A careful motor and reflex examination can often distinguish between UMN and

**Table 3.7** Involuntary movements

| Movement  | Features                                                                     |
|-----------|------------------------------------------------------------------------------|
| Tremor    | Note frequency, amplitude, resting vs. intention                             |
| Myoclonus | Brief, twitching muscle jerk                                                 |
| Chorea    | Brief, irregular, jerky movements that flow from muscle to muscle            |
| Athetosis | Slow writhing of the extremities                                             |
| Ballismus | Large amplitude flinging                                                     |
| Tics      | Abrupt repetitive motor movements or vocalizations                           |
| Dystonia  | Sustained or repetitive muscle contraction leading to abnormal fixed posture |

**Table 3.8** Deep tendon reflexes

| Reflex          | Spinal cord level | Location to elicit                                                      |
|-----------------|-------------------|-------------------------------------------------------------------------|
| Biceps          | C5–6              | Anterior aspect of the elbow, insertion of biceps tendon on the forearm |
| Brachioradialis | C5–6              | Radial aspect of forearm, either proximally or distally                 |
| Triceps         | C7                | Posterior aspect of the elbow, just proximal to the olecranon           |
| Knee jerk       | L3–L4             | Anterior knee, just distal to the patella                               |
| Ankle jerk      | S1                | Posterior aspect of the ankle, on the Achilles tendon                   |

**Table 3.9** Features of upper motor neuron versus lower motor neuron dysfunction

| Upper motor neuron | Lower motor neuron |
|--------------------|--------------------|
| Spasticity         | Muscle atrophy     |
| Hyperreflexia      | Hyporeflexia       |
| Myoclonus          | Fasciculations     |
| Babinski's sign    |                    |
| Hoffman's sign     |                    |

lower motor neuron (LMN) lesions, as both will present with weakness, but UMN lesions lack inhibitory modulation via descending pathways (► Table 3.9).

## 3.6 Sensory Examination

### 3.6.1 Light Touch

To assess light touch, the examiner should ask the patient to close the eyes and indicate whether he or she feels touch in various regions of all extremities and the trunk. It is reasonable to begin more distally and then progress proximally.

### 3.6.2 Pain and Temperature

Pain is assessed in a similar manner to light touch, but with a sharp pin and asking the patient if it feels sharp or dull while the eyes are closed. Temperature sense is carried by the same afferent small fibers as pain, and can be assessed with a cold object (e.g., tuning fork).

### 3.6.3 Vibration

Vibration is assessed by placing a vibrating 128 Hz tuning fork against the patient's joints while the eyes are closed and asking if the patient feels vibration. If

the examiner can feel the tuning fork vibrating after the patient can no longer feel vibration, vibration sense may be partially impaired.

### 3.6.4 Proprioception

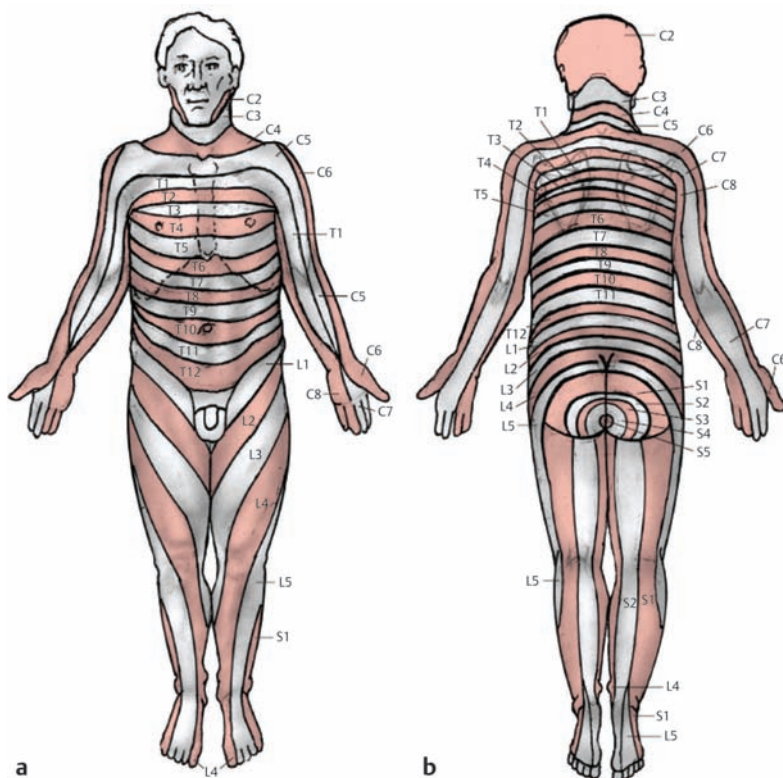
Proprioception refers to a sense of body position in space and can be assessed by having the patient close the eyes and state the direction of movement as the examiner moves a body part. Second, the examiner can perform the Romberg test, in which the patient stands up with the eyes closed and the examiner observes whether the patient loses balance without visual sensory information.

### 3.6.5 Sensory Localization

Findings from the sensory examination can be used for localization of lesions given the presence of dermatomes, which correspond to areas of sensory innervation arising from a single spinal nerve ganglion (► Fig. 3.1). It is worth remembering that the median nerve transmits sensation from the thumb, index finger, middle finger, and half of the fourth finger, while the ulnar nerve transmits sensation from the fifth finger and the other half of the fourth finger. In the leg, the common peroneal nerve transmits sensation from the lateral aspect of the lower leg and dorsum of the foot, while the tibial nerve transmits sensation from the posterior aspect of the lower leg and sole of the foot.

## 3.7 Gait and Coordination

Gait and coordination are critical aspects of the neurological examination because they can inform the examiner about the presence of a lesion in the cerebellum.



**Fig. 3.1** Sketch of human dermatome map with (a) anterior and (b) posterior views. (Reproduced from Khanna A, MRI Essentials for the Spine Specialist, ©2014, Thieme Publishers, New York.)

### 3.7.1 Gait

The examiner should begin by observing the patient's spontaneous gait. Following this, the examiner should have the patient walk on the heels and tiptoes. The examiner should also instruct the patient to perform tandem gait, where one foot is placed in front of the other for each step.

### 3.7.2 Coordination

The simplest coordination test is finger tapping, in which the patient taps the thumb to the index finger repeatedly as fast as possible. The examiner can also have the patient tap the thumb to each of the other fingers sequentially as fast as possible. Speed, accuracy, and rhythm should be assessed.

Rapid alternating movements can be tested by having the patient flip one hand back and forth as fast as possible against a flat surface or the other hand. Dysdiadochokinesis describes abnormal rapid alternating movements.

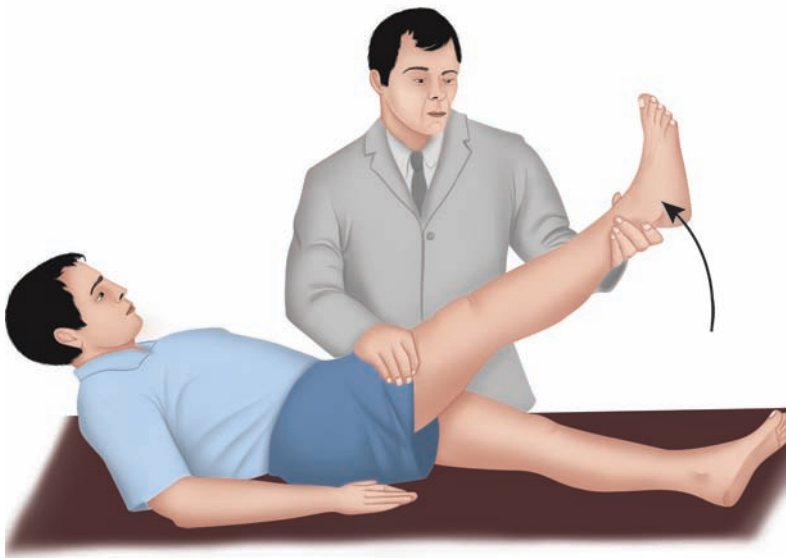
Finger-to-nose is performed by having the patient alternate touching the index finger to the examiner's index finger and then patient's own nose as the examiner moves his or her index finger to various positions. Heel-to-shin is performed by having the patient place the heel on the contralateral knee and move the heel down the shin. An abnormality in

accuracy with either of these tests is termed dysmetria.

## 3.8 Special Tests

### 3.8.1 Straight Leg Raise

The straight leg raise can be used to determine whether a patient may be suffering from lumbar radiculopathy, particularly of the L5 nerve root. The test is performed by having the patient lie supine and passively lifting the patient's straight leg. The examiner asks the patient whether this maneuver reproduces radiating sciatic pain down the leg (► Fig. 3.2).



**Fig. 3.2** Illustration of straight leg raise to evaluate for lumbar radiculopathy. (Reproduced from Albert T, Vaccaro A, *Physical Examination of the Spine*, 2nd edition, ©2016, Thieme Publishers, New York.)



**Fig. 3.3** Illustration of FABER test to evaluate for hip and sacroiliac joint pathology. (Reproduced from Vialle L, AOSpine Masters Series, Volume 8: Back Pain. 1st Edition, ©2016, Thieme Publishers, New York.)

### 3.8.2 FABER/FADIR Tests

The FABER (Flexion, ABduction, and External Rotation) test is used to evaluate hip and sacroiliac joint (SI) pathology, which may be important to distinguish from spinal pathology in evaluating a complaint of low back pain. The patient's leg is flexed, and the thigh is then abducted and externally rotated (► Fig. 3.3). A related test is the FADIR (Flexion, ADduction, and Internal Rotation) test where the patient's leg is flexed, and the thigh is then adducted and internally rotated. Each specific pain response guides decision-making regarding a corresponding pathology. Other tests to evaluate for sacroiliac joint pathology include distraction, compression, thigh trust, sacral trust, and Gaenslen's test.

### 3.8.3 Spurling Test

The Spurling test can be used to determine whether a patient may be suffering from cervical radiculopathy. The examiner performs the test by passively rotating the patient's head to the side while simultaneously applying downward and extending force on top of the patient's head. The examiner asks the patient whether this maneuver reproduces radiating pain from the neck on the same side of head rotation (► Fig. 3.4).

### 3.8.4 Lhermitte's Sign

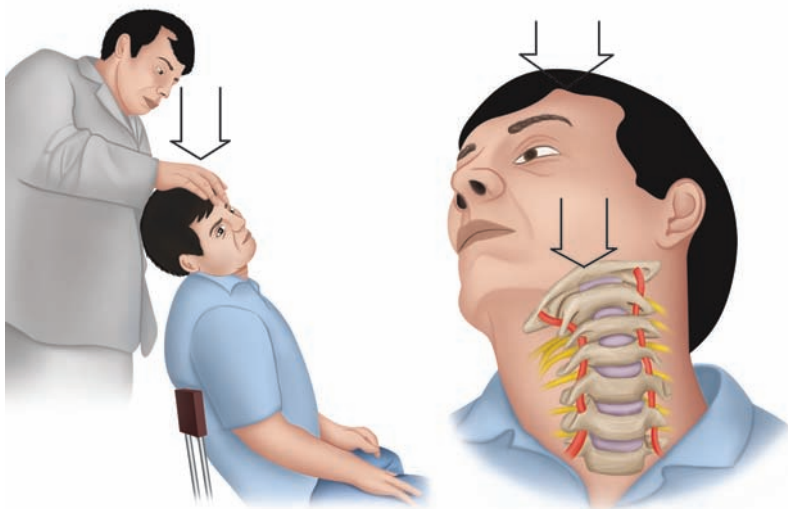
Lhermitte's sign suggests an upper cervical spinal cord lesion and is often described as an electrical shock sensation that passes down the neck and back and into the extremities. The examiner assesses for this sign by flexing the neck (i.e., bending the neck forward).

### 3.8.5 Tinel's Sign

Tinel's sign suggests irritated or damaged nerves and is performed by tapping directly over the nerve, resulting in paresthesias (i.e., tingling) within the sensory distribution of the nerve. Tinel's sign is commonly checked when evaluating for carpal tunnel syndrome from median nerve entrapment.

### Phalen's maneuver

Phalen's maneuver is specific to carpal tunnel syndrome and is performed by having the patient fully flex both wrists and then push the dorsal surfaces of the hands together for 60 seconds. Paresthesias within the sensory distribution of the median nerve during this maneuver suggests the presence of carpal tunnel syndrome.



**Fig. 3.4** Illustration of Spurling test to evaluate for cervical radiculopathy. (Reproduced from Albert T, Vaccaro A, *Physical Examination of the Spine*, 2nd edition, ©2016, Thieme Publishers, New York.)

### 3.8.6 Bulbocavernosus

The bulbocavernosus reflex involves S2–S4, and is a useful test for spinal shock or spinal cord injuries. The test is performed by monitoring internal or external anal sphincter contraction in response to squeezing the penis or clitoris, or tugging on an indwelling Foley's catheter (► Fig. 3.5).

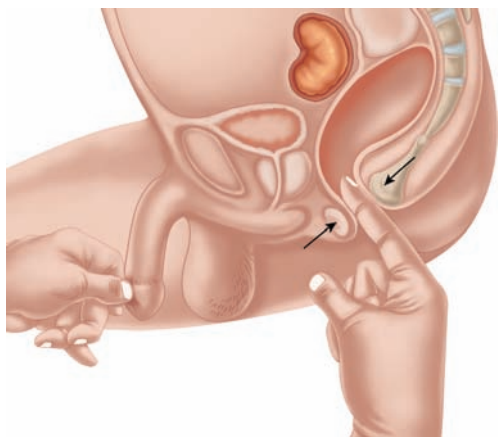
#### Pearls

- Use the neurological examination to corroborate pathology identified by other diagnostic modalities.
- Use the neurological examination to assess daily clinical status in the inpatient setting.
- Tailor the neurological examination to your own unique style as well as each patient and clinical situation.

## 3.9 Top Hits

### 3.9.1 Questions

1. A 26-year-old man with no relevant past medical history is brought into the ED following a motor vehicle collision. The patient's eyes are open and he was conversing with you appropriately. CT spine shows complete transection of cervical spinal cord. Patient is not moving any extremities. What is the GCS for this patient?
  - a) 9
  - b) 15
  - c) 14
  - d) 8
2. You ask a patient to name items in your white coat such as "pen" and "stethoscope", but the patient is unable



**Fig. 3.5** Illustration of eliciting the bulbocavernosus reflex (S2–S4) to evaluate for spinal shock after spinal cord injury. (Reproduced from Albert T, Vaccaro A, *Physical Examination of the Spine*, 2nd edition, ©2016, Thieme Publishers, New York.)

to do so. The patient is also unable to follow simple commands such as “stick out your tongue”. Otherwise, the patient speaks fluently, but the content is nonsensical. Where is the lesion?

- Broca's area
  - Arcuate fasciculus
  - Transcortical motor area
  - Wernicke's area
- You are called to evaluate a patient with a newfound facial droop. On examination, the corner of the patient's left mouth is drooping, there is nasolabial fold flattening, and the patient cannot close the left eye tightly. Where does the lesion localize?
    - Right-sided central CN VII
    - Right-sided peripheral CN VII
    - Left-sided central CN VII
    - Left-sided peripheral CN VII
  - On visual field examination, you ask the patient to cover up the right eye. The patient exclaims “Doc! The right side of your face is missing!” Intrigued, you ask the patient to cover up the left eye. The patient exclaims “Doc! Now the left side of your face is

missing!” Where does the lesion localize?

- Left optic nerve
  - Bilateral occipital lobes
  - Right thalamus
  - Optic chiasm
- A patient presents to the clinic with chief complaint of frequent tripping. When you ask the patient to walk up and down the hallway, the gait appears normal. When you ask the patient to walk on tippy-toes, you notice that the right heel barely lifts above the floor. To which spinal cord root does this motor deficit localize?
    - S1-S2
    - C8-T1
    - L4-L5
    - L2-L3
  - On a patient's MRI, you notice a lesion in the cortical region anterior to the central sulcus. What motor findings might you expect to see on neurological examination?
    - Pronator drift
    - Fasciculations
    - Diplopia
    - Positive Romberg sign

7. A 21-year-old college student was brought to ER for acute alcohol intoxication on Sunday morning after a night of festivities. On reflex examination, you notice that the biceps and brachioradialis reflexes are intact but the triceps reflex is diminished. To which spinal cord root does this deficit localize?
- C5
  - C6
  - C7
  - C8

8. A patient comes into the clinic complaining of back pain with radiation down the lateral aspect of the thigh and anterior aspect of the leg to the dorsum of the foot. On sensory examination, you also notice diminished pinprick sensation in the web space between the big toe and second toe. To which spinal cord root does this sensory deficit localize?
- L3
  - L4
  - L5
  - S1
9. A patient presents with a long history of pain in the right hand and wrist. On careful examination, you elicit tingling of the thumb, index, and middle finger by tapping the anterior aspect of the distal forearm. What other physical examination finding might you observe?
- Tingling in fifth finger
  - Atrophy of the thenar eminence
  - Weakness on wrist flexion
  - Positive Hoffman's sign
10. An 80-year-old patient presents to the clinic with a chief complaint of low back pain that gets worse after walking for 5 minutes and radiates along the lateral aspect of the right hip and thigh. On neurological examination, lower extremity strength is 5/5, reflexes are normal and symmetric, and

straight leg test is negative. What additional test would be helpful to localize the lesion?

- Bulbocavernosus reflex
- Babinski's sign
- Tandem gait
- FABER/FADIR

### 3.9.2 Answers

- b.** The patient has spontaneous eye opening (eye opening = 4) and oriented spontaneous speech (verbal = 5). Although he cannot move lower extremities, he is speaking appropriately which is indicative of full motor movement with his tongue (motor = 6).
- d.** The patient has deficits in comprehension, as manifested by impaired naming and an inability to follow commands. However, the patient speaks fluently though the content is nonsensical, which fits with a fluent aphasia from a lesion in Wernicke's area.
- d.** Central CN VII lesions result in contralateral facial weakness that spares the forehead, whereas peripheral CN VII lesions result in ipsilateral facial weakness that includes the forehead.
- d.** The clinical vignette describes bi-temporal hemianopia, meaning loss of temporal visual fields in both eyes. This usually results from compression of the optic chiasm, which contains crossing nasal retinal fibers.
- c.** The clinical vignette describes a case of foot drop, which is due to weakness in ankle dorsiflexion. This localizes to the L4–L5 spinal cord root, which contributes to the peroneal nerve and innervates the tibialis anterior muscle.



6. **a.** The cortical region anterior to the central sulcus corresponds to primary motor cortex. Thus, a lesion in this region may result in UMN findings, one of which is pronator drift. Fasciculations are a LMN finding.
7. **c.** The clinical vignette describes a case of radial neuropathy, colloquially known as “Saturday night palsy”, due to compression of the radial nerve in the axilla. The radial nerve is responsible for the triceps reflex and arises from the C7 spinal cord root. The biceps and brachioradialis reflexes correspond to the C5–C6 spinal cord root.
8. **c.** The distribution of the sensory deficit described in the clinical vignette corresponds to the L5 spinal cord root, which is particularly notable for carrying sensation from the web space between the big toe and the second toe.
9. **b.** The clinical vignette describes long-standing carpal tunnel syndrome that is confirmed on exam with Tinel’s sign. As compression of the median nerve underlies this syndrome, one would also expect atrophy of the muscles (thenar muscles) supplied by the median nerve over time.
10. **d.** The clinical vignette describes low back pain that might initially suggest radiculopathy with neurogenic claudication due to degenerative disc disease. However, given an unremarkable neurological examination with a negative straight leg test, it would be prudent to perform FABER/FADIR to evaluate for SI pathology, which can mimic lumbar spinal pathology. Additional tests for SI joint pathology include: compression, thigh thrust, distraction, and Gaenslen.

## Suggested Readings

- [1] Drislane F, Acosta J, Caplan L, Chang B, Tarulli A. Blueprints neurology. 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2013
- [2] Gelb DJ. The detailed neurologic examination in adults. 2012. [online] Available from: <https://www.uptodate.com/contents/the-detailed-neurologic-examination-in-adults>. Accessed June, 2017
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# 4 Neuroanatomy

David T Fernandes Cabral, Sandip S Panesar, Joao T Alves Belo, Juan C Fernandez-Miranda

## 4.1 Introduction

Neurosurgery as a surgical field relies on anatomical knowledge to successfully and safely perform a wide variety of procedures. These might be as simple as a lumbar puncture to the most complex skull base tumor resection. As such, this chapter reviews the most high-yield neuroanatomy topics.

## 4.2 Bones of the Skull

The human skull is divided into two regions: the face and cranium. The face is composed of 14 bones; while the cranium is composed of 8 bones. Here, we focus on cranial bones (► Table 4.1).

The cranial bones are joined via fibrous joints. Articulations between two adjacent bones are called sutures, and places where two or more sutures meet are named according to their location (► Fig. 4.1).

- **Nasion:** Suture between the frontal and nasal bones.
- **Bregma:** Located at the vertex of the skull vault at the point where the sagittal suture meets the coronal suture.
- **Pterion:** Located at the lateral aspect of the skull vault. The point where the greater wing of the sphenoid, the

frontal, parietal and squamous portion of the temporal bone meet.

- **Asterion:** Located posterolaterally. The point where the parietomastoid, occipitomastoid, and lamboid sutures meet.
- **Opisthion:** The name given to the posterior border of the foramen magnum at the midline.
- **Inion:** Also known as external occipital protuberance, correlates with the confluence of the venous sinuses on the internal surface. Routinely used as a surgical landmark.

### 4.2.1 Cranium

The cranium is an ovoid bony box which functions to protect the encephalon. For anatomical and clinical purposes, the cranium is divided into two segments—superolateral or vault, and inferior or skull base.

### Skull Vault

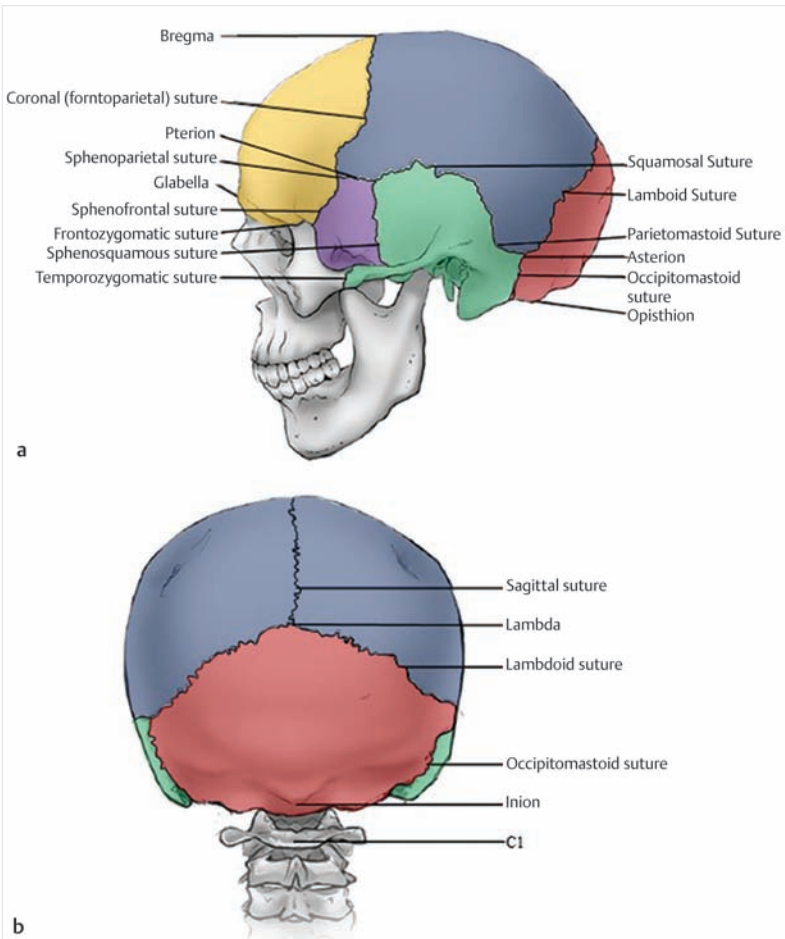
Comprised anteriorly by the vertical segment of the frontal bone; at its middle aspect by the parietal bones superiorly and the squamous portion of the temporal bones inferiorly; and posteriorly by the superior portion of the occipital bone.

### Skull Base

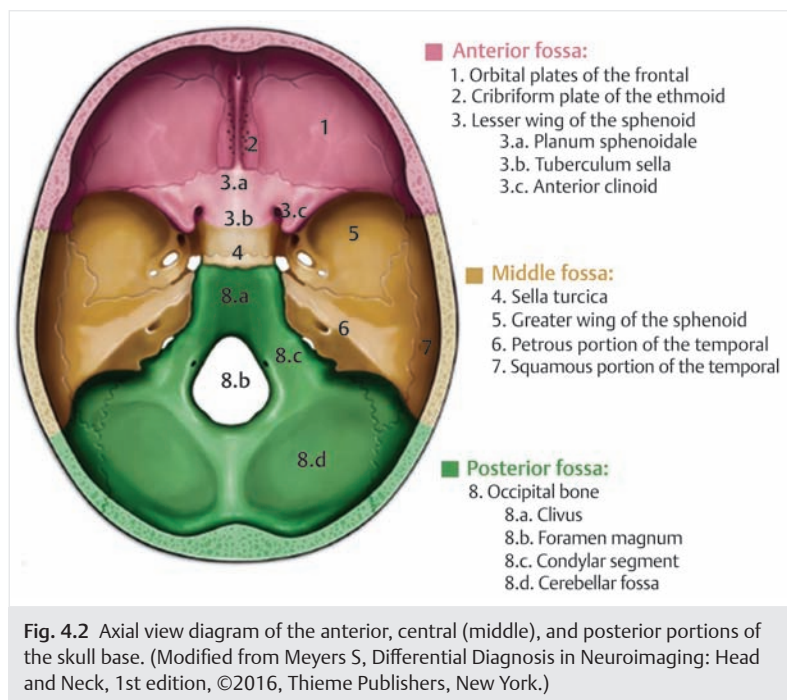
The internal surface of the skull base consists of three fossae, each with associated foramina which transmit efferent and afferent neurovascular structures (► Fig. 4.2 and ► Fig. 4.3).

**Table 4.1** Bones of the cranium (8 bones)

| Medial bones | Bilateral bones |
|--------------|-----------------|
| Frontal      | Parietal        |
| Ethmoid      | Temporal        |
| Sphenoid     |                 |
| Occipital    |                 |



**Fig. 4.1** Anatomic landmarks of the (a) lateral and (b) posterior skull. Frontal bone (yellow), parietal bone (blue), sphenoid bone (purple), temporal bone (green), occipital bone (red). (Modified from Di Ieva A, Lee J, Cusimano M, Handbook of Skull Base Surgery, 1st edition, ©2016, Thieme Publishers, New York.)



## 4.2.2 Clinical Applications

Kocher's point (► Fig. 4.4), Frazier's point. Please refer to chapter on *Operating Room* (► Table 6.2).

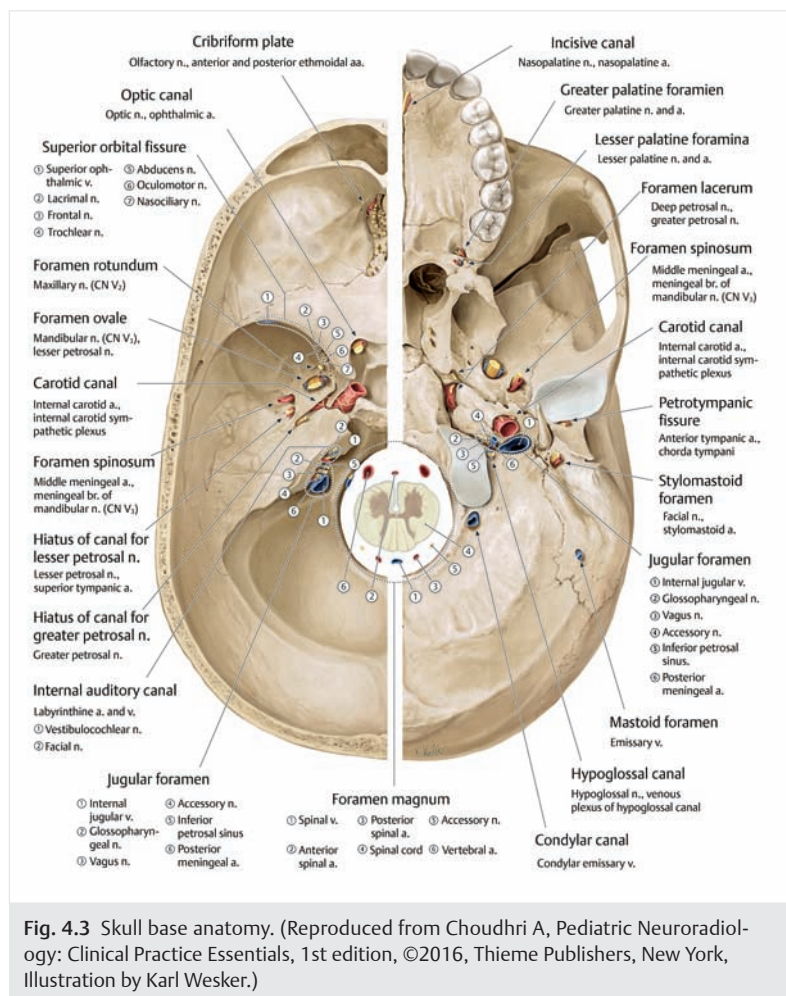
## Sinus Landmarks

A horizontal line across theinion delineates the trajectory of the transverse sinus. A vertical line going from the tip of mastoid and passing through the mastoid (digastric) groove delineates the sigmoid sinus. These landmarks are commonly used to plan craniotomies for retrosigmoid approaches (► Fig. 4.5).<sup>1</sup>

## 4.3 Cerebrum

### 4.3.1 Surface Anatomy

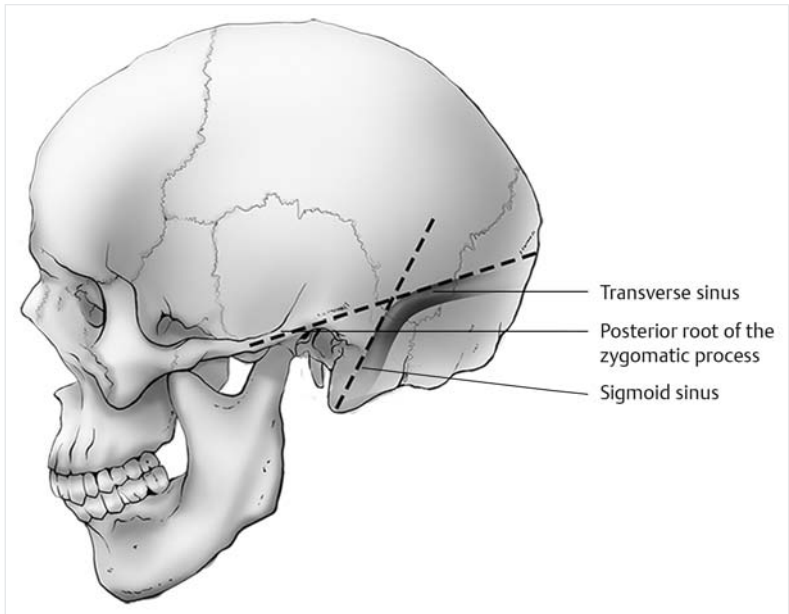
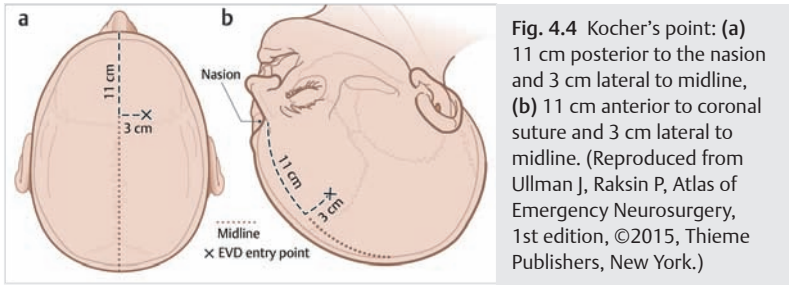
The brain is comprised of two hemispheres separated by an interhemispheric fissure (IHF), also known as longitudinal fissure of cerebrum. This fissure runs anteroposteriorly in the midline and it is occupied by an extension of the dura mater, known as the *falx cerebri*. Both hemispheres are joined together by the interhemispheric commissures: Corpus callosum, fornix, and the anterior commissure (► Fig. 4.6).



**Fig. 4.3** Skull base anatomy. (Reproduced from Choudhri A, Pediatric Neuroradiology: Clinical Practice Essentials, 1st edition, ©2016, Thieme Publishers, New York, Illustration by Karl Wesker.)

Each brain hemisphere is divided into five lobules. The divisions are centered around main sulci, which are deep and generally constant across subjects. Each

lobule has its own circumvolutions delineated by secondary and tertiary sulci, the latter demonstrating greatest intersubject variability (► Fig. 4.7).

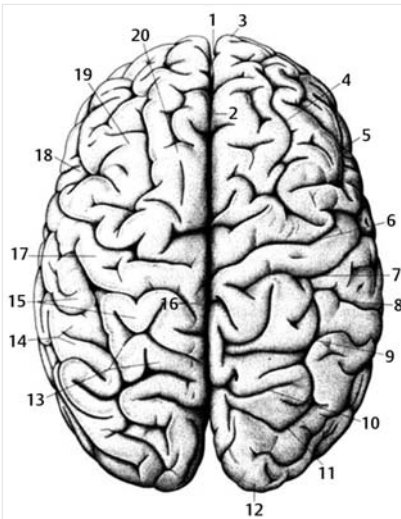


## Frontal Lobe

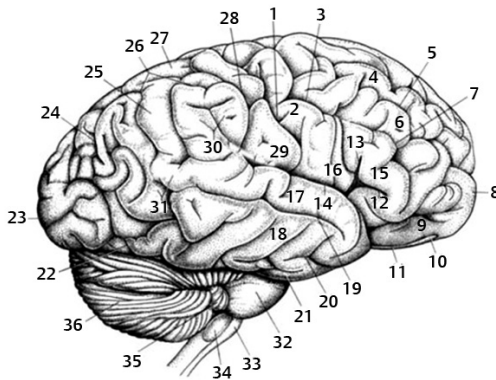
This is the largest cerebral lobe. When the brain is viewed from a lateral perspective, the frontal lobe is limited posteriorly by the central sulcus and inferiorly by the lateral sulcus (Sylvian fissure).

## Central Sulcus

Central sulcus separates the frontal and parietal lobes, following an oblique trajectory from superior to inferior, and posterior to anterior. It starts at the IHF and ends above the lateral sulcus, leaving a small



**Fig. 4.6** Brain surface anatomy, superior view. 1. Longitudinal fissure of cerebrum. 2. Superior margin of cerebrum. 3. Frontal pole. 4. Superior frontal sulcus. 5. Inferior frontal sulcus. 6. Precentral sulcus. 7. Central sulcus. 8. Postcentral sulcus. 9. Intraparietal sulcus. 10. Parietooccipital sulcus. 11. Transverse occipital sulcus. 12. Occipital pole. 13. Superior parietal lobule. 14. Inferior parietal lobule. 15. Postcentral gyrus. 16. Paracentral lobule. 17. Precentral gyrus. 18. Inferior frontal gyrus. 19. Middle frontal gyrus. 20. Superior frontal gyrus. (Reproduced from Von Frick H, Leonhardt H, Starck D, Human Anatomy, ©2016, Thieme Publishers, New York.)



**Fig. 4.7** Brain surface anatomy, right lateral view. 1. Central sulcus. 2. Precentral gyrus. 3. Precentral sulcus. 4. Superior frontal gyrus. 5. Superior frontal sulcus. 6. Middle frontal gyrus. 7. Middle frontal sulcus. 8. Frontal pole. 9. Orbital gyri. 10. Olfactory bulb. 11. Olfactory tract. 12–14. Lateral sulcus. 12. Anterior ramus. 13. Ascending ramus. 14. Posterior ramus. 15. Frontal operculum. 16. Frontoparietal operculum. 17. Superior temporal gyrus. 18. Middle temporal gyrus. 19. Superior temporal sulcus. 20. Inferior temporal sulcus. 21. Inferior temporal gyrus. 22. Preoccipital notch. 23. Occipital pole. 24. Transverse occipital sulcus. 25. Inferior parietal lobule. 26. Intraparietal sulcus. 27. Superior parietal lobule. 28. Postcentral sulcus. 29. Postcentral gyrus. 30. Supramarginal gyrus. 31. Angular gyrus. 32. Pons. 33. Pyramid (medulla oblongata). 34. Olive. 35. Flocculus. 36. Cerebellar hemisphere. (Reproduced from Von Frick H, Leonhardt H, Starck D, Human Anatomy, ©2016, Thieme Publishers, New York.)



communication between the frontal and parietal lobes, called the subcentral gyrus.

## Lateral Sulcus (Sylvian Fissure)

Lateral sulcus separates the frontal lobe from the temporal lobe. It is the deepest sulcus in the frontal lobe and covers the insula and branches of the middle cerebral artery (MCA). Two divisions—the anterior/horizontal, and the posterior/ascending—divide the inferior frontal gyrus into three segments, resembling the letter **M**.

The three segments of the inferior frontal gyrus are from anterior to posterior: pars orbitalis, pars triangularis, and pars opercularis (the latter two otherwise known as Broca's area within the dominant hemisphere).

- **Precentral sulcus:** Runs parallel to the central sulcus and delineates anteriorly the precentral gyrus or motor strip (Brodman area 4, primary motor cortex).

## Inferior Surface

The inferior surface of the frontal lobe is limited posteriorly by the medial projection of the Sylvian fissure (► Fig. 4.8). Medially, next to the IHF runs the gyrus rectus (straight gyrus), which is limited laterally by the olfactory sulcus with the olfactory nerve and bulb. This segment lies over the cribriform plate of the ethmoid bone. Lateral to the olfactory sulcus is the orbital segment of the frontal lobe, which is divided into four orbital gyri (anterior, posterior, lateral, and medial) by the orbital sulci which has an **H** shape.

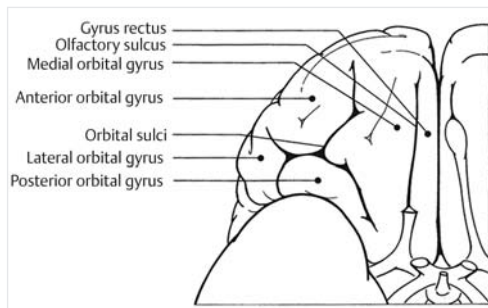
## Secondary Sulci

Secondary sulci divide the lateral surface of the frontal lobe into four gyri.

- **Superior frontal sulcus:** Divides the superior frontal gyrus (SFG) from the middle frontal gyrus (MFG).
- **Inferior frontal sulcus:** Divides the MFG from the inferior frontal gyrus (IFG).

## Parietal Lobe

The parietal lobe is limited anteriorly by the central sulcus, posteriorly by the parieto-occipital sulcus, inferiorly by the Sylvian fissure, and over the medial hemispheric surface by the subparietal sulcus. Two main sulci (i.e., the postcentral and intraparietal) divide this lobule into three main gyri.



**Fig. 4.8** The orbital surface of the right frontal lobe. (Reproduced from Yasargil M, Smith R, Young P et al, *Microneurosurgery*, Volume I, 1st edition, ©1984, Thieme Publishers, New York.)



## Postcentral Sulcus

This is the posterior limit of the postcentral gyrus or primary sensory cortex (Brodmann areas 3, 1, and 2). Its anterior limit is the central sulcus.

## Intraparietal Sulcus

Originates perpendicular to the postcentral sulcus, dividing the remainder of the lateral surface of this lobule into the superior parietal lobule (SPL) and inferior parietal lobule (IPL). The SPL continues within the medial surface of the hemisphere as the precuneus. The IPL contains the supramarginal gyrus (SMG), also known as Wernicke's area, and the angular gyrus (AG). Localizing the SMG involves following the Sylvian fissure until its termination within the parietal lobe. The AG can be located by following the superior temporal sulcus instead.

## Temporal Lobe

Considered as the most epileptogenic lobule, it is limited superiorly by the Sylvian fissure. Posteriorly, its limit is poorly defined although in some cases, it is possible to visualize a temporo-occipital sulcus. Two main sulci divide the lateral surface of temporal lobe into three gyri. The superior temporal sulcus separates the superior temporal gyrus (STG) from the middle temporal gyrus (MTG). The inferior temporal sulcus separates the MTG from the inferior temporal gyrus (ITG). The STG contains the primary auditory area, also known as transverse gyri of Heschl or Brodmann areas 41 and 42.

The inferior surface of the temporal lobe contains two main sulci. The occipitotemporal sulcus, located laterally, divides the ITG and the fusiform gyrus

located laterally on the inferior surface of the temporal lobe. The collateral sulcus, located medially, divides the fusiform gyrus and the parahippocampal gyrus, which continues posteriorly in the occipital lobe within the lingual gyrus. (► Fig. 4.9).

## Occipital Lobe

Located at the posterior aspect of the hemispheres, the occipital lobe assumes a pyramidal shape, limited dorsally by the parietooccipital sulcus. Ventrally, its boundary with the temporal lobule is not well-defined, as previously mentioned. Its lateral surface has three gyri. The superior gyrus continues anteriorly as the SPL; the middle gyrus continues as the AG, and the inferior occipital gyrus continues as the MTG and ITG. The inferior surface has two gyri, the lateral gyrus is continuous with the fusiform gyrus. The medial gyrus forms the lingual gyrus which continues anteriorly within the temporal lobe.

The medial surface of the occipital lobe is known as the cuneus and is limited by the parieto-occipital sulcus anteriorly and superiorly, and the calcarine sulcus inferiorly. The primary visual area (Brodmann area 17) surrounds the calcarine sulcus.

## Medial Surface

The cingulate gyrus is limited superiorly by the cingulate and subparietal sulci, and inferiorly by the sulcus of the corpus callosum. The cingulate sulcus separates the cingulum from the SFG and continues posteriorly and superiorly to form the posterior limit of the paracentral lobule. The paracentral lobule is a continuation of the precentral and postcentral gyri within the medial surface of the hemisphere (► Fig. 4.10).

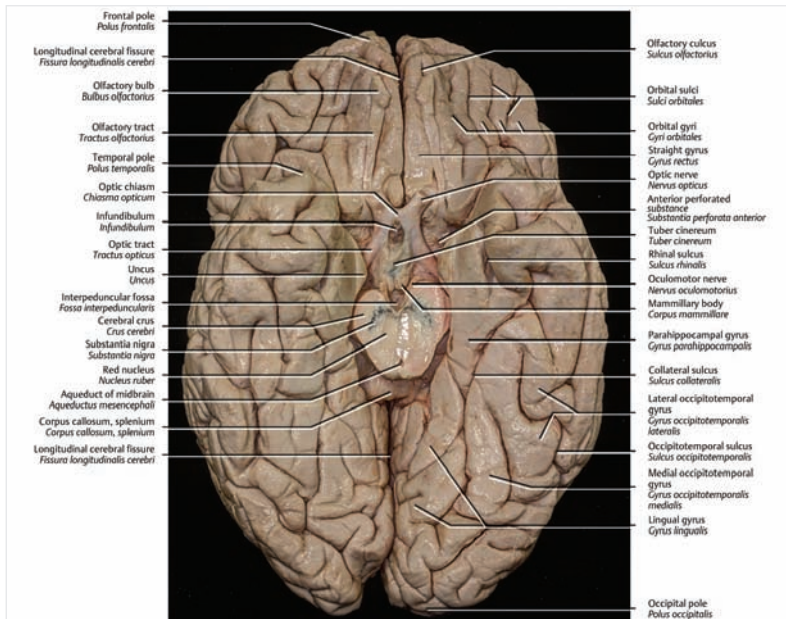


Fig. 4.9 Cerebrum, inferior view. (Reproduced from Peris-Celda M, Martinez-Soriano F, Rhoton A, Rhoton's Atlas of Head, Neck, and Brain, 1st edition, ©2017, Thieme Publishers, New York.)

### 4.3.2 Subcortical Structures

#### Basal Ganglia

The basal ganglia are gray matter nuclei located deep within the cerebral hemispheres (► Fig. 4.11). From medial to lateral these are:

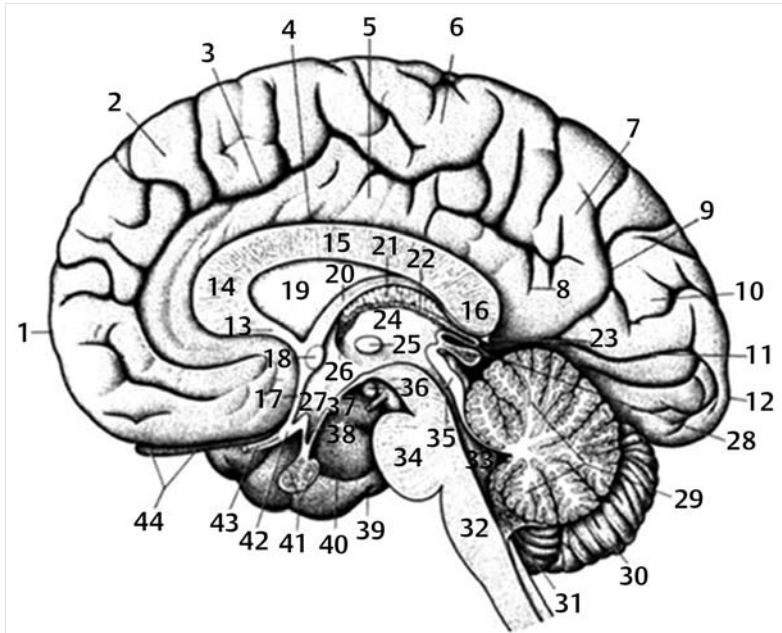
- Thalamus.
- Striatum:
  - Caudate nucleus, divided into head (lateral to the frontal horns of the ventricle and medial to the anterior limb of the internal capsule), body, and tail.
  - Lentiform nucleus, lateral to the internal capsule, it has a medial segment or globus pallidus (with its internal and external segments), and a lateral segment or putamen.

- **Clastrum:** Thin layer of gray matter separated from the insula by a thin layer of white matter (extreme capsule) and separated from the lentiform nucleus and the striatum by the white matter of the external capsule.

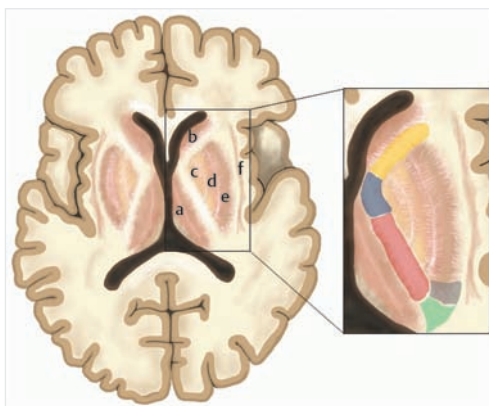
#### Internal Capsule

Thick layer of white matter running between the caudate nucleus and thalamus medially and the striatum laterally. It has five segments running from anterior to posterior<sup>2</sup>:

- **Anterior limb:**
  - Frontopontine fibers.
  - Thalamocortical fibers.
  - Corticothalamic fibers.
  - Caudatoputamenal fibers.



**Fig. 4.10** Brain surface anatomy, view of medial surface of right hemisphere. 1. Frontal pole of frontal lobe. 2. Medial frontal gyrus. 3. Cingulate sulcus. 4. Sulcus of corpus callosum. 5. Cingulate gyrus. 6. Paracentral lobule. 7. Precuneus. 8. Subparietal sulcus. 9. Parietooccipital sulcus. 10. Cuneus. 11. Calcarine fissure. 12. Occipital pole of occipital lobe. 13–16. Corpus callosum (cut surface). 13. Rostrum. 14. Genu. 15. Body. 16. Splenium. 17. Lamina terminalis (cut surface). 18. Anterior commissure (cut surface). 19. Septum pellucidum. 20. Fornix. 21. Tela choroidea of third ventricle. 22. Choroid plexus of third ventricle (cut edge). 23. Transverse cerebral fissure. 24. Thalamus. 25. Interthalamic adhesion (cut surface). 26. Interventricular foramen of Monro. 27. Hypothalamus. 28. Suprapineal recess and pineal body (cut surface). 29. Vermis of cerebellum (cut surface). 30. Cerebellar hemisphere. 31. Choroid plexus of fourth ventricle. 32. Medulla oblongata (cut surface). 33. Fourth ventricle. 34. Pons (cut surface). 35. Tectal lamina (cut surface) and mesencephalic aqueduct of Sylvius. 36. Mammillary body. 37. Oculomotor nerve. 38. Infundibular recess. 39. Temporal lobe lateral occipitotemporal gyrus. 40. Rhinal fissure. 41. Hypophysis (cut surface) with adeno-hypophysis (anterior lobe) and neurohypophysis (posterior lobe) of pituitary gland. 42. Optic chiasm (cut surface). 43. Optic nerve. 44. Olfactory bulb and tract. (Reproduced from Von Frick H, Leonhardt H, Starck D, Human Anatomy, ©2016, Thieme Publishers, New York.)



**Fig. 4.11** Subcortical structures of the brain. **a**, Thalamus. **b**, head of the caudate nucleus. **c**, internal globus pallidus. **d**, external globus pallidus. **e**, putamen. **f**, claustrum. Rectangle shows internal capsule: anterior limb (yellow), genu (blue), posterior limb (red), sublenticular part (gray), retrolenticular part (green). (Illustration by Joao T Alves Belo, MD.)

- **Genu:**
  - Corticobulbar fibers.
  - Corticoreticulobulbar fibers.
- **Posterior limb:**
  - Corticospinal fibers.
  - Corticorubral fibers.
  - Corticothalamic fibers.
  - Thalamocortical fibers.
- **Sublenticular segment:**
  - Auditory radiations.
  - Corticopontine fibers.
  - Optic radiations.
- **Retrolenticular segment:**
  - Optic radiations.
  - Corticotectal fibers.
  - Corticonigral fibers.
  - Corticotegmental fibers.

or horns, into the frontal, occipital, and temporal lobes. Their point of meeting is known as atrium or trigone. The lateral ventricles are connected to the 3rd ventricle through the interventricular foramen or foramen of Monro (one for each lateral ventricle).

The 3rd ventricle is located between the medial surface of both thalami and is connected to the 4th ventricle through the cerebral aqueduct, also known as the Sylvian aqueduct. From the 4th ventricle, CSF leaves the ventricular system and enters the subarachnoid space through three foramina—two Lateral (foramen of Luschka) and one Medial (foramen Magendie) (► Fig. 4.12).

## Ventricles of the Brain

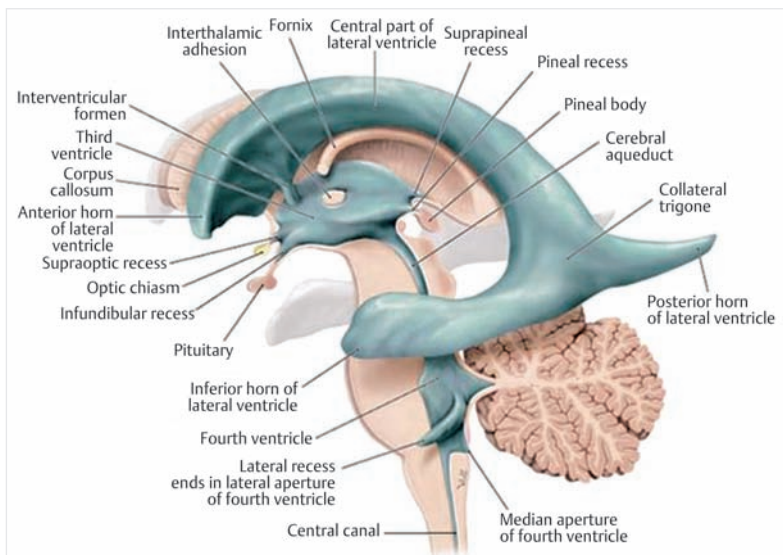
The ventricles of the brain are cavities containing the cerebrospinal fluid (CSF) covered by ependymal cells. There are four ventricles (two lateral, 3rd and 4th ventricles).

The lateral ventricles surround the caudate nucleus and the thalamus in each hemisphere. They present three extensions,

## 4.4 Brainstem

### 4.4.1 Surface Anatomy

The brainstem contains all major motor and sensory pathways traveling to and from the brain, cerebellum, and spinal cord. Furthermore, cranial nerves (CNs) II–XII also originate from nuclei within the brainstem. Topographically, it is



**Fig. 4.12** Overview of the ventricular system and important neighboring structures. Left lateral view. The ventricular system is an expanded and convoluted tube that is the upper extension of the central spinal canal into the brain. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Markus Voll.)

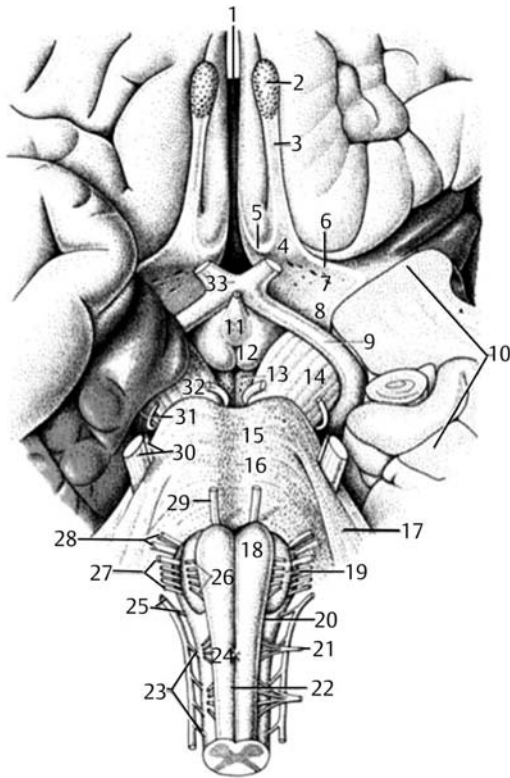
divided into three segments from superior to inferior: midbrain, pons, and medulla (► Fig. 4.13, ► Fig. 4.14, and ► Fig. 4.15).

## Midbrain

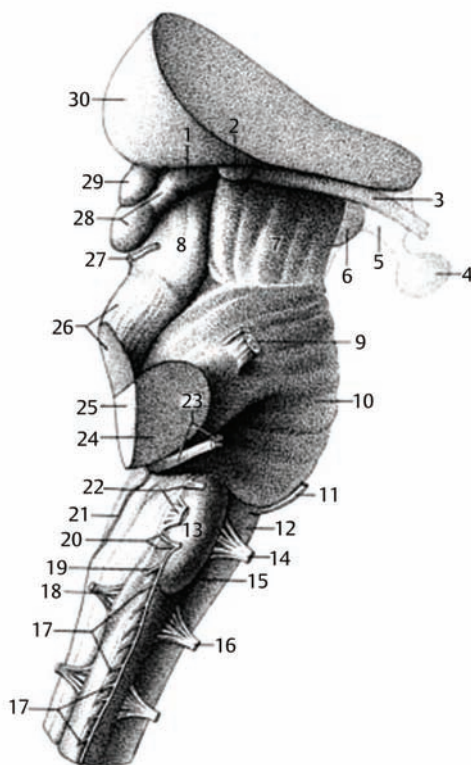
The midbrain is limited superiorly by an imaginary line between the mammillary body and the pineal gland; limited inferiorly by the pontomesencephalic sulcus which separates it from the pons. The anterior surface is denoted by two columns of white matter called cerebral peduncles. The peduncles are separated by the interpeduncular fossa where CN III (oculomotor nerve) exits, to reach the orbit. The posterior surface of the midbrain or tectum has four spherical structures, known as colliculi:

two superior (connected to the lateral geniculate nucleus of the thalamus) related to vision, and two inferior (connected to the medial geniculate nucleus of the thalamus) related to the auditory pathway. Immediately below the inferior colliculi and on each side of the midline, CN IV (trochlear nerve) exits the brainstem.

The trochlear nerve is the only CN that exits the brainstem via its posterior surface. Moreover, it is the only CN that decussates, resulting in contralateral motor innervation (► Fig. 4.16 and ► Fig. 4.17).

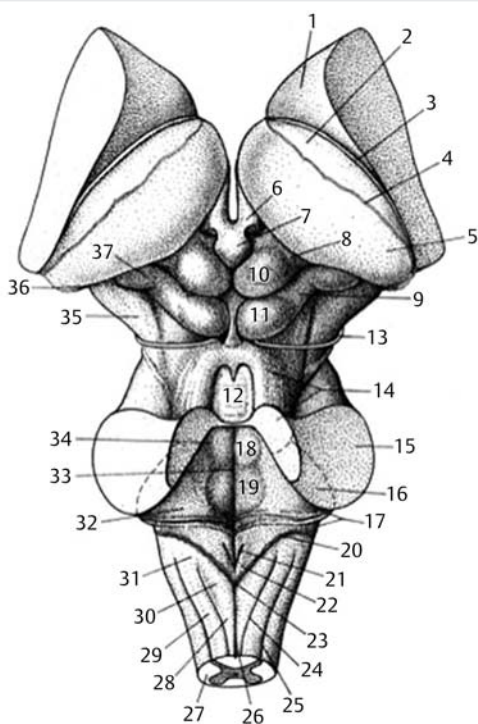


**Fig. 4.13** Ventral view of brainstem. 1. Corpus callosum in depths of anterior interhemispheric or longitudinal cerebral fissure. 2. Olfactory bulb. 3. Olfactory tract. 4. Olfactory trigone. 5. Medial olfactory stria. 6. Lateral olfactory stria. 7. Anterior perforated substance. 8. Diagonal band of Broca. 9. Optic tract. 10. Cut surface of left temporal lobe. 11. Infundibulum with hypophyseal stalk. 12. Mamillary body. 13. Interpeduncular fossa with interpeduncular perforated substance. 14. Ventral part of cerebral peduncle. 15. Pons. 16. Basilar sulcus. 17. Middle cerebellar peduncle. 18. Pyramid (medulla oblongata). 19. Olive. 20. Ventrolateral sulcus. 21. Ventral root of first cervical nerve. 22. Ventral median fissure. 23. Spinal roots of accessory nerve. 24. Decussation of pyramids. 25. Accessory nerve and cranial roots. 26. Hypoglossal nerve. 27. Glossopharyngeal and vagus nerve. 28. Facial nerve with nervus intermedius and vestibulocochlear nerve. 29. Abducens nerve. 30. Motor and sensory roots of trigeminal nerve. 31. Trochlear nerve. 32. Oculomotor nerve. 33. Optic chiasm. (Reproduced from Von Frick H, Leonhardt H, Starck D, Human Anatomy, ©2016, Thieme Publishers, New York.)



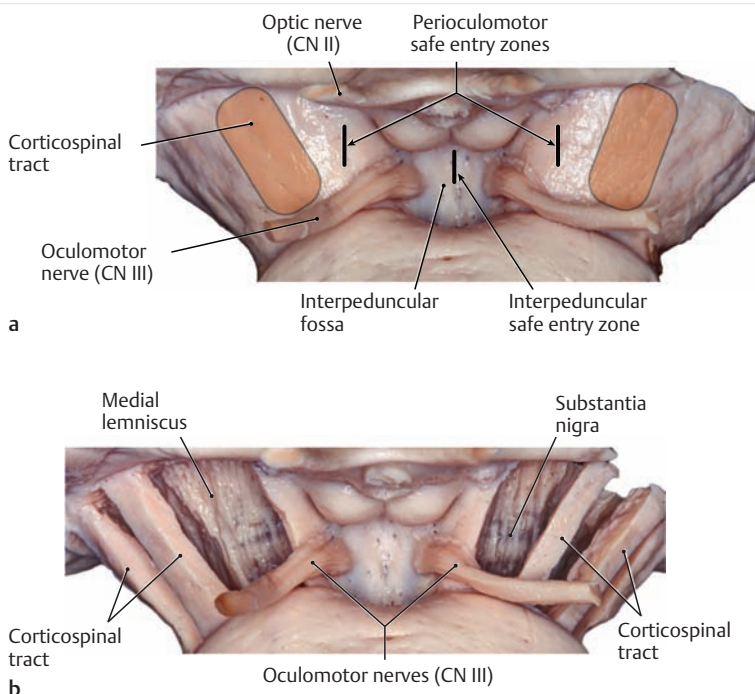
**Fig. 4.14** Lateral view of the brainstem. 1. Medial geniculate body. 2. Lateral geniculate body. 3. Optic tract. 4. Hypophysis. 5. Infundibulum. 6. Mamillary body. 7, 8. Cerebral peduncle. 7. Ventral part (crus cerebri). 8. Dorsal part (mesencephalic tegmentum). 9. Trigeminal nerve. 10. Pons. 11. Abducens nerve. 12. Pyramid (medulla oblongata). 13. Olive. 14. Hypoglossal nerve. 15. Ventrolateral sulcus. 16. Ventral root of the first cervical nerve. 17. Spinal roots of accessory nerve. 18. Dorsal root of first cervical nerve (retracted). 19. Dorsolateral sulcus (medulla oblongata). 20. Cranial roots of accessory and vagus nerve. 21. Tenia of fourth ventricle. 22. Glossopharyngeal and vagus nerves. 23. Facial nerve with nervus intermedius and vestibulocochlear nerve. 24. Middle cerebellar peduncle. 25. Inferior cerebellar peduncle. 26. Superior cerebellar peduncle. 27. Trochlear nerve. 28. Inferior colliculus and brachium of inferior colliculus. 29. Superior colliculus. 30. Pulvinar. (Reproduced from Von Frick H, Leonhardt H, Starck D, Human Anatomy, ©2016, Thieme Publishers, New York.)



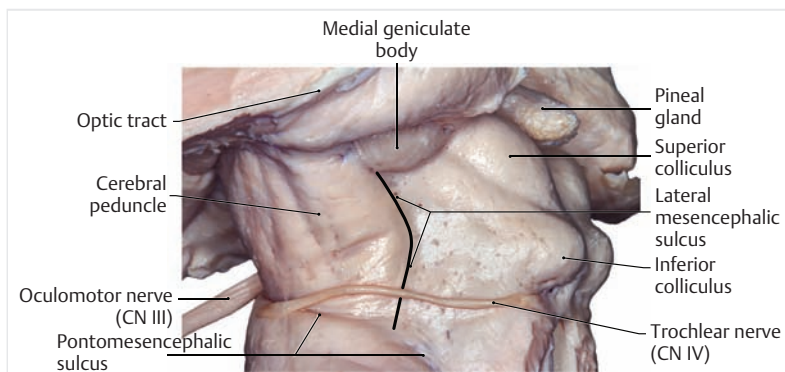


**Fig. 4.15** Dorsal view of brainstem with cerebellum removed. 1. Caudate nucleus. 2. Lamina affixa. 3. Terminal stria and superior thalamostriate vein in terminal sulcus. 4. Tenia choroidea. 5. Pulvinar. 6. Habenular trigone. 7. Pineal body. 8–11. Mesencephalon. 8. Brachium of superior colliculus. 9. Brachium of inferior colliculus. 10, 11. Tectum. 10. Superior colliculus. 11. Inferior colliculus. 12. Superior medullary velum. 13. Trochlear nerve. 14. Superior cerebellar peduncle. 15. Middle cerebellar peduncle. 16. Inferior cerebellar peduncle. 17. Stria medullares (fourth ventricle) and lateral recess of fourth ventricle. 18. Median eminence. 19. Facial colliculus. 20. Tenia of fourth ventricle. 21. Trigone of hypoglossal nerve. 22. Trigone of vagus nerve (ala cinerea). 23. Obex. 24. Dorsal intermediate sulcus. 25. Dorsolateral sulcus. 26. Dorsal median sulcus. 27. Lateral funiculus. 28. Fasciculus gracilis. 29. Fasciculus cuneatus. 30. Tuberculum gracile. 31. Tuberculum cuneatum. 32. Vestibular area. 33. Median sulcus. 34. Sulcus limitans. 35. Cerebral peduncle. 36. Lateral geniculate body. 37. Medial geniculate body. (Reproduced from Von Frick H, Leonhardt H, Starck D, Human Anatomy, ©2016, Thieme Publishers, New York.)





**Fig. 4.16** Ventral surface, safe entry zones, and internal structures of the midbrain. **(a)** The corticospinal tract is situated in the middle three-fifths of the crus cerebri. The anterior mesencephalic (periocolomotor) safe entry zone is directed through the frontopontine fibers and between the exit point of the oculomotor nucleus and the medial edge of the corticospinal tract. Alternatively, a second ventral safe entry zone, the interpeduncular safe entry zone, is located medial to the exit point of the oculomotor nerves (CN III) and directed through the interpeduncular fossa. **(b)** The removal of the frontopontine fibers exposes the medial lemniscus and substantia nigra. (Reproduced from Spetzler R, Kalani M, Nakaji P et al, *Color Atlas of Brainstem Surgery*, 1st edition, ©2017, Thieme Publishers, New York.)



**Fig. 4.17** Cadaveric dissection showing the lateral surface of the midbrain. The lateral mesencephalic sulcus extends from the pontomesencephalic sulcus inferiorly to the medial geniculate body superiorly, and it forms the border between the cerebral peduncle and the tectum of the midbrain. The tectum contains the superior and inferior colliculi. (Reproduced from Spetzler R, Kalani M, Nakaji P et al, *Color Atlas of Brainstem Surgery*, 1st edition, ©2017, Thieme Publishers, New York.)

## Pons

The pons is separated from the midbrain superiorly by the pontomesencephalic sulcus, and inferiorly from the medulla by the pontomedullary sulcus. From the pontomedullary sulcus and on each side of the midline, the CNs VI (abducens), VII (facial), and VIII (vestibulocochlear) exit the brainstem. CN VI exits right above the pyramids of the medulla, CN VII above the olivary nucleus, and the CN VIII from the outermost portion of the pontomedullary sulcus, a region known also as the pontocerebellar angle. The anterior surface of the pons has an impression over its midline known as the basilar sulcus. Laterally, the anterior surface is limited on each side by CN V (trigeminal nerve). The posterior surface of the pons will be described along with the posterior surface of the upper medulla, as both form the rhomboid fossa.

## Medulla

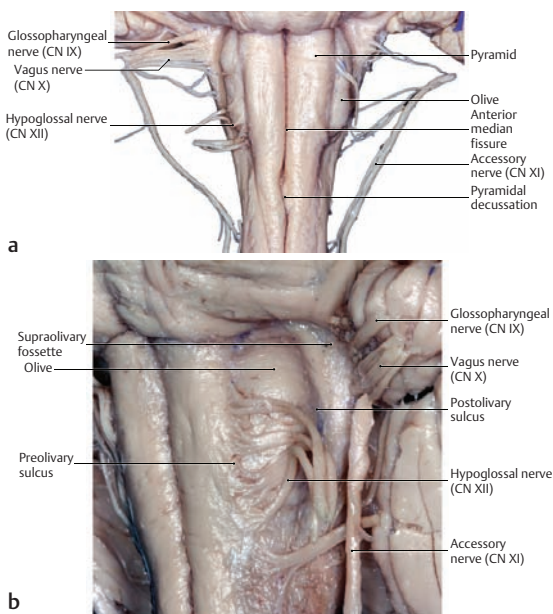
The medulla is the most caudal brainstem segment, limited superiorly by the

pontomedullary sulcus and inferiorly by an imaginary plane running below the motor decussation and above the roots of the first cervical nerves. The anterior surface has a vertically oriented fissure on its midline known as the anterior median fissure, representing the medial limit of the pyramids. The lateral limit of the pyramids is the anterolateral sulcus. The anterior median fissure and anterolateral sulcus continue inferiorly to the spinal cord, except for the anterior median fissure on the lower third of the medulla where the motor decussation takes place and momentarily efface it. On the superior portion of the anterolateral sulcus, CN XII (hypoglossal nerve) exits the brainstem anterior to the olives, on each side. The lateral surface of the medulla is limited anteriorly by the anterolateral sulcus and posteriorly by the posterolateral sulcus. From superior to inferior, the CNs IX, X, and XI exit the brainstem via the posterolateral sulcus. The posterior surface of the medulla is divided into a superior and an inferior segment. The inferior segment

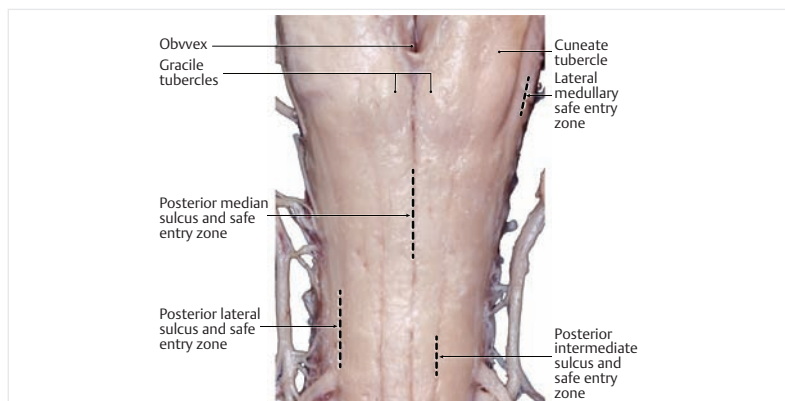
has on its midline the posterior median fissure separating the gracile fasciculi on either side. These fasciculi are laterally limited by the posterior intermedius sulci which separate the gracile and cuneate fasciculi. The latter are limited laterally by the posterolateral sulcus (► Fig. 4.18 and ► Fig. 4.19).

## Rhomboid Fossa

The superior segment of the posterior surface of the medulla, forms with the posterior surface of the pons the so-called rhomboid fossa or floor of the 4th ventricle. For didactic purposes, the pontomedullary sulcus is employed as a reference to



**Fig. 4.18** (a) The medulla contains the glossopharyngeal (CN IX), vagus (CN X), accessory (CN XI), and hypoglossal (CN XII) nerves. The medulla is divided in the midline by the anterior median fissure. The corticospinal tract runs within the pyramid. (b) Lateral view of the medulla. The preolivary sulcus is located between the pyramid and olive, and the postolivary sulcus is located behind the olive. The hypoglossal nerve exits from the preolivary sulcus, and the accessory nerve exits from the postolivary sulcus. The depression rostral to the olive, the supraolivary fossa, is just below the junction of the facial nerve (CN VII) and the vestibulo-cochlear nerve (CN VIII) with the brainstem. The glossopharyngeal, vagus, and accessory nerves exit the medulla just dorsal to the postolivary sulcus, which is located between the olive and the inferior cerebellar peduncle. (Reproduced from Spetzler R, Kalani M, Nakaji P et al, *Color Atlas of Brainstem Surgery*, 1st edition, ©2017, Thieme Publishers, New York.)



**Fig. 4.19** The surface anatomy and safe entry zones of the dorsal medulla. There are three dorsal medullary sulci, which have been used to gain entry to the dorsal medulla and have been described as safe entry zones. These include the posterior median sulcus below the obex in the midline, the posterior intermediate sulcus between the gracile tubercle and the cuneate tubercle, and the posterior lateral sulcus along the lateral margin of the cuneate tubercle. An additional safe entry zone, the lateral medullary (inferior cerebellar peduncle) safe entry zone, has been proposed. (Reproduced from Spetzler R, Kalani M, Nakaji P et al, *Color Atlas of Brainstem Surgery*, 1st edition, ©2017, Thieme Publishers, New York.)

divide the rhomboid fossa into an inferior or medullary triangle and a superior or pontine triangle.

### Inferior or Medullary Triangle

The medullary triangle is limited laterally by the inferior cerebellar peduncles (► Fig. 4.20). Three important structures occupying this area from medial to lateral include:

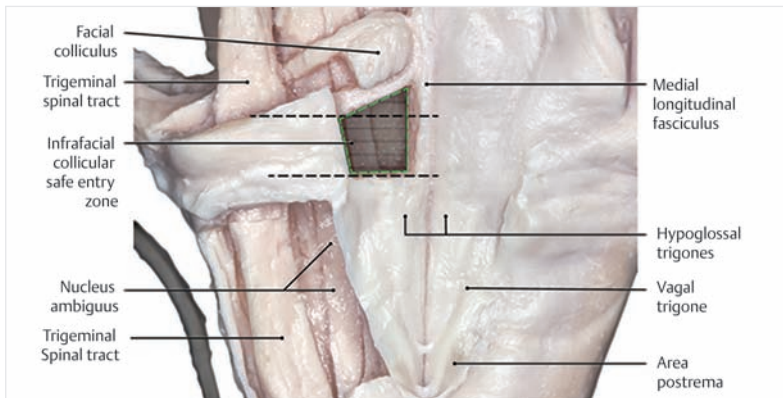
- Hypoglossal trigone, related to the nucleus of the CN XII.
- Vagal trigone, related to the motor nucleus of the CN X. On the inferolateral aspect of the trigone is the area postrema which controls vomiting.
- Vestibular trigone, related to the vestibular and dorsal cochlear nuclei.

### Superior or Pontine Triangle

At each side of the midline and just above an imaginary plane from the pontomedullary sulcus, the facial colliculi are located (► Fig. 4.20). The abducens nucleus and the fibers of the CN VII make an indentation in the white matter as they loop around this nucleus.

In the superolateral segment, the motor nucleus of the trigeminal nerve makes an impression. Lateral to the trigeminal impression lies the *locus coeruleus* which is the main source of noradrenaline in the central nervous system (CNS).<sup>3</sup>

A lesion of the pons at the level of the abducens nucleus may cause Millard-Gubler syndrome characterized by CNs VI and VII palsies and contralateral body hemiplegia.



**Fig. 4.20** The infrafacial collicular safe entry zone (shaded area inside green dashed lines) is limited medially by the medial longitudinal fasciculus, laterally by the nucleus ambiguus, superiorly by the facial colliculus, and inferiorly by the hypoglossal trigone. Thus, the lateral border of the infrafacial collicular safe entry zone corresponds to the most medial point of attachment of the tela choroidea along the lower margin of the lateral recess, whereas the rostral and caudal borders are the same as the upper and lower edges of the lateral recess. (Reproduced from Spetzler R, Kalani M, Nakaji P et al, *Color Atlas of Brainstem Surgery*, 1st edition, ©2017, Thieme Publishers, New York.)

## 4.5 Cisterns

The cisterns are areas where the pia matter and arachnoid are separated and filled with CSF. Additionally, these spaces are also occupied by blood vessels and cranial nerves. ► Fig. 4.21 summarizes the different cisterns and their relationship with the anatomical structures in the posterior fossa.

## 4.6 Spinal Cord

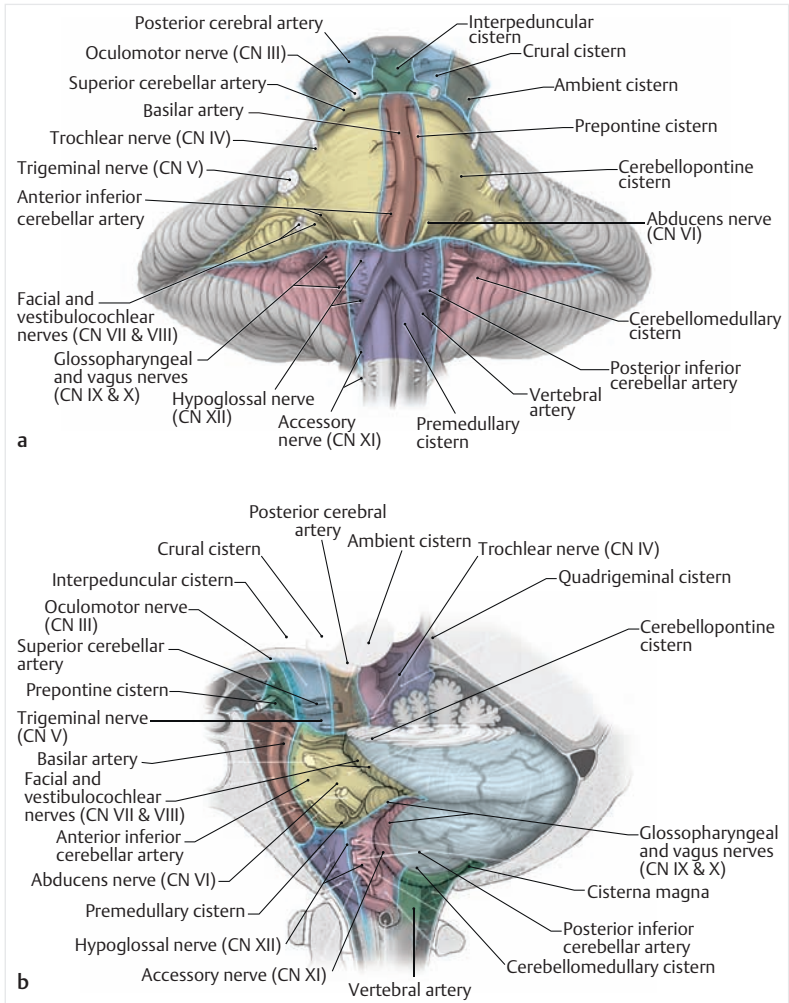
### 4.6.1 Surface Anatomy

The spinal cord is the most caudal segment of the CNS. It is located in the superior two-third of the spinal canal, ending at the level of L2 (second lumbar vertebrae). Along its length, the spinal cord has two regions where its maximal diameter increases. One of these regions lies in its

cervical portion and one in the lumbar portion, representing areas where the brachial and lumbar plexi are respectively located.

Generally, there are 31 spinal cord segments, each of which give off a pair of spinal nerves:

- Eight pairs of cervical spinal nerves, the first spinal nerve (C1) exits between the occipital bone and the atlas or first cervical vertebra. For this reason, there are eight cervical pairs, the last being located between C7 and T1.
- Twelve thoracic spinal nerves. The first thoracic nerve pairs (T1) start below the first thoracic vertebrae, this order continues for the remaining segments.
- Five lumbar pairs.
- Five sacral pairs.
- One coccygeal pair.



**Fig. 4.21** The brainstem and the cisterns that are associated with the cranial nerves. **(a)** Ventral view and **(b)** lateral view. (Reproduced from Spetzler R, Kalani M, Nakaji P et al, *Color Atlas of Brainstem Surgery*, 1st edition, ©2017, Thieme Publishers, New York.)



Above C7, the spinal nerves exit above the vertebra with the same name, except for C8, which exits below C7 and above T1. From T1 and below, the spinal nerves exit below the vertebra with the same name.

Topographically, the spinal cord is divided into three columns on each side:

- Anterior column, between the anterior median fissure and anterolateral sulcus.
- Lateral column, between the anterolateral and posterolateral sulci. These sulci represent the exit of the ventral (motor) and the entry of the dorsal (sensory) nerve roots that form the spinal nerve.
- Posterior column, between the posterolateral sulcus and posterior median fissure. From T6 and above, the posterior column is further divided into two tracts by the posterior intermediate sulcus. A medial tract (fasciculus gracilis), limited medially by the posterior median fissure and laterally by the posterior intermediate sulcus, and a lateral tract (fasciculus cuneatus) limited medially by the posterior intermediate sulcus and laterally by the posterolateral sulcus.

## Fixation of the Spinal Cord

The spinal cord is maintained in its position via the following structures:

- Superiorly, its continuation with the brainstem.
- Laterally, spinal nerves exiting through the intervertebral foramina.
- Dura mater, two attachments: Filum terminalis with the anterior coccyx and sacrum, and the periosteum of the skull.
- Dentate ligaments, located between the ventral and dorsal nerve roots.

These are extensions of the pia mater and arachnoid towards the dura mater.

## 4.6.2 Internal Configuration

Understanding the anatomical arrangement and physiology of the spinal cord is essential for determination of different pathological syndromes that may affect it. Opposite to the brain, white matter surrounds the gray matter in the spinal cord. Spinal gray matter lies centrally around the central canal, assuming the shape of an “H.” ▶ Fig. 4.22 and ▶ Fig. 4.23 show an axial cut of a spinal cord segment, the Rexed laminae configuration and the ascending and descending white matter tracts (▶ Table 4.2). ▶ Fig. 4.24 shows the myotomes and dermatomes.

## 4.7 Vertebral Column

The spine is composed of 33–35 vertebrae in the following distributions:

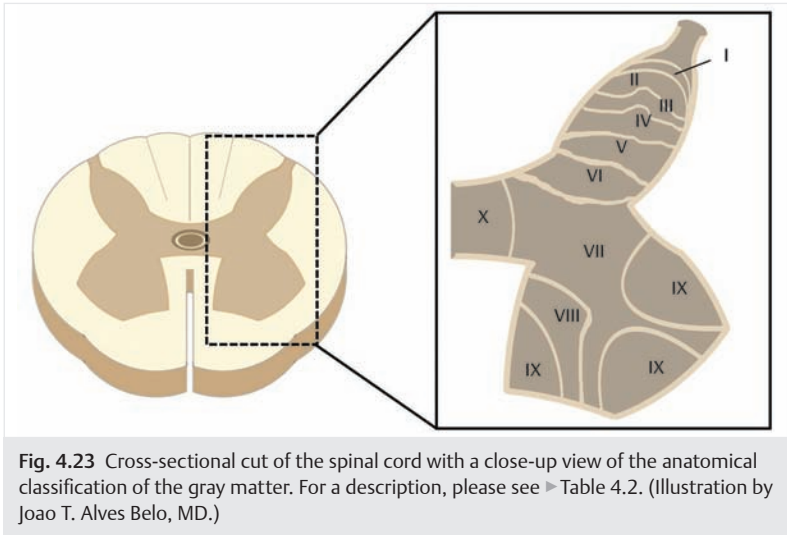
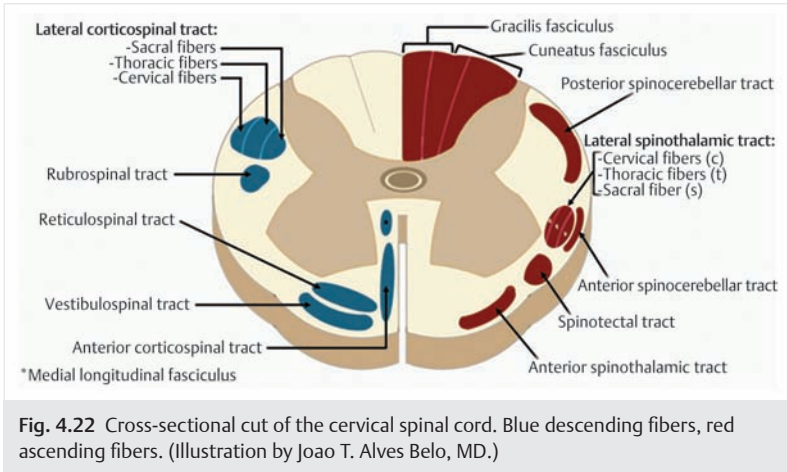
- 7 cervical.
- 12 thoracic.
- 5 lumbar.
- 3–5 coccygeal.

### 4.7.1 Vertebrae Constitution

Except for the first (C1 or atlas) and second (C2 or axis) vertebrae, six segments can be identified in a standard vertebra (▶ Fig. 4.25):

1. **Vertebral body:** Forms the anterior portion of the vertebra and has two horizontal portions (superior and inferior) in which the intervertebral disc sits. The posterior wall forms the anterior arch of the vertebral canal.
2. **Pedicles:** There are two pedicles (left and right) extending from the posterolateral aspect of the vertebral body.





body. They serve as attachments for the transverse processes, the laminae, and the facets (articular processes). The superior and inferior borders of the pedicles form the inferior and superior borders of the intervertebral

- foramina (spaces where the nerve roots exit the spinal canal).
3. **Laminae:** Extend from the pedicles in a posteromedial direction relative to the spinous processes. They form the posterior arch of the spinal canal. The



**Table 4.2** Configuration of the gray matter in the spinal cord

| Rexed laminae | Classical terminology                                                                                                                           | Function                                                                                                                                                                                                                                                                                                                                           |
|---------------|-------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| I             | Posteromarginal nucleus                                                                                                                         | Exteroceptive sensations                                                                                                                                                                                                                                                                                                                           |
| II            | Substantia gelatinosa                                                                                                                           |                                                                                                                                                                                                                                                                                                                                                    |
| III           | Nucleus proprius                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                    |
| IV            |                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                    |
| V             | Neck of the posterior horn                                                                                                                      | Proprioceptive sensations                                                                                                                                                                                                                                                                                                                          |
| VI            | Base of the posterior horn                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                    |
| VII           | Two groups:<br>1. Medial, thoracic nucleus<br>2. Lateral, divided in two other nuclei:<br>a) Intermediomedial zone<br>b) Intermediolateral zone | 1. Medial, thoracic nucleus: from C8–L3 receive information from the muscle spindle and Golgi tendon organ<br>2. Lateral:<br>a) Intermediomedial zone: $\gamma$ motor neurons involved in motor reflexes<br>b) Intermediolateral zone: motor visceral function. From C8–L2–3 sympathetic thoracolumbar column. S2–S4 parasympathetic sacral nuclei |
| VIII          | Commissural nucleus                                                                                                                             | Regulates skeletal muscle contraction                                                                                                                                                                                                                                                                                                              |
| IX            | Ventral horn                                                                                                                                    | Main motor area composed by $\alpha$ motor neurons                                                                                                                                                                                                                                                                                                 |
| X             | Grisea centralis/substantia gelatinosa centralis                                                                                                | Contains motor nuclei from the autonomic nervous system                                                                                                                                                                                                                                                                                            |

internal surface of the laminae serves as an attachment for the yellow ligament.

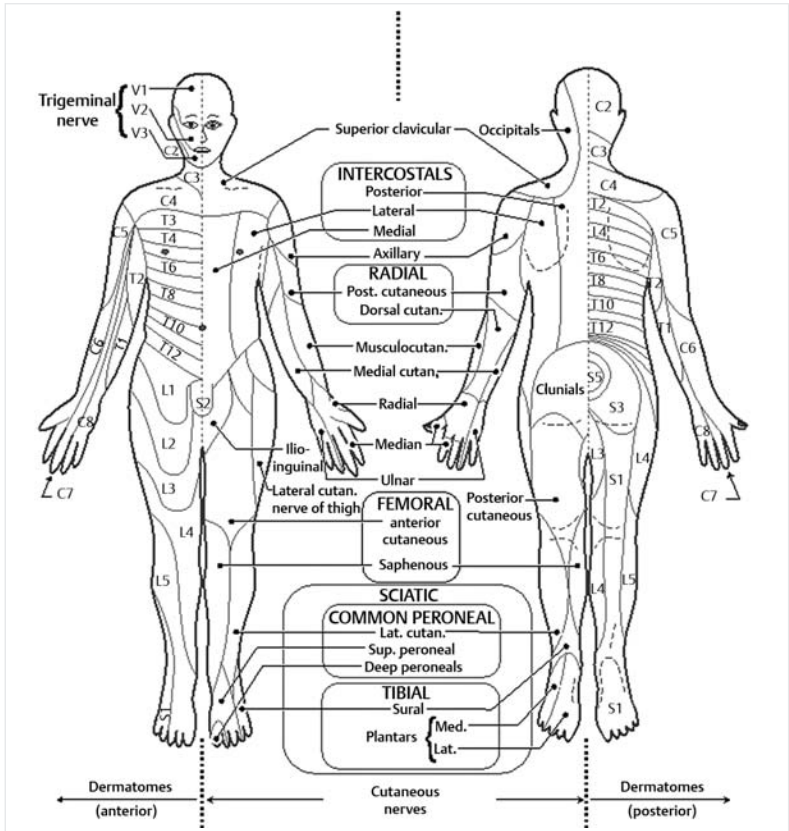
4. **Spinous process:** Starts from the point where laminae join in the midline and follows a posterior trajectory. The inferior and superior edges of the spinous processes serve as an attachment for the interspinous ligament. The supraspinous ligament runs over the tip or free edge of the spinous process in the midline.
5. **Facet or articular process:** There are four facets, two on each side (superior

and inferior) which articulate with their superior and inferior vertebral counterparts.

6. **Transverse process:** Attached to the pedicles on either side. Their shape varies according to the segment of the spine they originate from.

## Intervertebral Foramen

As previously mentioned, this is the space where the spinal nerves exit the spinal



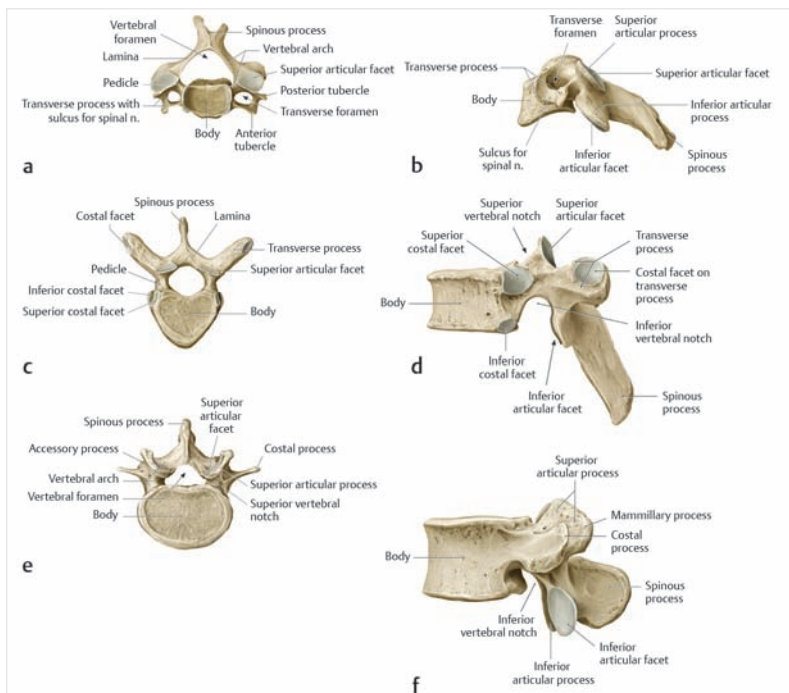
**Fig. 4.24** Dermatomes and sensory distributions of peripheral nerves. (Reproduced from Baaj A, Mummaneni P, Uribe J et al, Handbook of Spine Surgery, 2nd edition, ©2016, Thieme Publishers, New York.)

canal. Its limits are important from a surgical standpoint (► Fig. 4.26):

- **Superior:** Inferior border of the overlying vertebral pedicle.
- **Inferior:** Superior border of the underlying vertebral pedicle.
- **Anterior:** Posterolateral aspect of the intervertebral disc.
- **Posterior:** The capsule of the facets and the yellow ligament.

## Cervical Vertebrae

The vertebrae of the cervical spine have unique characteristics differentiating them from the thoracic and lumbar vertebrae (► Fig. 4.27). The first and second vertebrae possess unique morphology including presence of the transverse foramina on the transverse processes.



**Fig. 4.25** (a) Anatomic drawing of a typical cervical vertebra from a superior projection. (b) Anatomic drawing of a typical cervical vertebra from a lateral projection. (c) Anatomic drawing of a typical thoracic vertebra from a superior projection. (d) Anatomic drawing of a typical thoracic vertebra from a lateral projection. (e) Anatomic drawing of a typical lumbar vertebra from a superior projection. (f) Anatomic drawing of a typical lumbar vertebra from a lateral projection. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Karl Wesker.)

The vertebral arteries and veins run within the transverse foramina of C6 to C1 and C7 to C1 respectively, entering the cranial vault via the foramen magnum.

Some of these special features are summarized here:

- **C1 (Atlas):** The first cervical vertebra lacks a body. Instead, it possesses two

lateral masses that articulate with the occipital condyles superiorly, and C2 (axis) inferiorly. From these lateral masses, two arches (one anterior and one posterior) enclose anteriorly and posteriorly the spinal canal at this level. In the midline, the interior surface of the anterior arch of C1 articulates with the anterior segment of the odontoid process of C2 (axis). The anterior surface



**Fig. 4.26** Lateral view of two adjacent vertebral segments showing the boundaries of the intervertebral foramen. (Illustration by Joao T. Alves Belo, MD.)

of the anterior arch also possesses an anterior tubercle, which serves as the insertion point for the longus colli muscle. The posterior arch possesses a posterior tubercle on its exterior surface, in the midline, which serves as an insertion for the rectus capitis posterior minor muscle. The medial aspect of the lateral masses has tuberculae where the transverse ligament originates and runs posteriorly to the odontoid process before attaching to C1. The transverse process and foramen of C1 are located on the lateral surface of the C1 masses.

- **C2 (Axis):** This vertebra is characterized by its odontoid process (dens). The dens articulates with the anterior arch of the atlas. The left and right occipitodontoid ligaments (alar ligaments) attach firmly to either side of the dens. The spinous process of the axis serves as an attachment for the rectus capitis posterior major muscle and the obliquus capitis inferior muscle.
- **C6:** Unique to this vertebra is the presence of a tubercle at the anterior aspect of its transverse process. This tubercle is called carotid tubercle or Chassaignac tubercle. It denotes the entry of the vertebral artery into the transverse foramen.
- **C7:** This vertebra possesses features similar to the thoracic vertebrae. Its

spinous process is prominent and its transverse foramen is smaller or absent, and is occupied by the vertebral vein.

## Thoracic Vertebrae

The most distinguishing feature of the thoracic vertebrae is the presence of transverse costal facets, which articulate with the ribs.

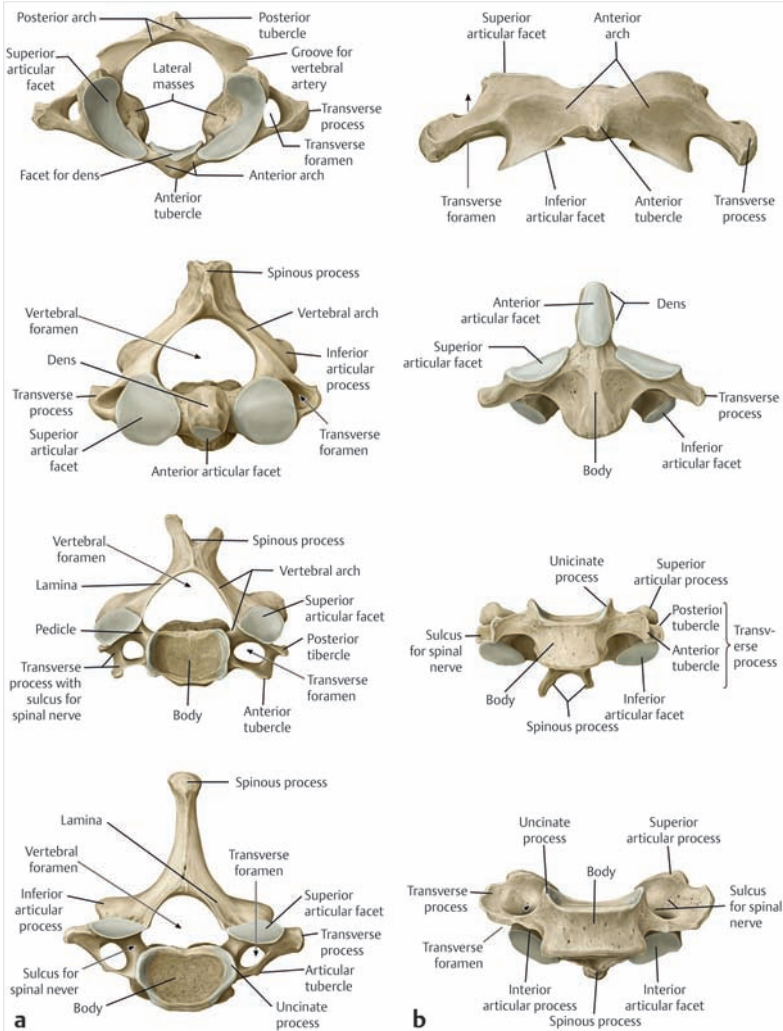
## Lumbar Vertebrae

The lumbar vertebral bodies are larger than those of other segments; this is functionally related with their weight-bearing role.

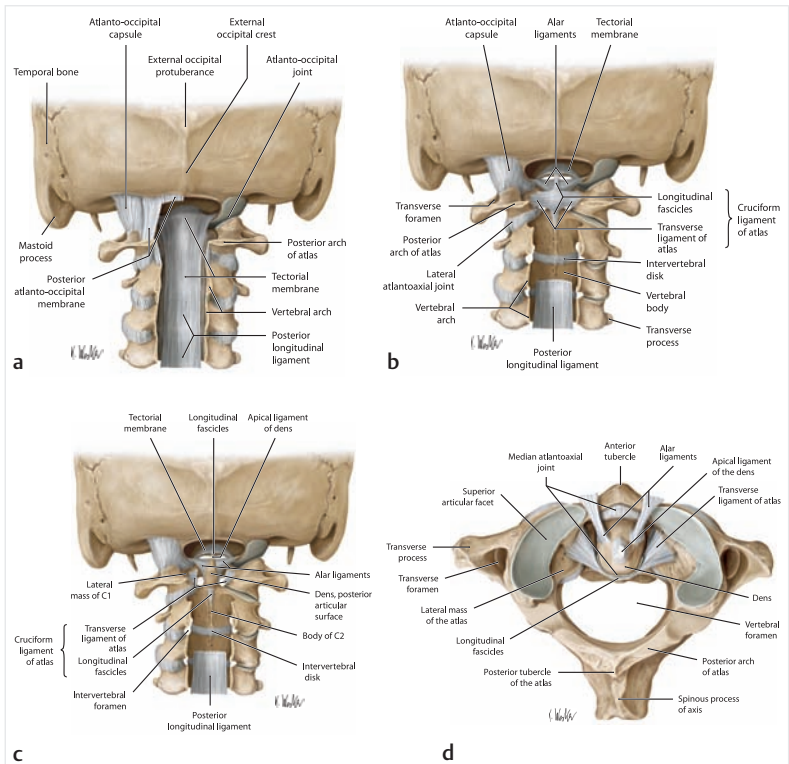
### 4.7.2 Ligaments of the Occipitoatlantoaxial Junction

#### Transverse and Cruciate Ligaments

The transverse ligament is a short ligament attached laterally to the transverse tubercle, at the medial aspect of the lateral mass of C1 (► Fig. 4.28). It runs posteriorly to the dens of the axis and for this reason it has an anterior concave trajectory. At the



**Fig. 4.27** (a) Superior and (b) anterior view of the first, second, fourth, and seventh cervical vertebrae. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Karl Wesker.)



**Fig. 4.28** Craniocervical ligaments. Views of the upper part of the vertebral canal with the spinous processes and parts of the vertebral arches removed to expose the ligaments on the posterior vertebral bodies viewed posteriorly (a) before and (b) and (c) after removal of the posterior longitudinal and transverse atlas ligaments. (d) The ligaments of the median atlantoaxial joint are shown from a superior view. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Karl Wesker.)

midline are two more bands of vertically oriented ligaments: The superior and inferior longitudinal bands constitute the transverse and cruciate ligaments. The superior band ends at the anterior edge of the foramen magnum, whereas the inferior extension ends attach to the body of C2.

## Alar Ligaments

These are two short and strong ligaments (left and right) connecting the superolateral segments of the dens of the axis to the medial segment of the occipital condyles.

## Apical Ligament

The apical ligament is a short ligament, attaching the vertex of the dens to the anterior edge of the foramen magnum.

## Tectorial Membrane

This membrane lies posteriorly to the alar and apical ligaments. It is divided into a medial segment and two lateral segments.

The medial segment runs from the anterior edge of the foramen magnum to the body of C2 where it continues to the posterior longitudinal ligament of the spine.

The lateral segments (left and right), connect C2 with the occipital condyles.

## Atlanto-Occipital Membrane

This membrane is composed of two segments:

- **Anterior segment:** Connects the anterior arch of C1 with the anterior edge of the foramen magnum. Considered to be an extension of the anterior longitudinal ligament of the spine.
- **Posterior segment:** Connects the posterior arch of C1 to the posterior edge of the foramen magnum. The posterior atlantooccipital membrane is traversed by the vertebral arteries after they exit the transverse foramen to enter the cranium via the foramen magnum. It is also the equivalent of the ligamentum flavum for the remaining segments of the spine.

### 4.7.3 Common Ligaments

#### Anterior Longitudinal

This ligament runs anteriorly to the vertebral bodies of the spine from the basilar portion of the occipital bone, to the anterior segment of the second vertebra of the sacrum. (► Fig. 4.29)

## Posterior Longitudinal

Like its anterior counterpart, this ligament runs over the posterior surface of the vertebral bodies from the internal aspect of the basilar segment of the occipital bone to the coccyx.

## Supraspinous Ligament

This is a thick fibrous band attached to the vertex of the spinous processes throughout the entire length of the spine. At the cervical segment, this ligament turns into the ligamentum nuchae.

## Interspinous Ligament

Differing from the previously described ligaments, the interspinous ligament has a segmental distribution, joining the space between spinous processes. It attaches superiorly at the inferior border of the overlying spinous process and inferiorly at the underlying spinous process. Posteriorly it attaches to the supraspinous ligament, whereas anteriorly it attaches to the ligamentum flavum.

## Ligamentum Flavum

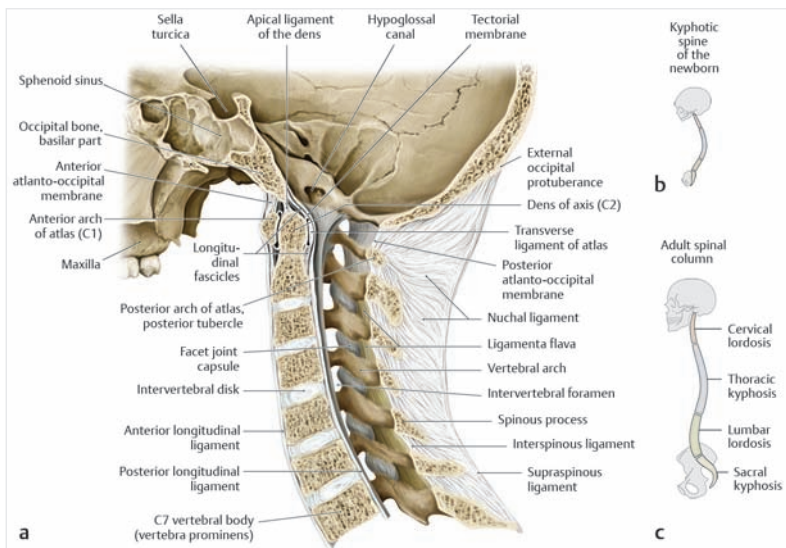
This ligament has two segments (left and right). Each are thick, short, strong, and elastic. They attach superiorly at the anterior segment of the lamina and inferiorly over the superior border of the underlying lamina.

## 4.8 Vascular Anatomy

### 4.8.1 Arterial Anatomy

The vascular supply of the intracranial CNS components is from branches and anastomoses of the carotid and vertebral arteries (► Fig. 4.30).





**Fig. 4.29** (a) Artist's drawing of a midsagittal section of the bones and ligaments of the skull base, craniocervical junction, and cervical spine. Diagrams showing the differences in sagittal alignment of the vertebral column in (b) infancy and (c) in adulthood. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. (Illustration by Karl Wesker.)

## Common Carotid Artery

The common carotid arteries (CCAs) differ in their origin. On the right side, the brachiocephalic trunk bifurcates into the right CCA and the right subclavian artery; on the left, it arises directly from the aortic arch.

Generally, both CCAs bifurcate into the external carotid artery (ECA) and internal carotid artery (ICA) 1 cm superior to the thyroid cartilage corresponding to the level of the 4th cervical vertebra (C4).<sup>4</sup>

## External Carotid Artery

**Collateral branches:** These follow an ascending order of bifurcation (► Fig. 4.31):

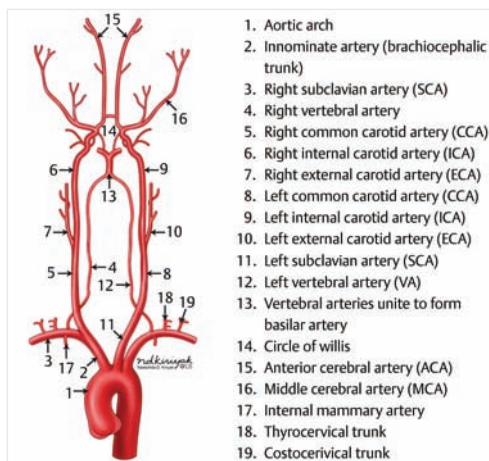
- Superior thyroid artery.

- Lingual artery.
- Ascending pharyngeal artery.
- Facial artery.
- Occipital artery.
- Posterior auricular artery.
- Parotid arteries.

**Terminal branches:** The ECA bifurcates into two terminal branches approximately 4 cm superior to the mandibular angle. These two terminal branches are:

1. Superficial temporal artery.
2. Maxillary artery: This artery gives off approximately 14 different branches (variable). Relevant are:
  - Middle meningeal artery: Enters the skull via the foramen spinosum. Its trajectory along the internal surface of the squamous portion of the temporal bone makes it highly





**Fig. 4.30** Coronal view of the arteries from the aortic arch, which supply the brain. (Reproduced from Meyers S, *Differential Diagnosis in Neuroimaging: Brain and Meninges*, 1st edition, ©2016, Thieme Publishers, New York.)

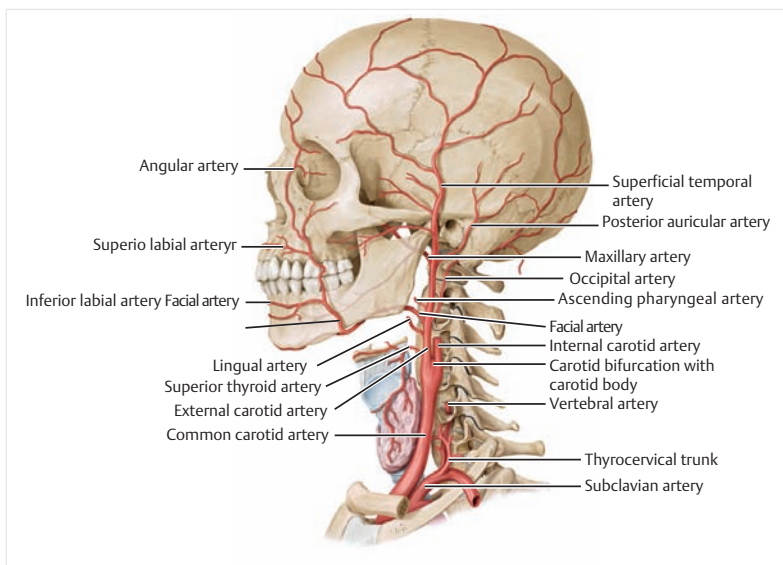
susceptible to bleeding after pterional trauma, which may result in epidural hematoma.

- Accessory meningeal artery: This artery is inconstant, entering the skull via the foramen ovale.
- Anterior and posterior deep temporal arteries supply the anterior and posterior portions of the temporal muscle.

## Internal Carotid Artery

From the carotid bifurcation, the ICA travels directly into the cranial cavity via the carotid foramen before ending at the level of the optic nerve<sup>3</sup>(► Fig. 4.32). For anatomical purposes, the ICA has been divided into seven segments:

- **C1 or cervical segment:** From the carotid bifurcation to the carotid foramen at the skull base, no branches originate from this segment.
- **C2 or petrous segment:** From the carotid foramen to the posterior edge of the foramen lacerum. The segment of the petrous bone where the ICA runs is known as the carotid canal. In this segment, it gives off the caroticotympanic artery.
- **C3 or lacerum segment:** Small segment where the ICA passes over the foramen lacerum.
- **C4 or cavernous segment:** From the foramen lacerum to the anterior clinoid process. Multiple branches originate from this segment:
  - Meningohypophyseal trunk: A surgically important branch giving off three arteries:
    - Tentorial artery or Bernasconi and Cassinari artery.
    - Dorsal meningeal artery.
    - Inferior hypophyseal artery.
  - Inferolateral trunk.
  - Medial trunk or McConnell's artery, goes to the capsule of the pituitary gland.
- **C5 or clinoid segment:** Between the proximal and distal dural rings.
- **C6, ophthalmic segment:** From the distal dural ring to the posterior communicating artery (P-Comm). Two important branches from this segment:
  - Ophthalmic artery.
  - Superior hypophyseal artery.
- **C7 or communicating segment:** From the P-Comm artery to the bifurcation of the ICA into anterior and middle



**Fig. 4.31** Overview of arteries of the head. Left lateral view. The common carotid artery divides into internal and external carotid arteries at the carotid bifurcation, which is usually at the level of the fourth cervical vertebra. There are eight branches of the external and none of the cervical internal carotid artery. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Karl Wesker.)

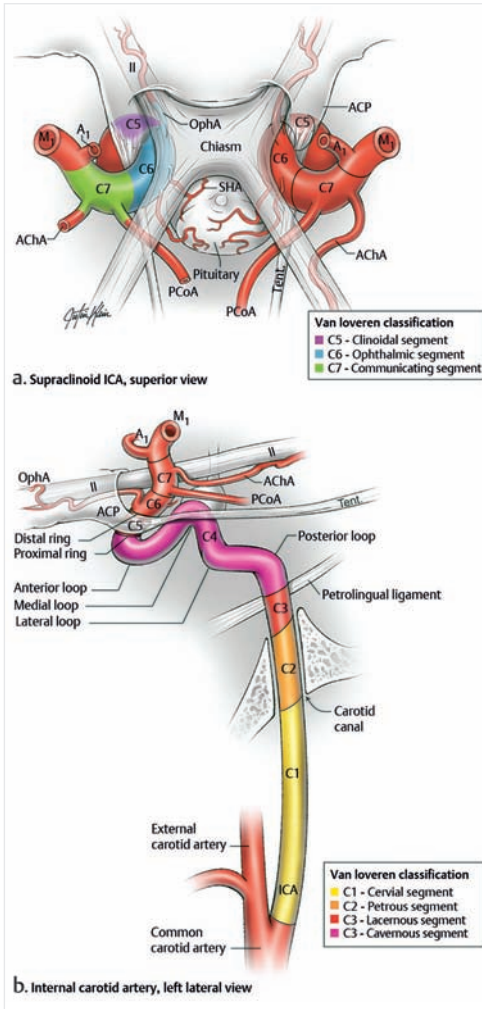
cerebral artery. The branches of this segment are:

- P-Comm.
- Anterior choroidal artery (ACh).

## Anterior Cerebral Artery

The anterior cerebral artery (ACA) arises from the ICA lateral to the optic chiasm, it supplies the medial surface of the cerebral hemisphere except for the medial occipital lobes (► Fig. 4.33). Grossly, the ACA can be divided into precommunicating and post-communicating segments based upon their proximal and distal location to anterior communicating artery (ACoA). Another classification dividing the ACA into five segments follows<sup>5</sup>:

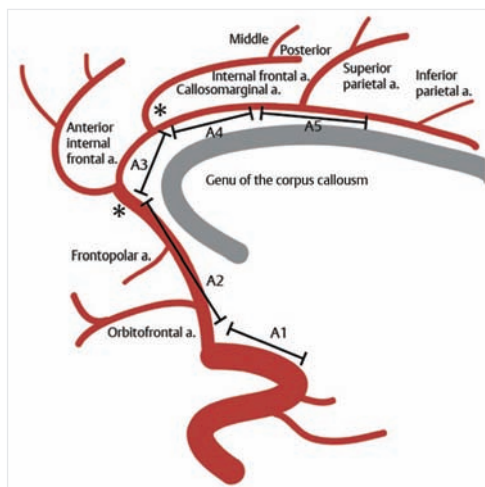
- **A1 or precommunicating segment:** From the ICA bifurcation to the ACoA.
- **A2:** From the ACoA to the junction of the rostrum and genu of the corpus callosum. The recurrent artery of Heubner may arise either from A1, A2, or at the A1/A2 junction. The A2 segment commonly gives off the infraorbital artery and the frontopolar artery.<sup>6</sup>
- **A3:** This artery travels around the genu of the corpus callosum and continues to the A4 segment after turning sharply, posterior to the genu. The branches of the A3 segment are highly variable and include the callosomarginal artery which may give off three further arteries including anterior internal frontal artery, middle internal frontal



**Fig. 4.32** Microsurgical anatomy of the internal carotid artery and ophthalmic artery. (a) Superior and (b) left lateral view of the internal carotid artery showing its segmental anatomy: C1, cervical segment; C2, petrous segment; C3, lacernous segment; C4, cavernous segment; C5, clinoidal segment; C6, ophthalmic segment; and C7, communicating segment. Dolenc's loops of cavernous ICA are also shown: anterior loop, medial loop, lateral loop, and posterior loop. AChA, anterior choroidal artery; ACP, anterior clinoid process; OphA, ophthalmic artery; PCoA, posterior communicating artery; SHA, superior hypophyseal artery; Tent, tentorium. (Reproduced from Lawton M, *Seven Aneurysms: Tenets and Techniques for Clipping*, 1st edition, ©2011, Thieme Publishers, New York.)

artery, and the posterior internal frontal artery.<sup>6</sup> In some cases, these three arteries may arise directly from the A3 segment. Additionally, the pericallosal artery may arise from the A3 segment or it could be a direct continuation of the ACA.

- **A4 and A5:** Segments run over the body of the corpus callosum. These segments are themselves separated from each other by a vertical line running posterior to the coronal suture. The A4 segment gives off the paracentral lobular artery, whereas the A5



**Fig. 4.33** Schematic representation of the relevant anatomy of the distal anterior cerebral artery and its surrounding structures. The most common sites for traumatic aneurysms are denoted (\*). a., artery. (Reproduced from Spetzler R, Kalani M, Nakaji P, *Neurovascular Surgery*, 2nd edition, ©2015, Thieme Publishers, New York.)

segment gives off the superior internal parietal artery and the inferior internal parietal artery.<sup>6</sup>

travel to the cortical surfaces of the hemispheres.

## Middle Cerebral Artery

The middle cerebral artery (MCA) arises from the ICA (► Fig. 4.34). Its branches terminate at the lateral surface of the cerebral hemispheres. For anatomical purposes, the MCA is divided into four segments<sup>7</sup>:

- **M1 or sphenoidal, horizontal segment:** From the origin of the MCA to the bifurcation of the MCA into a superior and inferior trunk. The lateral lenticulostriate arteries arise from this segment.
- **M2 or insular segment:** Runs in the depth of the Sylvian fissure from its bifurcation.
- **M3 or opercular segment:** From the depth of the Sylvian fissure on its posterior segment to the surface of the Sylvian fissure.
- **M4 or cortical segment:** Starts at the surface of the Sylvian fissure posteriorly and gives multiple branches which

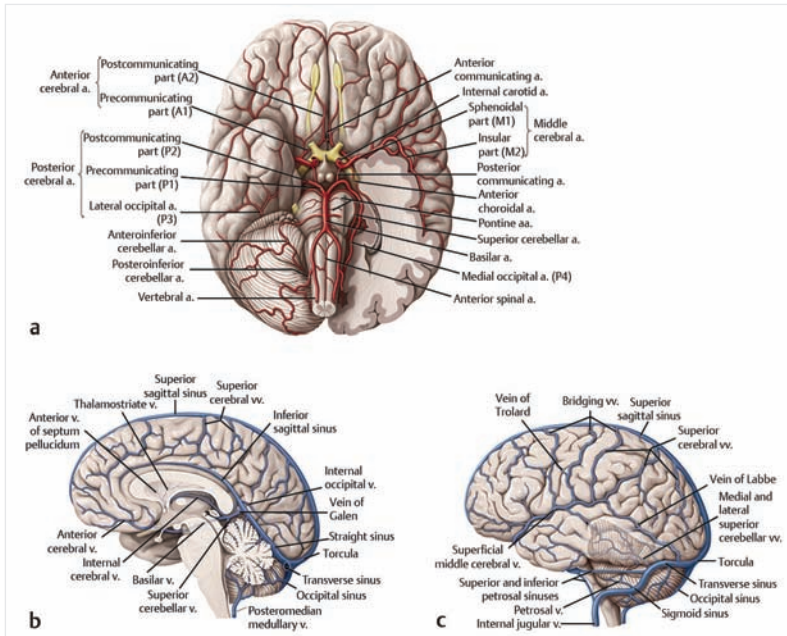
## Vertebral Artery

The vertebral artery (VA) arises directly from the subclavian artery on each side from where it runs superiorly to enter the transverse foramen of C6 on its way to the posterior cranial cavity. The VA is divided into four segments:

- **V1 or prevertebral:** Goes from its origin at the subclavian artery to C6.
- **V2 or vertebral segment:** Runs within the transverse foramen from C6 to C2.
- **V3 or extradural segment:** From C2 to the foramen magnum.
- **V4 or intradural:** From its entry to the dura of the foramen magnum until its junction at the contralateral VA forming the basilar artery (BA).

## Collateral Branches

- Anterior meningeal artery.
- Posterior meningeal artery.
- Posterior spinal artery.



**Fig. 4.34** Vascular anatomy. (a) Diagram of the arterial supply to the brain, including the circle of Willis formed by anastomoses between the anterior circulation (i.e., the anterior and middle cerebral arteries, arising from the internal carotid artery) and the posterior circulation (the basilar artery and posterior cerebral arteries, supplied by the vertebral arteries). (b) Midsagittal venous anatomy showing the major venous sinuses and the contributing veins. (c) Surface venous anatomy depicted from a lateral projection. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Karl Wesker.)

- Anterior spinal artery, formed from two branches (left and right) originating from each of the VAs prior to their continuation as the single BA. This artery runs in the surface of the anterior median fissure.
- Posterior inferior cerebellar artery (PICA), supplies the posterolateral medulla, the 4th ventricle, and the posteroinferior cerebellar hemispheres.

## Basilar Artery

The BA originates from the union of the two VAs over the anterior brainstem surface (► Fig. 4.34). It runs over the anterior surface of the pons giving off numerous

CN III travels on either side of the SCA and posterior cerebral arteries.

collateral branches. It terminates at the level of the interpeduncular cistern, where it contributes to the posterior cerebral arteries. The branches of the BA are:

- Anterior inferior cerebellar artery.
- Labyrinthine artery.
- Pontine arteries.
- Superior cerebellar artery (SCA).

## Posterior Cerebellar Artery

The posterior cerebellar artery (PCA) arises from the bifurcation of the BA at the interpeduncular cistern (► Fig. 4.34). It terminates at the medial surface of the occipital lobe. It is divided into four segments<sup>7</sup>:

- **P1 or precommunicating segment:** From the bifurcation of the BA to the junction of the P-Comm. This segment gives off multiple perforators to the thalamus, hypothalamus, subthalamus, and the anterolateral segment of the midbrain.
- **P2 or ambient segment:** From the junction of the P-Comm to the posterior edge of the midbrain. Some of the PCA branches at this segment are the lateral posterior choroidal artery and thalamogeniculate arteries.
- **P3 or quadrigeminal segment:** From the posterior edge of the midbrain to the anterior limit of the calcarine fissure. The branches of this segment supply the posteroinferior temporal lobe (posterior temporal artery), occipital lobe (parieto-occipital artery and calcarine artery) and the posterior segment of the corpus callosum (posterior pericallosal artery).

## Circle of Willis

The ICA and vertebrobasilar arterial system are connected through a polygon located between the interpeduncular

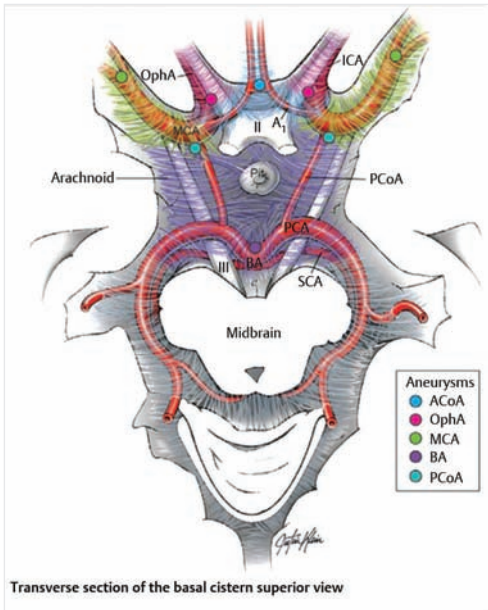
fossa, mammillary bodies, infundibulum and optic chiasm (► Fig. 4.35). This arterial polygon (which is complete in approximately 20% of the population)<sup>2</sup> is formed by the anastomoses of the tip of the BA, PCA (P1), and P-Comm posterolaterally, and the ICA, ACA (A1), and ACoA anterolaterally. The circle of Willis gives off multiple penetrating arteries to anatomical structures within its vicinity.

## 4.8.2 Venous Anatomy

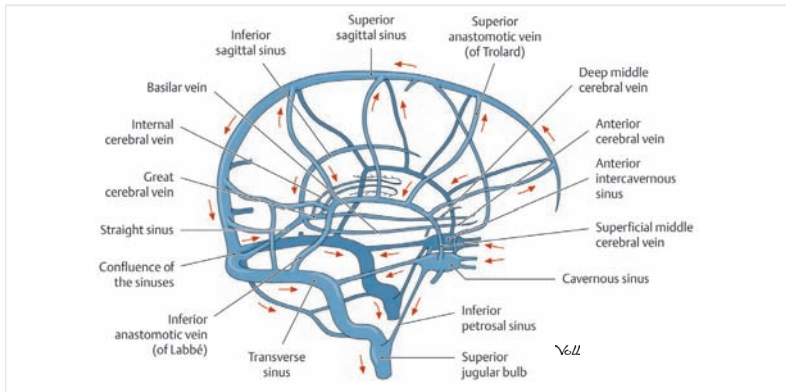
### Dural Sinuses

- **Superior sagittal sinus (SSS):** From the foramen cecum at the cribriform laminae of the ethmoid bone to the internal occipital protuberance, where the confluence of the sinuses is located (► Fig. 4.36). Trauma to the vertex of the skull may cause rupture of the SSS, resulting in vertex epidural hematoma.<sup>8</sup>
- **Inferior sagittal sinus (ISS):** Runs within the inferior edge of the falx cerebri and is formed by smaller cortical veins from medial hemispheric surfaces.
- **Straight sinus:** Formed by the Vein of Galen (deep vein of the brain) and the ISS. Also ends at the sinusoidal confluence.
- **Transverse sinuses:** One per side, originating from the confluence of the sinuses. Runs laterally and continues drains into the sigmoid sinus. Receives drainage from the vein of Labbé.
- **Sigmoid sinus:** Continuation of the transverse sinus and the point at which transverse sinuses meet. Receives an anastomosis from the superior petrosal vein which drains the cavernous sinus. The sigmoid sinus ends at the jugular foramen, where it receives an anastomosis from the inferior petrosal sinus. It continues as the internal jugular vein following its exit from the jugular foramen.





**Fig. 4.35** Subarachnoid cisterns around the circle of Willis, as viewed from above the brain, which has been sliced axially. The relationship between aneurysms in the circle of Willis and their associated cisterns is shown. (Reproduced from Lawton M, *Seven Aneurysms: Tenets and Techniques for Clipping*, 1st edition, ©2011, Thieme Publishers, New York.)



**Fig. 4.36** Dural sinus tributaries from the cerebral veins (after Rauber and Kopsch). Right lateral view. Venous blood collected deep within the brain drains to the dural sinuses through superficial and deep cerebral veins. The red arrows in the diagram show the principle directions of venous blood flow in the major sinuses. (Reproduced from Schuenke, Schulte, and Schumacher, *Atlas of Anatomy*, 2nd edition, ©2014, Thieme Publishers, New York. Illustration by Markus Voll.)

## Cerebral Veins

### Superficial Veins

The superficial veins of the brain form multiple anastomoses which terminate within two main veins:

- **Vein of Trolard:** Located superiorly, drains from the sylvian fissure to the SSS.
- **Vein of Labbé:** Located inferiorly, drains from the sylvian fissure to the transverse sinus.

### Deep Veins

- **Internal cerebral vein:** Receives the thalamostriate vein (caudate and thalamus) at the foramen of Monro, and the septal vein (septum pellucidum, anterior corpus callosum and head of the caudate).<sup>2</sup>
- **Basal vein of Rosenthal:** This vein drains the base of the brain (anterior and medial temporal lobe) from the anterior perforated substance to join the internal cerebral vein and form the vein of Galen.
- **Vein of Galen or Great cerebral vein:** Formed by the internal cerebral veins and the veins of Rosenthal. The vein of Galen then joins the ISS to form the straight sinus.

## 4.9 Top Hits

### 4.9.1 Questions

1. The middle meningeal artery enters the skull through:
  - a) Foramen lacerum
  - b) Foramen ovale
  - c) Foramen rotundum
  - d) Foramen spinosum
2. What are the branches of the meningo-hypophyseal trunk?
  - a) Anterior choroidal artery—posterior choroidal artery—dorsal meningeal artery

### Pearls



- Knowing surface anatomy is key to perform bedside procedures such as lumbar punctures/drains and external ventricular drains.
  - Understand the different anatomical segments for the main arteries supplying the brain: ICA, MCA, ACA, PCA, and vertebral artery.
  - Recognize the main venous structures such as dural sinuses as well as Trolard and Labbé veins.
  - A firm command of the various dermatomes and myotomes is essential to ensure a proper neurological exam for patients with spinal cord injury.
- b) Anterior choroidal artery—tentorial artery—anterior meningeal artery
  - c) Tentorial artery—anterior meningeal artery—inferior hypophyseal artery
  - d) Tentorial artery—dorsal meningeal artery—inferior hypophyseal artery
  - e) Tentorial artery—dorsal meningeal artery—superior hypophyseal artery
3. Which of the following options better describes the trajectory of the cortico-spinal tract:
    - a) Primary motor cortex—internal capsule—corona radiata—cerebellar peduncle—anterior pons—pyramids—spinal cord
    - b) Primary motor cortex—corona radiata—cerebral peduncle—anterior pons—pyramids—posterior column of the spinal cord
    - c) Primary motor cortex—corona radiata—cerebellar peduncle—anterior pons—pyramids—anterior and lateral columns of the spinal cord
    - d) Primary motor cortex—corona radiata—cerebral peduncle—anterior pons—pyramids—anterior and lateral columns of the spinal cord



- e) Primary motor cortex—corona radiata—internal capsule—cerebral peduncle—anterior pons—pyramids—spinal cord
4. Which of the following is correct regarding the interventricular foramen, also known as foramen of Monro?
    - a) Connects the 4th ventricle with the subarachnoid space
    - b) Connects the right lateral ventricle with the left lateral ventricle
    - c) Connects each of the lateral ventricles with the 3rd ventricle
    - d) Connects the 3rd and 4th ventricles
    - e) It is located at the atrium
  5. Which of the following better describes the 3rd cranial nerve?
    - a) It crosses between the PCA and SCA
    - b) It has sympathetic fibers coming from the Edinger-Westphal nucleus
    - c) It reaches the orbit through the optic canal
    - d) It arises from the pontomedullary sulcus
  6. Please select the correct statement regarding the pterion:
    - a) Suture between the frontal-zygomatic-temporal-sphenoid bones
    - b) Suture between the frontal-sphenoid-temporal-parietal bones
    - c) Suture between the frontal-zygomatic-parietal-sphenoid bone
    - d) Suture between the frontal-zygomatic-parietal-temporal bones
  7. The ambient cistern is located at the level of:
    - a) Anterior midbrain
    - b) Anterolateral midbrain
    - c) Posterolateral midbrain
    - d) Posterior midbrain
    - e) None of the above
  8. The ophthalmic artery most commonly arises from:
    - a) ACoA
    - b) A1
    - c) C6
    - d) Clinoid segment of the ICA
    - e) Common ophthalmic artery
  9. The body of the  $\alpha$ -motor neurons are most commonly located in which of the followings:
    - a) Dorsal root ganglia
    - b) Rexed lamina IX
    - c) Anterior spinal root
    - d) Rexed lamina II
  10. Which of the following statements is true regarding the brainstem?
    - a) The only cranial nerve arising from the posterior surface is the 4th cranial nerve
    - b) The basilar artery provides blood supply to the entire anterior surface of the brainstem
    - c) The CN V exits through the pontomedullary sulcus
    - d) The superior cerebellar peduncle crosses between the corticospinal tracts in the anterior pons

## 4.9.2 Answers

1. **d.** The middle meningeal artery (branch of the internal maxillary artery), enters the skull through the foramen spinosum. The foramen lacerum is occupied by fibrocartilage resulting from the confluence of the petrous portion of the temporal bone with the sphenoid and occipital bones. The deep and greater petrosal nerves cross the lacerum. The foramen ovale is occupied by the mandibular nerve (V3) and lesser petrosal nerve. The maxillary nerve (V2) crosses the foramen rotundum.
2. **d.** The meningohypophyseal trunk arises from the cavernous segment of the ICA. Three main branches from this trunk have been described: Tentorial artery (Bernasconi and Cassinari artery), dorsal meningeal artery, and the inferior hypophyseal artery.

3. **f.** Following a craniocaudal order: The body of the upper motor neuron is located at the primary motor cortex, the axons form the corona radiata which travels through the posterior limb of the internal capsule to reach the middle three-fifth of the cerebral peduncle, they continue down to the anterior pons. On the medulla, it forms the pyramids decussating approximately 90% of the fibers in the lower one-third to finally reach the spinal cord where it travels in two different bundles (anterior and lateral corticospinal tract).
4. **c.** There are two foramen of Monro. Each of them connects the ipsilateral lateral ventricle with the 3rd ventricle. The 4th ventricle drains CSF to the subarachnoid space through one medial foramen (Magendie) and two lateral foramen (Luschka). There are not normal connections between the right and left lateral ventricles. The 3rd and 4th ventricles are connected through the cerebral aqueduct.
5. **a.** Once the CN III leaves the interpeduncular cistern, it crosses between the PCA (superiorly) and SCA (inferiorly). The Edinger-Westphal nucleus provides parasympathetic fibers. The only CN occupying the optic canal is the optic nerve (CN II). CN III reaches the orbit through the superior orbital fissure. The CNs at the pontomedullary sulcus are (from medial to lateral) CNs VI, VII, and VIII.
6. **b.** The pterion is the suture between the frontal-sphenoid-temporal-parietal bones.
7. **c.** The ambient cistern is located at the posterolateral midbrain. The interpeduncular cistern is located anterior. The quadrigeminal cistern is located posterior to the midbrain.
8. **c.** The most common origin for the ophthalmic artery is the C6 segment of the ICA, also known as ophthalmic segment (from the distal dural ring to the P-Comm). This segment also gives the superior hypophyseal artery.
9. **b.** The  $\alpha$ -motor neuron in the spinal cord are located on Rexed lamina IX. Dorsal root ganglia have the body for the sensory neurons. The anterior spinal root has the motor axons. Rexed lamina II has the substantia gelatinosa for exteroceptive neurons.
10. **a.** The only CN arising from the posterior surface of the brainstem is the CN IV or trochlear nerve. It is also the only CN which decussates. The BA provides irrigation mostly to the pons. The CN V exits at the anterolateral surface of the pons. The superior cerebellar peduncle crosses at the inferior midbrain.

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## 5 Neuroradiology for the Neurosurgeon

David R Hansberry, Kofi-Buaku Atsina, Mougnyan Cox, Adam E Flanders

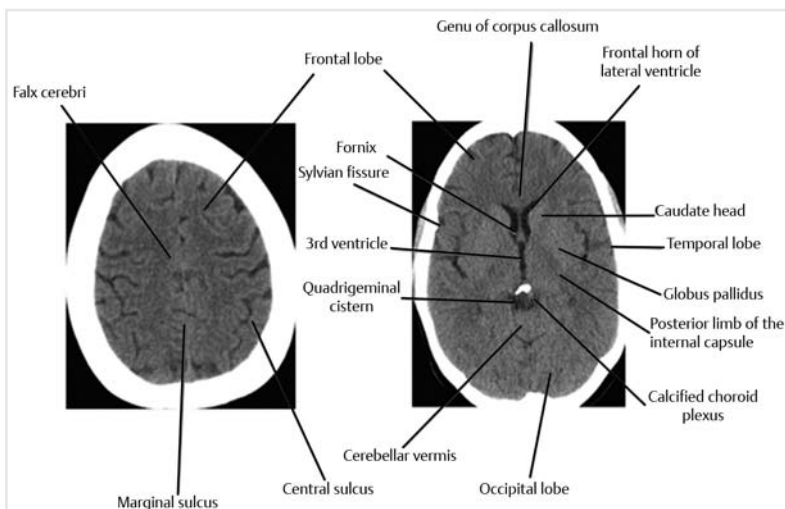
### 5.1 Introduction

Timely and accurate performance and interpretation of neuroimaging are essential for the care of the acute neurological patient. While a detailed neurological examination can provide a wealth of specific information about the site of pathology in the neuroaxis, the majority of the central nervous system (CNS) is occult to the human eye, ear, and touch. It is one of the few systems that cannot be visually inspected, auscultated, or palpated noninvasively. As such, most patients with a neurological problem undergo some form of imaging, with the specific imaging test determined by the patient's presentation and the acuity of the symptoms. Computed tomography (CT), conventional magnetic resonance imaging (MRI), and ultrasound comprise the majority of neuroimaging

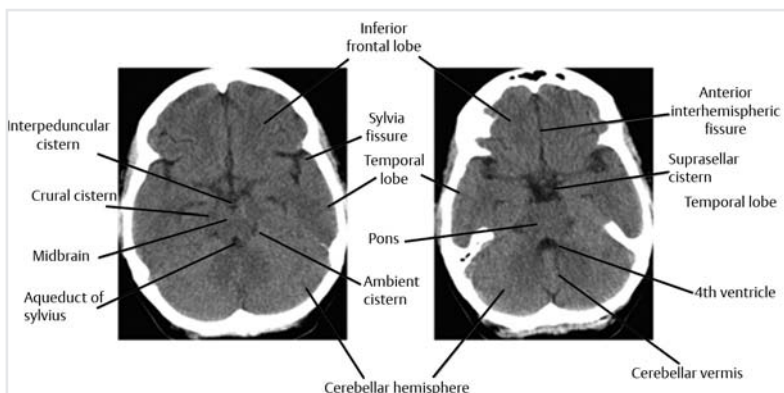
studies performed during the course of the typical neurological workup. Advanced imaging modalities such as magnetic resonance (MR) perfusion, MR spectroscopy, and diffusion tensor imaging are reserved for special indications such as brain tumor imaging at specialized centers.

### 5.2 Computed Tomography

CT is the workhorse for the acute neurological patient (►Fig. 5.1, ►Fig. 5.2); it is fast, widely available, and is able to exclude the majority of cranial and spinal emergencies that would require a trip to the operating room. Unlike MRI, there are no compatibility issues with CT for clinical monitoring devices in critically ill patients, and no metal



**Fig. 5.1** Axial non-contrast CT of the brain; slice above the ventricles (left), and slice at the ventricles (right). (Images are provided courtesy of Thomas Jefferson University Hospital.)



**Fig. 5.2** Axial non-contrast CT of the brain; slice below the ventricles and at the mid-brain (left), and slice slightly lower at the pons (right). (Images are provided courtesy of Thomas Jefferson University Hospital.)

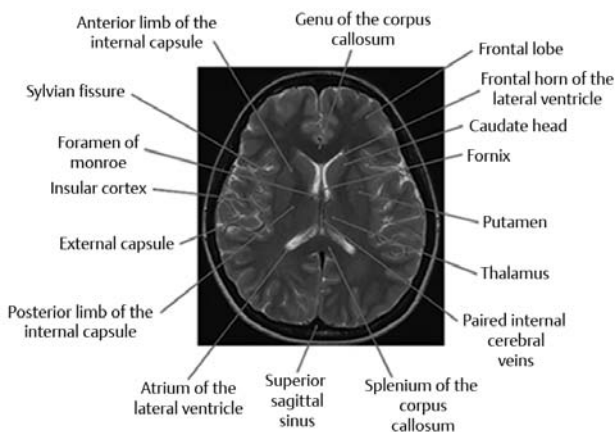
screening is required. In the trauma patient, CT readily shows the presence of blood in the various intracranial compartments. Acute hemorrhage is hyperdense on non-contrast CT in comparison to brain and cerebrospinal fluid (CSF), and is readily detected when present even in small amounts. Other pertinent information, such as the presence of midline shift, ventriculomegaly/hydrocephalus, herniation, depressed skull fractures, and radiopaque foreign bodies can also be evaluated by CT. In the patient presenting with an acute stroke syndrome, a non-contrast CT can distinguish between hemorrhagic and ischemic strokes, enabling timely administration of intravenous tissue plasminogen activator (tPA) in the absence of other contraindications. It can also help to differentiate conditions that might mimic other neurologic diseases.

In addition to the detection of acute hemorrhage, CT is also excellent for assessing bony pathology and calcification.

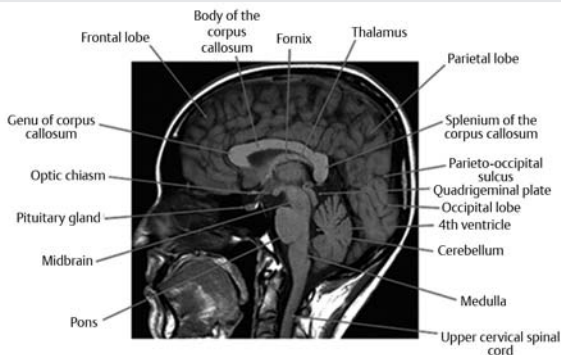
Subtle skull fractures, paranasal sinus/mastoid pathology, and temporal bone disease are better evaluated on CT than on radiographs or MRI.

## 5.3 Magnetic Resonance

MRI provides exquisite soft tissue contrast and detail of the intracranial (► Fig. 5.3, ► Fig. 5.4, ► Fig. 5.5) and intraspinal structures, and is therefore the imaging test of choice whenever direct parenchymal assessment of the brain, orbits, skull base, cranial nerves, or spinal cord is required. Proper interpretation of an MRI study requires familiarity with the various sequences, the information they provide, and their pitfalls/associated artifacts. Some standard MR sequences include T1-weighted images (T1WI), T2-weighted images (T2WI), fluid-attenuated inversion recovery (FLAIR), gradient-recalled echo (GRE), diffusion weighted imaging (DWI), and post-contrast T1-weighted images.



**Fig. 5.3** Axial T2-weighted image of the brain. (Image is provided courtesy of Thomas Jefferson University Hospital.)

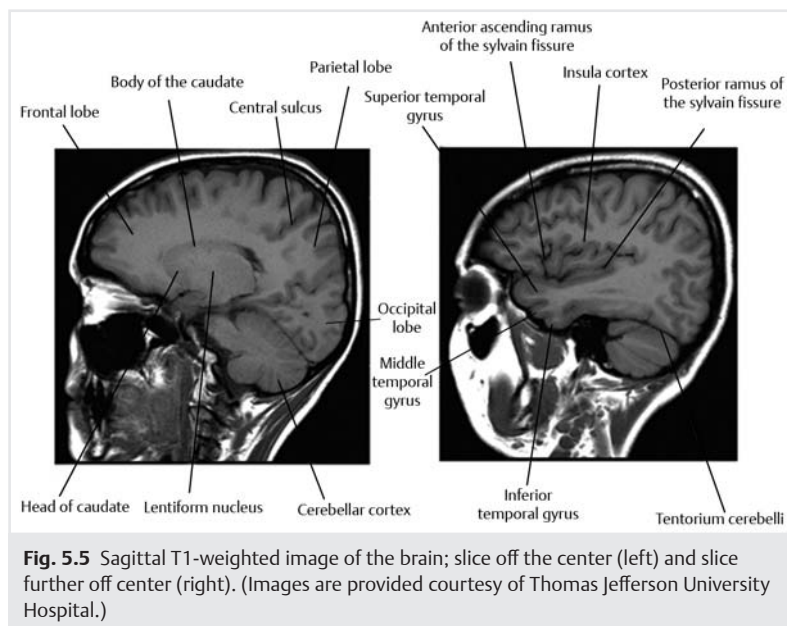


**Fig. 5.4** Sagittal T1-weighted image of the brain; slice through the midline. (Image is provided courtesy of Thomas Jefferson University Hospital.)

An important caveat is that MRI is not adequate for the detection of fractures, therefore, MRI may be used to supplement but not replace CT in the setting of trauma.

### 5.3.1 MRI Sequences

T1WI are good for evaluating anatomy. Fat, blood, and proteinaceous products can appear whiter in signal on T1WI.<sup>1</sup> Application of fat-suppression on T1WI can distinguish between fat and blood in



cases of a T1 hyperintense mass.<sup>2</sup> T2WI highlight many pathologic processes in the brain that produce either edema or areas of signal abnormality which tend to be lighter in signal intensity on T2WI. FLAIR images are also T2WI, but with suppression of signal from bulk water such as CSF in the subarachnoid space. This allows T2-bright pathologic processes in the brain or CSF space to be more conspicuous and easier to detect. GRE images are sensitive for the detection of subacute or chronic blood products in the brain because of their magnetic properties yielding a dark, low, or hypointense signal. Hypointensity on GRE is not specific for blood products however, and other substances like calcium or metal can also appear hypointense to varying degrees. DWI is the most sensitive and specific MR

technique for the diagnosis of acute cerebral infarction.<sup>3</sup> Areas of acute infarction will appear bright on the DWI sequence and dark on the corresponding apparent diffusion coefficient maps.<sup>3</sup> Post-contrast imaging increases the sensitivity of MRI for detecting pathologic changes in the brain. Areas of subtle T1 or T2 signal abnormality sometimes show striking enhancement on the post-contrast images, increasing the likelihood that they will be detected. Contrast enhancement can also distinguish between truly cystic/nonenhancing lesions and cyst-like brain masses which will enhance along their periphery. In general, most patients with suspected intracranial infection or tumor who undergo MRI should also have contrast-enhanced imaging, as this helps with detection and characterization of intracranial abnormalities.

## 5.4 Clinical Scenarios

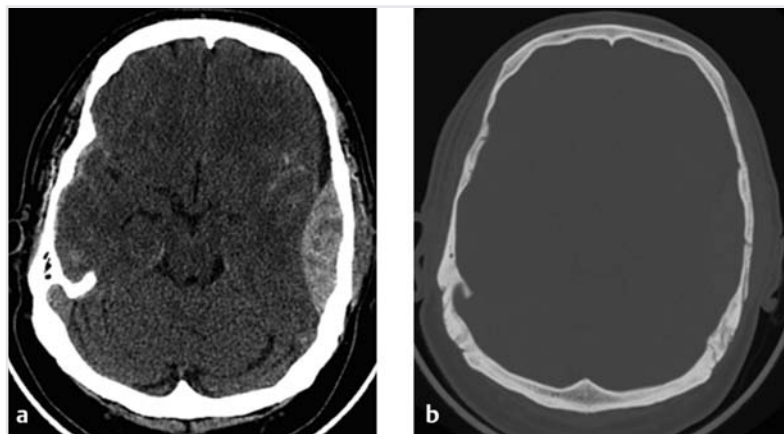
### 5.4.1 Epidural Hematoma

Imaging of epidural hematomas is primarily done with CT, as these patients may be unstable or under consideration for emergent decompression. The classic appearance of an acute epidural hematoma is a lentiform or convex hyperdense extra-axial (external to the brain) mass that does not cross the lambdoid or coronal suture lines (► Fig. 5.6). However, epidural hematomas can cross the midline sagittal suture as the periosteal layer of the calvarium forms the outer layer of the dura, and extravasated blood would be external or “epi”-dural to this layer. Epidural hematomas can cross

the tentorial leaflets for a similar reason. The hematoma usually causes mass effect on the underlying brain, and there may be midline shift to the contralateral side. The hematoma usually happens on the same side as the soft tissue swelling (i.e., the site of the traumatic blow), and there is usually an underlying skull fracture which leads to laceration of the middle meningeal artery. In some instances, epidural hematomas may also be venous in origin, particularly in the posterior fossa.<sup>4</sup>

### 5.4.2 Subdural Hematoma

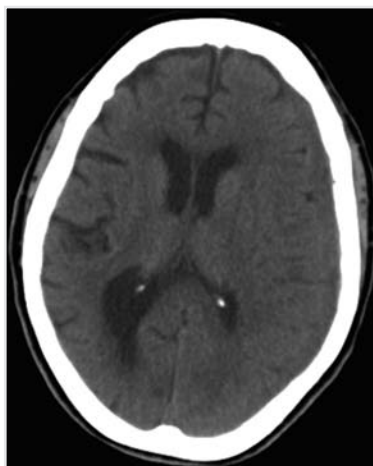
Subdural hematomas are located in the potential space between the dura mater and the pia-arachnoid mater. In older



**Fig. 5.6** Left epidural hematoma. A 32-year-old male with witnessed fall from a ladder. Axial nonenhanced CT scan was performed in the emergency room. **(a)** Soft tissue window shows lentiform-shaped hyperdense blood products along the left frontotemporal convexity. The hematoma does not cross suture lines indicating that it is within the epidural space. There is mild mass effect on the underlying brain tissue. Also note overlying scalp swelling adjacent to the extra-axial blood. **(b)** Bone window shows a nondisplaced temporal bone fracture in the region of the hematoma. Findings are compatible with acute epidural hematoma, and is most likely from injury to the left middle meningeal artery. (Images are provided courtesy of Thomas Jefferson University Hospital.)

patients, these collections may occur after minimal trauma as a result of brain atrophy and stretching of the cortical bridging veins, which makes them vulnerable to injury. In younger patients, these collections occur after substantial trauma, and are usually located opposite to the side of traumatic head impact. On CT, subdural hematomas typically appear as hyperdense crescentic collections that cross suture lines. In the region of the vertex or falx cerebri, subdural hematomas layer along the falx and tentorial leaflets without crossing these structures. One important pitfall on CT to be aware of are older hematomas that have degraded and therefore may appear of similar density to the adjacent brain (i.e., an isodense subdural collection), and may be difficult to detect without a high index of suspicion (► Fig. 5.7). In the absence of significant midline shift, abnormal thickening or blurring of the gray matter on the side of the isodense subdural hematoma may be the only finding on CT.

Equivocal cases of suspected isodense or thin subdural hematomas can be confirmed on MRI, which can show extremely thin collections on FLAIR images.



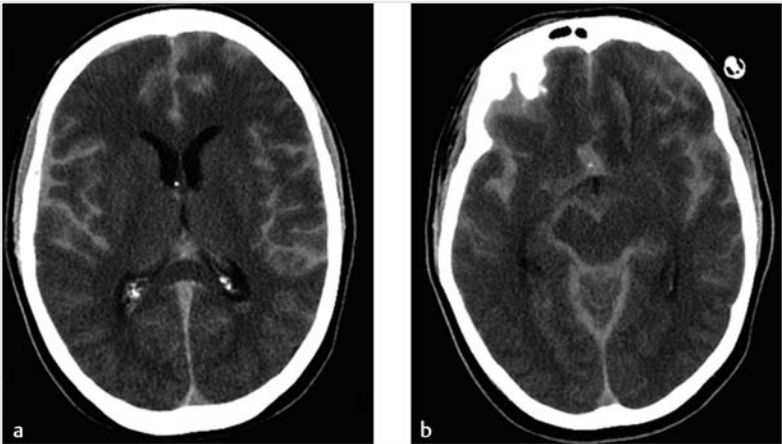
**Fig. 5.7** Isodense left subdural hematoma. A 69-year-old female presents with chronic headache. Axial nonenhanced CT scan shows concave-shaped isodense blood products along the left hemispheric convexity. The hematoma crosses suture lines indicating that it is within the subdural space. There is mild mass effect on the underlying parenchyma but no midline shift. These findings are compatible with subacute subdural hematoma. (Image is provided courtesy of Thomas Jefferson University Hospital.)

### 5.4.3 Subarachnoid Hemorrhage

Subarachnoid hemorrhage (SAH) has a distinctive appearance on CT, with hyperdensity conforming to the cisterns and sulci of the brain (► Fig. 5.8). The most common cause of SAH is trauma, which usually presents with scattered areas of sulcal hyperdensity on CT. This is in contradistinction to aneurysmal SAH, which usually presents with large or diffuse dissemination of hyperdense material in the sulci and cisterns at the base of the brain (► Fig. 5.8).

The location of the greatest amount of SAH can be a clue to the location of the ruptured aneurysm; focal clot in the anterior interhemispheric fissure is classic for a ruptured anterior communicating aneurysm, or a focal clot or large SAH in the Sylvian cistern is suggestive of a ruptured middle cerebral artery (MCA) aneurysm.<sup>5</sup> A pertinent finding to include in every imaging evaluation of aneurysmal SAH is the presence or absence of hydrocephalus. Ventricular dilatation, particularly of the temporal horn, is a key imaging feature of acute hydrocephalus on CT.<sup>6</sup>





**Fig. 5.8** Diffuse subarachnoid hemorrhage. A 41-year-old male presents with a thunderclap headache and syncope. Axial nonenhanced CT scan is performed in the emergency room. (a) There is diffuse distribution of high density material, representing acute blood products within the cerebral sulci of the temporal, insula, and frontal lobes, as well as along the anterior interhemispheric fissure. (b) There are acute blood products within the cerebral sulci bilaterally, Sylvian fissures, as well as the interpeduncular, crural, and ambient cisterns. There is an intraparenchymal component of hemorrhage within the left medial frontal lobe. Findings are compatible with aneurysmal type SAH. The accumulation of blood products within the region of the anterior communicating artery suggests the possibility of anterior communicating artery aneurysm rupture as the cause. (Images are provided courtesy of Thomas Jefferson University Hospital.)

Abnormally low signal may be seen around the ventricles in cases of acute hydrocephalus, which represents transependymal CSF flow or flow that is impeded from the normal resorption pathway at the convexity.

On MRI, SAH can be seen as abnormally bright signal in the CSF spaces on FLAIR imaging. Hypointense material in the sulci may also be seen on the GRE sequence.

#### 5.4.4 Parenchymal Hemorrhage

Hypertension is the most common cause of nontraumatic parenchymal hematoma in older patients. In nonhypertensive elderly patients, cerebral amyloid angiopathy is a leading cause. Hemorrhagic conversion of a recent infarct or hemorrhage into an existing neoplasm should also be considered in older patients. An intraparenchymal hematoma in a young adult raises a different specter of diseases, with other etiologies like an underlying vascular malformation or

illicit drug use being among the leading considerations.<sup>7</sup>

Acute parenchymal hematomas appear as hyperdense space-occupying masses on CT. If hemorrhage occurs close to the ventricular surface, the hematoma may dissect into the ventricle with secondary intraventricular hemorrhage and possibly hydrocephalus. The volume of parenchymal hematoma has been correlated with risk of morbidity and mortality.<sup>8</sup> Other important imaging findings to note (or to ask the radiologist about) are the presence and degree of midline shift, and evidence of herniation (manifested as effacement/obliteration of the CSF spaces surrounding the brain). As acute hematomas evolve, the degree of surrounding edema increases, peaks, and then gradually subsides. The hematoma eventually fades and disappears from the outside in, reminiscent of a melting ice cube.

### 5.4.5 Cerebral Edema

Diffuse cerebral edema can be seen after trauma or prolonged anoxia, and findings on CT can be subtle when imaging is performed early in the disease course. Typical CT findings include loss of gray-white differentiation, effacement of the basal cisterns and cortical sulci (due to cerebral swelling), and increased attenuation of the falx, tentorium, and subarachnoid spaces.

The increased attenuation of the CSF spaces in diffuse cerebral edema is multifactorial, but can be mistaken for SAH (so-called “pseudo-subarachnoid” pattern).<sup>9</sup>

There may also be relatively low attenuation of the cerebral hemispheres compared with the cerebellum, causing the cerebellum to appear artifactually dense (so called

“dense cerebellum” sign).<sup>10</sup> CT findings in early cerebral edema can be easily missed, particularly in young patients without much atrophy. However, the basal cisterns should always be visible on head CT in every patient.

### 5.4.6 Ischemic Stroke

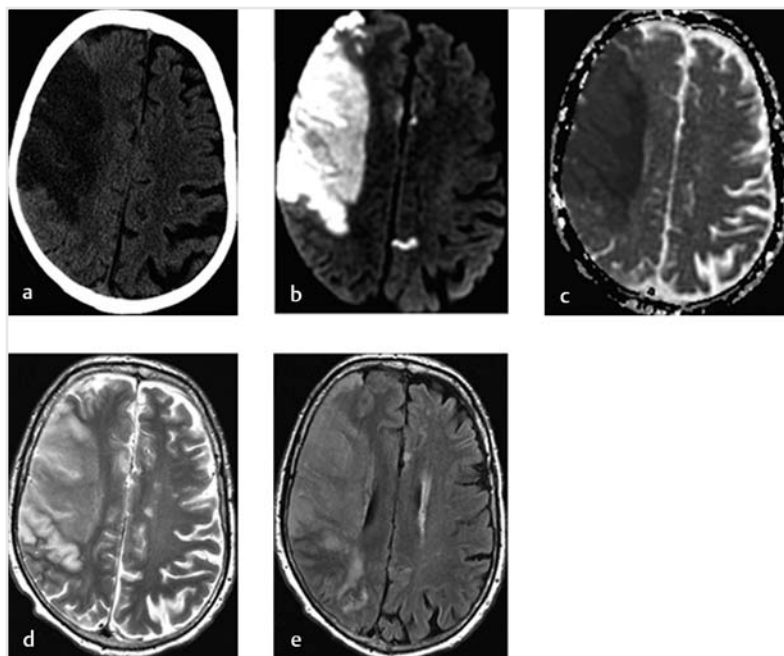
CT is insensitive for early acute infarction. The main role of CT is to exclude intracranial hemorrhage or large areas of completed infarction prior to intravenous tPA infusion.

Imaging findings in early acute ischemic stroke are subtle, but include loss of gray-white differentiation, blurring/indistinctness of the basal ganglia, loss of the insular cortex, and a hyperdense vessel (from thrombus).<sup>11</sup>

MRI is much more sensitive for the detection of acute stroke, and shows restricted diffusion conforming to the territory of the occluded artery (►Fig. 5.9, ►Fig. 5.10, ►Fig. 5.11, ►Fig. 5.12, ►Fig. 5.13).<sup>3</sup> MRI can also be used to detect subtle hemorrhagic conversion of acute ischemic stroke, which would be best visualized on the GRE sequences.

### 5.4.7 Aneurysms

Familiarity with imaging, treatment, and surveillance of intracranial aneurysms is an important part of any neurosurgical practice. In general, the two main noninvasive methods for diagnosing intracranial aneurysms are CT or MR angiography. CT has several advantages over MRI in the acute setting. In addition to being more widely available and quicker to perform,

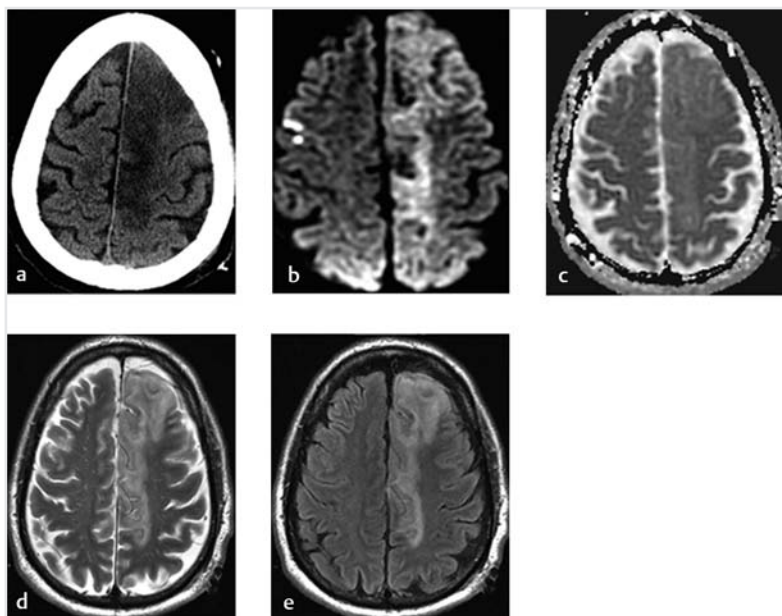


**Fig. 5.9** Acute right middle cerebral artery distribution infarct. A 55-year-old male presents with left hemiparesis and confusion. **(a)** CT scan shows wedged-shaped area of low attenuation involving both gray and white matter in the right MCA territory consistent with cytotoxic edema. **(b)** Diffusion weighted imaging and **(c)** apparent diffusion coefficient maps show corresponding areas of high signal and low signal respectively consistent with restriction of diffusion. **(d)** T2 and **(e)** fluid-attenuated inversion recovery maps show corresponding white matter signal abnormality. Findings are compatible with an acute right MCA territory infarction. (Images are provided courtesy of Thomas Jefferson University Hospital.)

virtually all invasive monitoring devices for acutely ill patients are essentially CT compatible.

The spatial resolution of CT is superior to MRI, however, even 1–2 mm aneurysms are readily identified on with modern MR angiography (MRA) techniques.

MRI is advantageous in younger patients undergoing surveillance for small unruptured/untreated aneurysms as no radiation is involved and contrast administration is not required. On both imaging modalities, aneurysms appear as focal dilatations or outpouchings in the vessel wall, usually at branching points or areas of stress. While all the vessels should be inspected, common sites of occurrence that should undergo additional scrutiny

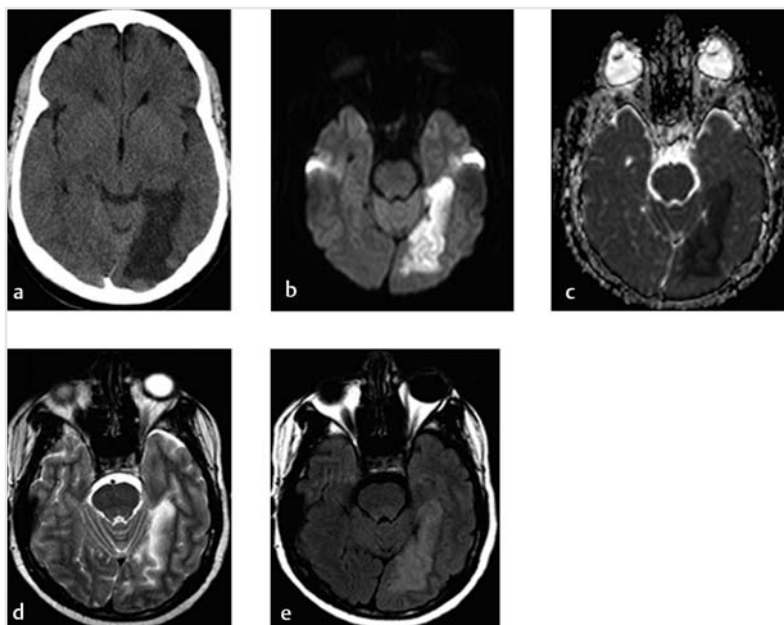


**Fig. 5.10** Subacute left anterior cerebral artery distribution infarct. A 59-year-old male presents with right lower extremity weakness. (a) Non-contrast CT scan shows an area of low attenuation involving both gray and white matter in the left anterior cerebral artery territory consistent with cytotoxic edema. (b) Diffusion weighted imaging and (c) apparent diffusion coefficient maps show corresponding patchy areas of high signal respectively consistent with facilitated diffusion. (d) T2 and (e) FLAIR maps show corresponding white matter signal abnormality. Findings are compatible with a subacute left anterior cerebral artery territory infarction. (Images are provided courtesy of Thomas Jefferson University Hospital.)

include the anterior communicating (AComm) complex, MCA bifurcation, basilar tip, and origins of the posterior communicating (PComm) arteries. In general, angiography is better for surveillance of surgically clipped aneurysms as the artifacts produced by the metallic clips prohibit adequate assessment of the adjacent vasculature, while MRA is superior for follow-up of coiled aneurysms.<sup>12,13</sup>

### 5.4.8 Arterial Dissection

Arterial dissections occur as a result of a tear in the intima of the vessel wall, with dissection of blood into the media of the wall creating a false lumen adjacent to the true lumen. On cross-sectional imaging, there is usually irregularity and narrowing of the true lumen, with eccentric thickening or slight dilatation of the outer circumference of the vessel wall by thrombus/subacute



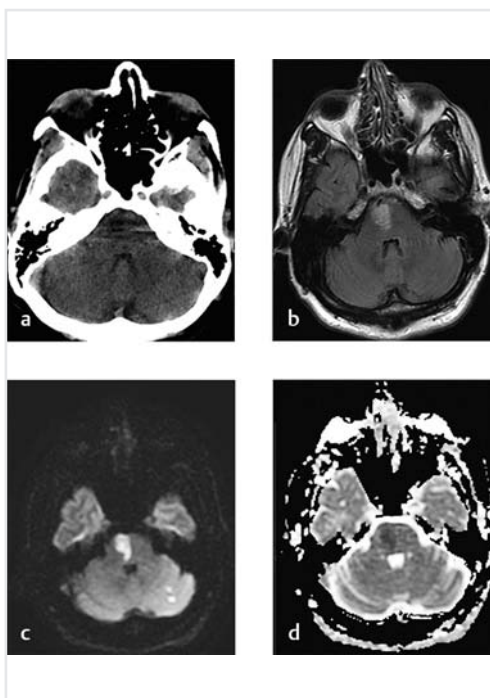
**Fig. 5.11** Acute left occipital lobe infarct. A 32-year-old male presents with syncope and visual disturbance. **(a)** Non-contrast CT scan shows an area of low attenuation involving both gray and white matter in the left posterior cerebral artery territory consistent with cytotoxic edema. **(b)** Diffusion weighted imaging and **(c)** apparent diffusion coefficient maps show corresponding areas of high signal and low signal respectively consistent with restriction of diffusion. **(d)** T2 and **(e)** fluid-attenuated inversion recovery maps show corresponding white matter signal abnormality. Findings are compatible with an acute left posterior cerebral artery territory infarction. (Images are provided courtesy of Thomas Jefferson University Hospital.)

blood in the media of the vessel wall. Conventional MR images may show loss of the expected flow void in the compromised vessel, or narrowing of the flow void with abnormal hyperintense signal in the vessel wall on T2WI or fat-suppressed T1WI.<sup>14</sup> Arterial dissections may be complicated by formation of a pseudo-aneurysm if the dissecting blood weakens the adventitial lining of the vessel wall. Thromboembolic complications can also occur if the intramural hematoma re-enters the true lumen, with

resultant local or distal vascular occlusion and infarction.

### 5.4.9 Intracranial Infection

Imaging for meningitis is usually performed to exclude any related process such as abscess. The main role of MRI is to exclude complications of meningitis, and contrast-enhanced MRI is the modality of choice. MR findings in meningitis include abnormal hyperintensity of the CSF spaces



**Fig. 5.12** Acute right pontine infarct. A 53-year-old female with a history of basilar thrombosis who presents with new right hemianopia and change in mental status. **(a)** CT scan shows an area of low attenuation involving right pons. **(b)** Fluid-attenuated inversion recovery image shows corresponding signal hyperintensity in the region in question. **(c)** Diffusion weighted imaging and **(d)** apparent diffusion coefficient maps show corresponding areas of high signal and low signal respectively consistent with restriction of diffusion. Findings are compatible with an acute right pontine infarction. Also note additional punctate areas of restricted diffusion in the left cerebellar hemisphere. (Images are provided courtesy of Thomas Jefferson University Hospital.)

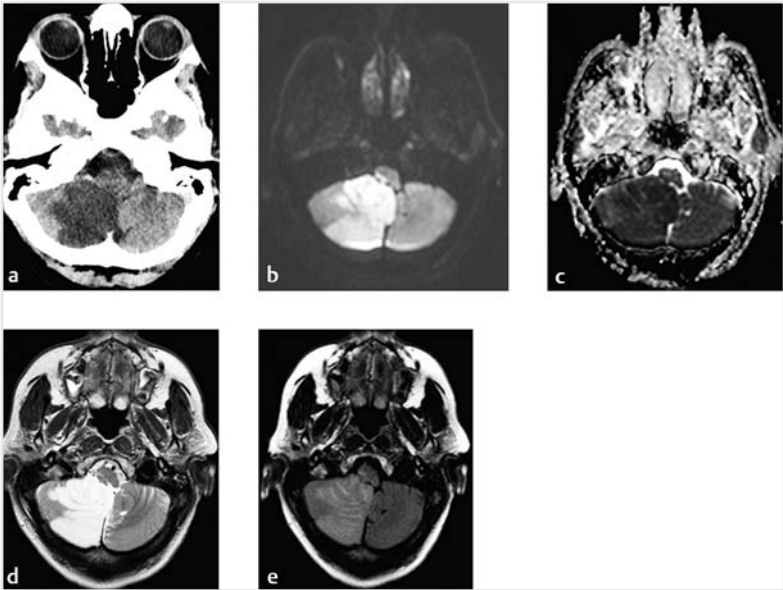
from exudate on FLAIR images, with abnormal leptomeningeal enhancement and/or enhancement of the basal cisterns.<sup>15</sup> However, the MRI may also be normal in many cases of viral meningitis, and all clinically suspected cases of meningitis should undergo lumbar puncture and CSF analysis to exclude infection. Complications of meningitis include hydrocephalus, empyema formation, and vasculopathy with cerebral infarction.

Requests to exclude cerebral abscesses are a common reason for imaging patients with suspected CNS infections. Mature cerebral abscesses are focal parenchymal collections of purulent material, surrounded by a well-vascularized wall.<sup>15</sup> These histologic characteristics are reflected on imaging,

with CT/MR showing a ring-enhancing collection in the parenchyma, with surrounding vasogenic edema. Restricted diffusion on DWI sequences may be seen within the central portion of the abscess reflecting purulent material, a finding that is helpful in distinguishing abscesses from tumors on MRI.<sup>16</sup>

### 5.4.10 Brain Tumor

The initial analysis of any brain tumor on imaging begins with an assessment of whether the mass is intra-axial (within the substance of the brain) or extra-axial (intra-cranial, but external to the substance of the brain). Intra-axial masses include primary brain tumors (of which glioblastoma



**Fig. 5.13** Right posterior inferior cerebellar artery distribution infarct. A 59-year-old female presents with dizziness and change in mental status. (a) CT scan shows an area of low attenuation involving both gray and white matter in the right cerebellar hemisphere within the region supplied by the right posterior inferior cerebellar artery. (b) Diffusion weighted imaging and (c) apparent diffusion coefficient maps show corresponding areas of high signal and low signal respectively consistent with restriction of diffusion. (d) T2 and (e) fluid-attenuated inversion recovery maps show corresponding white matter signal abnormality. Notice that there is right cerebellar edema, with mass effect on the right dorsal upper medulla. Findings are compatible with an acute right posterior inferior cerebellar artery territory infarction. (Images are provided courtesy of Thomas Jefferson University Hospital.)

multiforme [GBM] is the most common) and metastases. Extra-axial masses include tumors arising from the meninges (classically the meningioma), calvarium, synchondroses, and metastases. The distinction between intra-axial and extra-axial masses is not always clear-cut, but in general, extra-axial masses have a well-demarcated interface between the cortex/brain parenchyma and the mass, while intra-axial

masses tend to arise from and expand the brain parenchyma. There may also be a rim or “claw” of brain tissue reaching around the mass, which is another clue that the lesion is intra-axial in origin. In cases where an extra-axial mass subsequently invades the adjacent brain parenchyma, or an intra-axial mass secondarily involves the meninges, it can be difficult to determine the origin of the mass.



## Extra-axial Masses

Meningiomas are the classic extra-axial mass, and probably the most common extra-axial masses encountered on imaging in any neurosurgical practice. Meningiomas are usually dural based, with a broad contact surface with the dura. There may be an enhancing dural tail at the edge of the mass, which is commonly associated with (but not specific for) meningiomas. On non-contrast CT, meningiomas are hyperdense relative to the brain parenchyma and may also have calcification. There is usually hyperostosis (sclerosis and thickening) of the bone adjacent to the meningioma. On post-contrast CT and MR, meningiomas usually enhance homogeneously. Dural-based metastases can look similar, so it is always important to ask about a history of cancer when one encounters an enhancing extra-axial mass.

## Intra-axial Masses

GBM is the most common primarily malignant brain tumor in adults, and is the quintessential primary intra-axial mass. GBMs are usually centered in the supratentorial cerebral hemispheres and preferentially infiltrate the brain widely through white matter tracts, sometimes involving the contralateral hemisphere via the corpus callosum and anterior commissure. The enhancing component of a GBM is usually just the most obvious (usually necrotic) component of the tumor. Viable nonenhancing tumor is usually present in the surrounding T2/FLAIR signal abnormality in the region of the tumor. Other disease processes that tend to favor involvement of or spread along white matter tracts include lymphoma and demyelinating disease.

The other major consideration for an intra-axial tumor is metastasis, which is

the most common CNS malignancy in adults. Metastases are frequently multiple, bilateral, of varying sizes, and centered in the gray-white matter junction. However, solitary brain metastases are also common, can occasionally be difficult to distinguish from primary brain malignancy.<sup>17</sup>



One helpful finding is that metastases tend to incite extensive vasogenic edema in the surrounding brain parenchyma, best visualized on the FLAIR images.

Small cortical metastases may have little, if any, vasogenic edema, and may only be conspicuous as enhancing masses on the post-contrast images. In unclear cases, imaging the chest, abdomen, and pelvis to look for an occult primary can provide some guidance regarding the origin of a solitary brain tumor.

### Pearls



- Develop a systematic method evaluating each imaging modality to ensure no pathology is inadvertently missed.
- Evaluate all imaging personally and do not rely solely on radiologic interpretation of imaging.
- Utilize 3D reconstructions to better delineate fractures, extra-axial hematomas, and the location of intracranial pathology.
- Review all sequences when reviewing an MRI as each can distinctly highlight a variety of pathologies.
- Compare changes over time utilizing the same imaging modality. However, be aware that the gantry angle of a CT can change the appearance of a lesion.



## 5.5 Top Hits

### 5.5.1 Questions

- What imaging modality is first required for the evaluation of neurological injury in the acute trauma setting?
  - MRI
  - CT with contrast
  - CT without contrast
- Which is the most sensitive MR sequence for evaluation of acute cerebral infarction?
  - T1 sequence
  - DWI sequence
  - GRE sequence
- Why is MRI performed in the setting of meningitis?
  - To rule out meningitis
  - To evaluate for complications of meningitis
  - Because it is cheaper than CT scan
- Does a negative MRI rule out meningitis in a patient with high clinical suspicion.
  - Yes
  - No
  - Both

### 5.5.2 Answers

- c.** This can expediently evaluate for intracranial hemorrhage, contusions and skull fractures in the acute setting. The presence of contrast can confuse evaluation for hemorrhage as contrast is also hyperdense.
- b.** Acute infarctions show restricted diffusion on diffusion maps.
- b.** To evaluate for complications of meningitis such as abscess, empyema, thrombosis and infarction.

- b.** A negative MRI does not rule out meningitis. Lumbar puncture and CSF analysis should be performed.

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# 6 Operating Room

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## 6.1 Introduction

The operating room may be a confusing landscape for the trainee to navigate, especially early in one's training. While much focus is rightfully placed on the techniques and steps to a given operation there are a multitude of additional workings, preparations, and members which are key to any successful procedure. Familiarizing oneself with ancillary staff and appropriate positioning, in addition to technical maneuvers, will both streamline and improve the likelihood of a positive outcome for the operation.

## 6.2 Operating Room

### 6.2.1 Etiquette

Understanding the roles of operating room staff members and the expectations of the trainee are essential to a promising operative learning experience. Ultimately, the role of the student is at the discretion of the surgical staff. Politely asking the attending or resident surgeon to "scrub in" is a start. Regardless of being able to assist with the procedure or not, students are expected to assist with preoperative and postoperative care. Assisting with insertion of Foley's catheters and lines, patient positioning, Mayfield placement, and additional adjunctive measures are helpful. Transferring the patient to a bed and assisting with transport postoperatively are also helpful. Asking thoughtful questions is invited but should not be done during critical portions of the case. If permitted to assist with the procedure, the trainee's role is highly dependent on the wishes of the lead surgeon and residents.



Being prepared as a trainee is essential, including reading regarding the case at hand, knowing the basic anatomy, instruments, and basic suturing and knot tying.

## 6.3 Cranial Positioning

### 6.3.1 Pterional

The pterion is the region where the frontal, parietal, temporal, and sphenoid bones meet. Patients are placed supine in Mayfield three-point fixation. If the head is rotated more than 30°, an ipsilateral shoulder roll is placed to reduce muscular tension and venous outflow obstruction. The thorax is elevated 10–15° to reduce venous distension and the neck is extended 10–15° to aid in retracting frontal lobe so skull base is more accessible; a good landmark is the maxillary eminence which will be the highest point of the field. The pterional craniotomy is tremendously versatile and the degree of head rotation is useful in projecting the approach towards different segments of the anterior and middle fossae (► Table 6.1).<sup>1,2</sup>

### 6.3.2 Frontal

Patients are placed supine in Mayfield three-point fixation with the head rotated 20–30° towards the contralateral shoulder depending on the side of the operation. A shoulder roll may be placed beneath the ipsilateral shoulder. Similarly to the pterional craniotomy, the thorax may be elevated.<sup>3</sup>

**Table 6.1** Pterional craniotomy positioning

| Head rotation | Exposure  | Example                                   |
|---------------|-----------|-------------------------------------------|
| 30            | Posterior | Posterior communicating/basilar aneurysms |
| 45            | Middle    | Middle cerebral artery aneurysms          |
| 60            | Anterior  | Anterior communicating aneurysms          |

### 6.3.3 Temporal

Patients are placed supine in Mayfield three-point fixation with the thorax elevated 10–15°. Importantly, the head is rotated nearly a full 90° towards the contralateral shoulder such that it is horizontal; an ipsilateral shoulder roll is essential to achieve this degree of rotation without injury, postoperative muscular rigidity, and blockage of venous outflow through the jugular system which prevents brain relaxation (► Fig. 6.1).<sup>1,4</sup> Due to the significant degree of head rotation required, many surgeons prefer to actually position these patients in the lateral decubitus position.

#### 6.3.4 Occipital

Multiple positions are used for the occipital craniotomy, all in Mayfield three-point fixation. Positions include three-quarter prone, semi-sitting position, or lateral oblique.<sup>1,3</sup> Variants will allow positioning for retromastoid, suboccipital, far lateral, and infratentorial supracerebellar approaches.

#### 6.3.5 Transsphenoidal

Patients are placed supine in either Mayfield three-point fixation or with their head placed on a gel donut or horseshoe. As in most craniotomies the head is extended approximately 15°. The head may be kept midline or angled 15–20° towards the neurosurgeon. Especially in endoscopic procedures where ENT surgeons are often present, proper positioning of surgeons around the patient is vital for ease of instrumentation and visualization on adjacent screens.<sup>5</sup> The surgeon may opt to

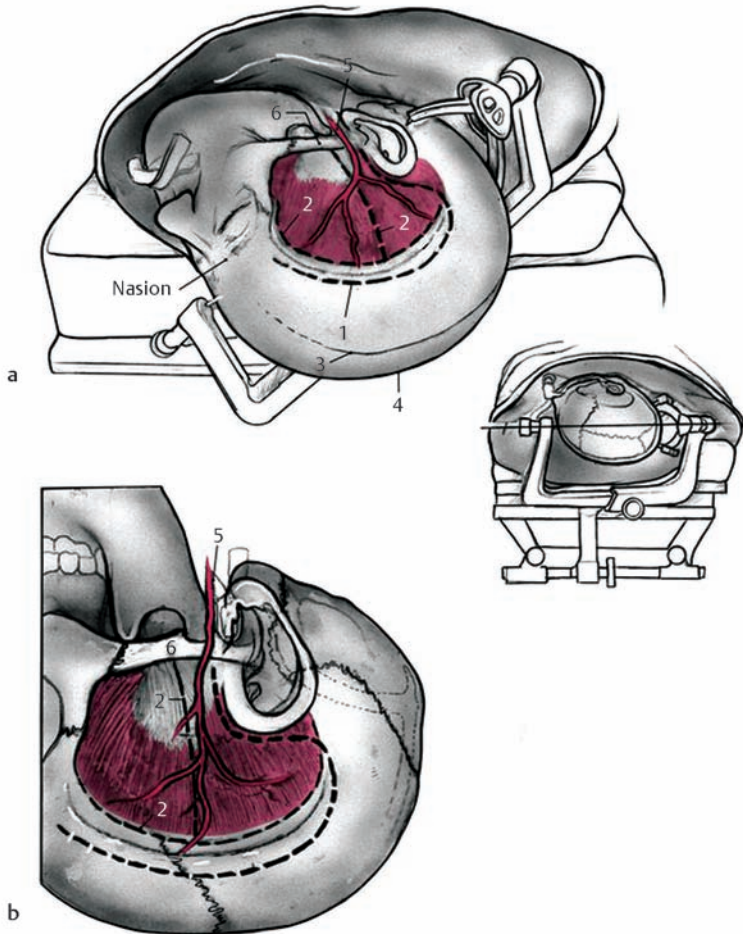
prep a portion of the abdomen for harvesting of a fat graft used in closure of the defect. Adjunctive measures utilized include an orogastric tube and packing the nose with pledgets soaked in oxymetazoline prior to surgery to prevent drainage of blood into the esophagus and bleeding, respectively.<sup>6</sup>

## 6.4 Spinal Positioning

### 6.4.1 Anterior Cervical

Anterior cervical approaches are commonly used for anterior cervical discectomy and fusion (ACDF) and odontoid fractures but also in cases of carotid endarterectomy. Patients are positioned supine, in slight extension, with the head supported on a soft gel pad or horseshoe. Interscapular rolls to maximize extension are used based on surgeon's preference. Depending on the pathology, head rotation may be helpful in reaching high cervical lesions. The approach is usually off of midline and many prefer approaching from the left due to relatively increased protection of the left recurrent laryngeal nerve by the esophagus and trachea compared to the right nerve.<sup>7</sup> Incision is often made through a pre-existing skin crease to enhance postoperative cosmesis.

Typically the hyoid bone approximates the C3–C4 vertebrae, thyroid cartilage approximates C4–C5, cricothyroid membrane approximates C5–C6, and C6–C7 is often two fingerbreadths above the clavicle.<sup>3</sup>



**Fig. 6.1** Temporal craniotomy positioning. Right temporal craniotomy approach positioning. **(a)** Location of the temporalis and superficial temporal artery. The degree of head rotation is near 90° and an ipsilateral shoulder roll is placed to achieve additional rotation. **(b)** The incision and location of temporalis muscle detachment is noted with a dotted lines. A cuff of muscle is often left for reattachment of the temporalis muscle to prevent temporal wasting. Relationship of the superficial temporal artery and muscle to the coronal suture, zygoma, and tragus can be seen. 1. Skin incision; 2. temporalis muscle incision; 3. midline; 4. vertex; 5. superficial temporal artery; 6. zygoma. (Reproduced from Nader R, Gragnaniello C, Berta S et al, *Neurosurgery Tricks of the Trade: Cranial*, 1st edition, ©2013, Thieme Publishers, New York.)

## 6.4.2 Posterior Cervical

Posterior cervical approaches are well-suited for a number of pathologies including radiculopathies, cervical spine fractures, cervical spondylosis, and high cervical pathologies which are difficult to reach anteriorly. Patients are placed prone typically on a Jackson-frame table, in slight flexion, and in either Mayfield fixation or on a gel donut/horseshoe with adequate padding to avoid postoperative visual loss.<sup>3</sup> Arms are either abducted to a maximum of 90° to prevent axillary nerve stretch injury and flexed at the elbow or slung at the patient's side in a "ski-jump" position. Appropriate padding of weight-bearing areas, including the chest are necessary to prevent bruising. The sitting position for posterior cervical procedures has many appealing advantages including more easily verified spinal alignment, reduced radiographic shoulder artifact, and a drier operative field. The major theoretical complication is air embolism in this position however data suggests the occurrence of this event relative to the multitude of benefits is rare.<sup>8</sup>

## 6.4.3 Posterior Thoracolumbar

Positioning and preparation of cases, especially for spine, begins early with acquisition of preop imaging. Obtaining flexion-extension films may allow detection of dynamic instability which impacts surgical and positioning decision making. The prone position on either a Jackson table, Wilson frame, or Andrews frame is the typical setup for posterior thoracolumbar cases. Care is taken to pad the appropriate pressure points to avoid injury. Depending on the procedure, a variety of adjuncts are available to the surgeon. In cases where manipulation of the spinal cord and nerve roots is expected, surgeons may opt to use somatosensory evoked

potentials (SSEPs), motor evoked potentials (MEPs), and/or electromyography.<sup>6</sup> Many cases will use a C-arm or O-arm for intraoperative imaging. C-arm provides intraoperative two-dimensional fluoroscopy whereas the O-arm has three-dimensional capabilities. The O-arm allows quicker placement of pedicle screws, less radiation to the surgeon staff, but more exposure to the patient when compared with standard fluoroscopy.<sup>9</sup>

## 6.5 Positioning-Related Complications

### 6.5.1 Peripheral Nerve Injuries

Perioperative peripheral nerve injuries (PPNI) are most often caused by ischemia, stretch, or compression. The ulnar nerve is the most commonly injured and may cause weakness of opposition and abduction in the 5th digit with reduced sensation of the 4th and 5th digits. Brachial plexus injury is the second most common PPNI and is often due to prolonged and extensive stretch. The superman prone position places multiple components of the brachial plexus at risk of stretch-related injury; tucking of arms at the side may reduce risk. Use of appropriate padding beneath elbows and care to avoid excessive neck extension, shoulder abduction, and nonphysiologic positions help reduce risk of these injuries.<sup>10,11,12</sup>

### 6.5.2 Visual Loss

Postoperative visual loss is a serious complication often occurring in prolonged prone cases such as spine surgery. Injury is primarily attributed to ischemic optic neuropathy and/or central retinal artery occlusion. Excessive blood loss, hypotension, and prolonged operative time are risk

factors for postoperative visual loss. Appropriate padding and maintaining mean arterial pressure and hemoglobin levels close to preoperative values is especially useful in high-risk patients.<sup>10</sup>

## Air Embolism

Air embolism is a complication encountered when air enters the venous system due to an opening in non-compressible veins. The reported incidence varies but is much higher in surgical positions where the head is elevated relative to the right atrium (e.g., sitting position). For instance, recent estimates of air embolism in the semi-sitting position are 21%; however, there were few direct effects on postoperative morbidity in that study.<sup>13</sup> Entry of air with the head elevated blocks venous return at the right atrium and leads to hypotension. The earliest indicator may be a drop-in end-tidal  $p\text{CO}_2$ . Treatment upon identification includes occluding further air entry at site, lowering level of the head below the right atrium, compressing jugular veins to prevent further air entry, 100% oxygen ventilation, and aspirating air from the right atrium if a central venous pressure (CVP) catheter was employed. If sitting position must be used, there are useful adjuncts to reduce risk of air embolism including elevating legs to level of right atrium which reduces the pressure gradient by which air embolism may occur.<sup>1,14</sup>

## 6.6 Cerebral Relaxation

- Head rotation, flexion, and extension for gravity-based lobe retraction.
- Maintain venous outflow. For example, avoid tight overly tight cervical collars or over-rotating head.
- Administration of hyperosmolar agents including mannitol.
- Knowledge of cisternal anatomy and selective cerebrospinal fluid (CSF) drainage.

- Preoperative placement of external ventricular or lumbar drain, especially in endoscopic endonasal approaches.<sup>5</sup>
- Intraoperative burst suppression.

## 6.7 Bedside Procedures

### 6.7.1 Lumbar Puncture/ Drain

**Equipment:** Lumbar puncture kit (spinal needle with plug, collection tubes, iodine preparation sponges, sterile draping, lidocaine with epinephrine, opening pressure barometer and connecting valve, sterile normal saline, syringe), marking pen, sterile gloves.

1. Properly set-up the work area and position patient in the lateral decubitus position with hip and knee flexion. Ensure that patient's shoulders are squared.
2. Mark appropriate entry zone. Anterior superior iliac crests mark L4–L5 disc space. One space above or below will avoid risking spinal cord injury. Note, it will be easier to palpate midline at the thoracic spine due to its kyphotic curvature and then extrapolate midline into the lumbar spine assuming no scoliotic spine.
3. After marking, set up your sterile lumbar access kit and don sterile gloves.
4. Widely prepare the region with betadine and place sterile drapes over top.
5. Inject lidocaine with epinephrine subcutaneously and deeper along the track of the spinal needle.
6. Repalpate and aim the needle to enter with the spinal needle at a slightly rostral angle in between two spinous processes.
7. Upon entry of spinal needle, you will often feel bone which may be the spinous process or lamina and will require repositioning the needle towards

the inter-laminar space. Do not swing the needle but rather draw back slightly, re-angle, and move forward. A “pop” may be felt upon entry through dura.

8. Remove the spinal needle stylet and observe for CSF egress. When egress is confirmed, take care to reduce the amount of additional CSF that is lost.
9. When entry into thecal sac is confirmed, take care to avoid moving the spinal needle and attach the barometer for an opening pressure reading. An opening pressure is most accurate when patients straighten their legs from their flexion position. The flexion position provides a slight overestimate of opening pressure. \*
10. After removing the barometer, fill collection tubes with CSF (often 4–6 cc of CSF per tube). Excessive drainage should be avoided with posterior fossa crowding or with suspected ruptured aneurysms.
11. When CSF is completely collected, the barometer may be connected for a closing pressure.
12. Remove the barometer, replace spinal needle plug, and carefully remove the needle apparatus.
13. Place a bandage or dressing over the site and clean the area of betadine which is a skin irritant.

\*The below steps diverge from the above if a lumbar drain is being placed.

10. The lumbar drain spinal needle is placed into the interspinous space similarly to a lumbar puncture. The bevel should be facing up on insertion and should be rotated to face rostral prior to threading of the catheter.
11. The lumbar drain catheter will be rapidly fed into the spinal needle so that 3–4 black dots are visualized on the outer segment.

**Caution:** Avoid excessive loss of spinal fluid which may cause collapse of the thecal sac, thus making threading the catheter more difficult.

12. After ensuring continued CSF flow, carefully remove the spinal needle. Grasp the catheter to prevent its mobilization further inside or outside the canal.

**Caution:** Avoid rotating the spinal needle which may sever the proximal catheter in the canal.

13. Pledget jackets can be used to secure the catheter in place.
14. Coil the excess catheter tubing in a strain relief loop and secure at the midline on the back using staples and/or suture. Take care to avoid puncturing the catheter.
15. Lead the catheter over to the side of the patient's lower back and secure the drain system in place with multiple Tegaderm bandages.
16. Set up the lumbar drain system to the external collection system.

### 6.7.2 External Ventricular Drain

**Equipment:** External ventricular drain (EVD) catheter and cranial access kit, lidocaine with epinephrine, sterile attire, nylon suture, sterile instruments (clamp, forceps, scissor), skin stapler, sterile normal saline, razor/scissors for hair removal.

Follow institution-specific protocols; some will require a single dose of antibiotics such as cefazolin (Ancef) prior to



placement. EVDs will most often be placed on the right side unless the clinical situation suggests otherwise.

1. Clear the appropriate work area and position the patient to ensure your comfort and access to instruments.
2. Shave and clean the site.
3. Make preliminary markings based on measures and anatomical landmarks.
  - Measure 11 cm posterior to the nasion (nasion: divot between nose and glabella).
    - If the anatomy is unusual (e.g., growth hormone-secreting adenoma) then a rough approximation may be 1 cm anterior to the coronal suture, if palpable.
  - Measure 3 cm to right of midline which is approximately at the mid-pupillary line (drawing a sagittal line and examining from a distance can ensure appropriate placement).
4. Place trajectory marks. Upon insertion, EVD will be angled at ipsilateral medial canthus and 1 cm anterior to ipsilateral tragus.
5. Inject lidocaine with epinephrine to your site.

**Caution:** Excessive injection and swelling of tissue may slightly distort landmarks.

6. While lidocaine takes effect, open your sterile equipment, place at a nearby location, and ensure a trash receptacle is nearby. Make sure all appropriate components of the kit are in place. Open sterile items and drop them onto your field.
7. Don sterile attire.
8. Place the red cap on the plastic nipple to be able to cap the EVD after placement.
9. Assemble the drill and ensure the stopper's placement at about 1.0–1.5 cm

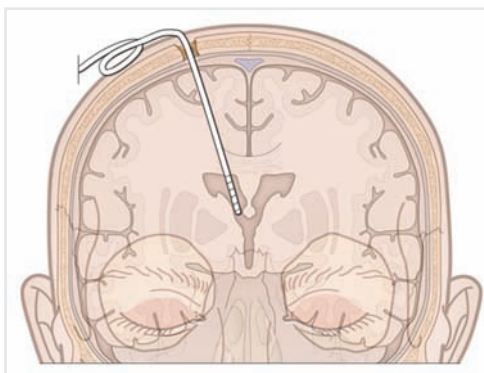
from the drill tip and tighten the drill-bit into the chuck.

**Caution:** Neglecting to use the drill stopper increases risk of plunging through dura and cerebral tissue.

10. Measure out 6.5–7.0 cm on the catheter either with a sterile marker or a 2–0 silk tie. This will be the mark for how deep the catheter should be passed. If 7.0 cm is used, the tied mark is often left at the outer table of cranium, 6.5 cm at the inner table of cranium (► Fig. 6.2).

**Caution:** Passing a catheter further than 7.0 cm drastically increases risk of damaging sensitive structures including mid-brain and prominent vasculature.

11. Carefully bend the tunneling trocar. Do not bend to an acute angle which can make tunneling more difficult.
12. Carefully clean the procedural site and place sterile drapes.
13. Remeasure your site. Make an approximately 2 cm incision to the bone at your marked site. Use the blunt scalpel end to strip pericranium from the site. Place a retractor.
14. Quickly achieve a satisfactory degree of hemostasis and remeasure your appropriate burr hole site. Mark the bone if desired.
15. Drill burr hole with careful attention to outer cortical, cancellous, and inner cortical bone. Upon reaching the inner cortical table of bone, we recommend placing one's hand at the tip of the drill and manually rotating rather than continuing to use the axle handle. An



**Fig. 6.2** External ventricular drain placement. Placement of a right external ventricular drain into the lateral ventricle towards the foramen of Monro. The catheter is inserted approximately 6.5 cm deep from the surface. (Reproduced from Ullman J, Raksin P, Atlas of Emergency Neurosurgery, 1st edition, ©2015, Thieme Publishers, New York.)<sup>15</sup>

errant burr hole will deflect your catheter in inappropriate directions.

16. Clean and remove bone fragments after the burr hole is made.
17. Use the trocar to create a durotomy.
18. Pass the catheter through the incision, aiming for the ipsilateral medial canthus and 1 cm anterior to the ipsilateral tragus with care to avoid placing the catheter deeper than 6.5 cm from the inner table of the cranium. Remove the stylet to check for flow. When flow is established, always ensure control of your catheter and its depth. A rough estimate of intracranial pressure (ICP) may be gauged by dropping and raising catheter above the external acoustic meatus. Take care to minimize the early loss of CSF.
20. Cap the catheter with the nipple and attached red cap.
21. Suture the catheter at the tunneled location to prevent inadvertent slipping.
22. Suture the incision site with running 3-0 nylon taking care to avoid puncturing the underlying catheter.
23. Coil the catheter externally in to a strain relief loop from the posterior exit. Secure the coiled catheter with suture and staples.
24. Remove the red cap and connect the EVD to the external drainage collection system. Using a 2-0 silk tie secure the catheter to the distal drainage tubing.

**Caution:** In aneurysmal subarachnoid hemorrhage patients, draining off large volumes of CSF may increase risk of rebleeding.

19. Attach trocar to catheter end and tunnel posteriorly and medially. While tunneling, it is helpful to grasp the catheter at its cranial entry site with the nontoothed portion of your forceps.

## 6.8 Cranial Approaches

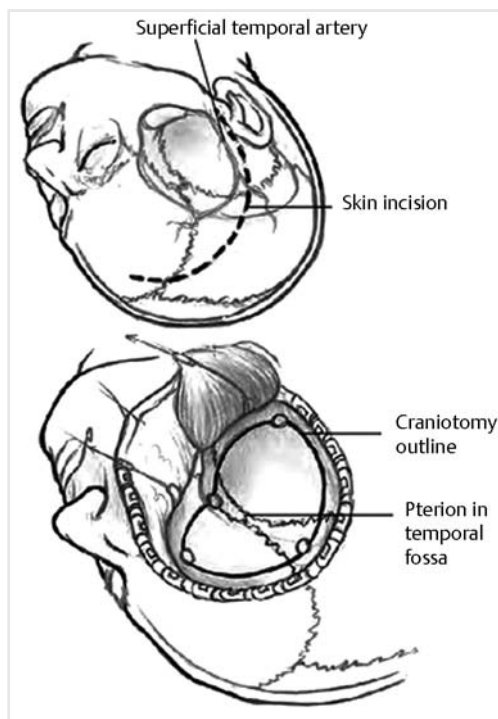
### 6.8.1 Pterional

The pterional (frontosphenotemporal) craniotomy is a versatile approach providing corridors to anterior and posterior circulation aneurysms, lobar pathologies, and sellar/suprasellar lesions. The incision is made anterior to the tragus and above the

zygomatic arch in a curvilinear fashion staying behind the hairline. Critical structures to avoid damaging are the frontal branches of the facial nerve, superficial temporal artery (STA), and supraorbital nerve. Below are techniques employed for avoiding each structure:

1. Frontal branches of facial nerve often branch below the zygomatic arch. Starting the incision slightly above the arch avoids injury. Anterior elevation of the fat pad overlying the deep portion of the temporal fascia avoids injury as well since the nerve runs through this fat pad.
2. STA injury is often prevented by keeping incision within 1 cm anterior to tragus of ear.
3. Upon anterior retraction of skin flap and temporalis, the supraorbital nerve should be identified emanating from the supraorbital notch before vigorous stripping of pericranium ensues.

Classically, two burr holes are used for the pterional approach but anywhere between one and four may be employed. One burr is placed at the intersection of the zygoma, superior temporal line, and supraorbital ridge. The second is placed at the posterior portion of the zygomatic arch in the squamosal temporal bone. On some occasions, a third burr is placed at the posterior portion of the superior temporal bone (► Fig. 6.3).<sup>16</sup> After connecting the burrs with a foot-plated tool and



**Fig. 6.3** Burr hole placement and craniotomy. Location of burr holes placed in pterional craniotomy. Number of burr holes may range from two to four depending on the surgeon's preference. (Reproduced from Connolly E, McKhann II G, Huang J et al, *Fundamentals of Operative Techniques in Neurosurgery*, 2nd edition, ©2010, Thieme Publishers, New York.)

rongeuring off additional bone, the dura is incised and, depending on what the pathology requires, the Sylvian fissure is sharply dissected.<sup>1,3,17</sup>

## 6.8.2 Orbitozygomatic

The orbitozygomatic craniotomy is actually a modification of a frontotemporal approach and is indicated for structures of lateral anterior cranial fossa or orbit and aneurysms of anterior communicating artery and basilar apex.<sup>16</sup> Removal of portions of the orbit and zygomatic arch allows for more inferior retraction of temporalis muscle and gains increased exposure to anterior and inferior structures.<sup>6</sup> The first phase is akin to a pterional craniotomy; the skin incision begins at the level of the zygomatic arch, approximately 1 cm anterior to the tragus, and is carried posteriorly before curving anteriorly towards the widow's peak of the hairline. Careful retraction of the skin flap and underlying fat pad ensures protection of the facial nerve branches coursing anteriorly; the retracted flap may be dissected off the temporalis muscle in a supra- or subfascial manner. Periorbital dissection of temporalis off the lateral orbit and root of zygoma may be necessary to ensure an inferior exposure for the McCarthy burr hole. This burr hole is placed approximately 7 mm superior and 5 mm posterior to the frontozygomatic suture and should ideally visualize the floor of anterior cranial fossa and periorbital.<sup>18</sup> Using a foot-plate, the craniotomy can then be fashioned around this burr hole prior to the orbital osteotomy. Further dissection at the osteotomy site may be needed to identify the supraorbital nerve. Next, the periorbital from the superior-lateral surface of the orbital rim is gently dissected and carried inferiorly until the inferior orbital fissure is felt. A series of orbital cuts are made to remove the superior

orbit and maxillary buttress points of attachment; additional craniectomy of additional bone with rongeurs is done to widen the viewing angle (► Fig. 6.4).<sup>6,16</sup>

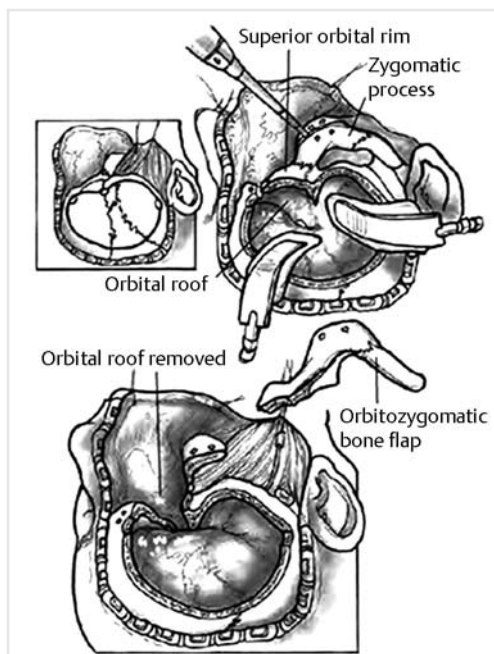
## 6.8.3 Temporal

The temporal craniotomy also serves as a versatile corridor for pathologies including temporal lobectomy, hematoma evacuation, lobar tumors, and access to middle cranial fossa floor. In cases requiring minimal exposure (i.e., chronic subdural hematoma, biopsy) a linear skin incision and burr hole suffice. However, a larger exposure is needed in most cases.

The skin incision is carried out as a "question-mark" shaped incision. The incision starts above the zygomatic arch and approximately 1 cm anterior to the tragus and courses superiorly to avoid injuring frontalis branches of the facial nerve and the STA. At the level of the pinna, the incision curves posteriorly and then superiorly to the level of the superior temporal line from which point it continues in an anterior direction towards the hair line.<sup>1,6</sup> The size of the incision can be varied depending on the extent of exposure desired and the depth of the pathology (► Fig. 6.5).<sup>4</sup>

Number of burr holes used is at the discretion of the surgeon, often three to four. Burr hole placement is often done at posterior point of zygomatic arch, anterior junction of zygoma in proximity to the frontozygomatic suture, and then along the posterior aspect of the skin incision.<sup>1</sup> Preparation of the flap and burr hole is demonstrated in ► Fig. 6.6.<sup>4</sup> In cases aimed at attacking petrous apex and internal auditory canal lesions, a middle fossa approach is often employed via a similar incision; however, a small temporal craniotomy is made with two-third anterior to external acoustic canal and one-third posterior to this landmark.<sup>3</sup>

When operating in the dominant hemisphere, one must caution the



**Fig. 6.4** Orbitozygomatic craniotomy. Burr hole placement and series of bone cuts made for orbitozygomatic craniotomy, including orbitectomy. (Reproduced from Connolly E, McKhann II G, Huang J et al, *Fundamentals of Operative Techniques in Neurosurgery*, 2nd edition, ©2010, Thieme Publishers, New York.)

superior temporal gyrus. The language centers in the dominant hemisphere are farthest anterior at the superior temporal gyrus. Safe margins are roughly estimated as up to 2.5 cm posterior on superior temporal gyrus and 4.5 cm posterior on the middle and inferior temporal gyri.<sup>16</sup> In many cases, the incision is taken a shorter distance posteriorly to the pinna when at the dominant hemisphere.<sup>6</sup>

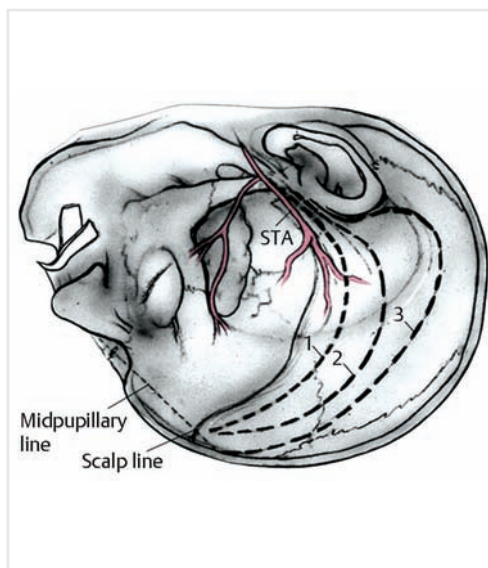
### 6.8.4 Occipital

The occipital craniotomy serves as a corridor not only to the occipital lobes but key structures of the posterior fossa including the tentorium and sinuses. Care must be taken to avoid damaging the sagittal, transverse, or sigmoid sinuses. By carefully marking midline and palpating the inion,

one may plan the incision/approach to minimize such damage. The incision begins midline at the area of the inion, continues superiorly, and then curves inferiorly towards the area of the squamosal suture posterior to the ear; some allow the incision to extend across midline to allow space for a burr hole which will not damage the superior sagittal sinus while widening the exposure.<sup>3</sup> Typically four to five burrs are placed with one approximately 1–2 cm lateral to midline and another 2 cm below the external occipital protuberance.<sup>6</sup>

### 6.8.5 Endonasal Transsphenoidal

The endonasal transsphenoidal approach is a method of increasing utility as a technique for a variety of lesions involving the



**Fig. 6.5** Craniotomy Incision Planning. Frontotemporal craniotomy incisions can be made of various sizes depending on pathology. Incision 1. Notes a typical pterional craniotomy incision, 2. Demonstrates a larger frontotemporal exposure, 3. Is for larger orbitobasal and middle fossa exposures. In cases of decompressive hemicraniectomies, the incision is extended farther posteriorly than incision 3. (Reproduced from Nader R, Gragnaniello C, Berta S et al, *Neurosurgery Tricks of the Trade: Cranial*, 1st edition, ©2013, Thieme Publishers, New York.)

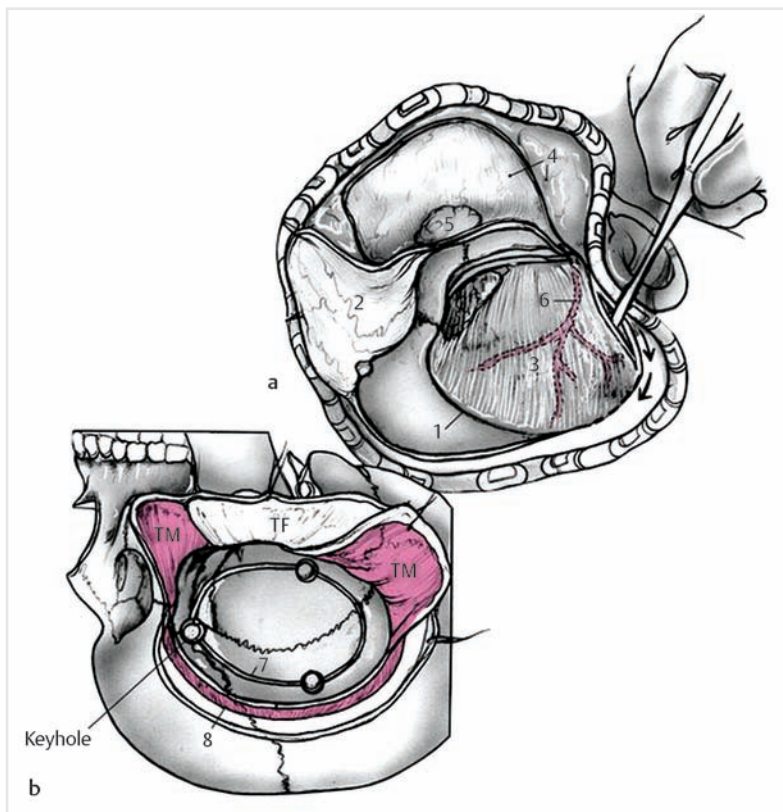
sella, suprasellar space, sphenoid, and even posterior structures including the clivus as far back as the upper cervical vertebrae. Classically, transsphenoidal access was accomplished via anterior mucosal or sublabial incisions; however, the direct endonasal corridor has gained favorability. Common lesions well-served by this approach include pituitary adenomas, Rathke pouch cysts, craniopharyngiomas, and clival chordomas.<sup>1,6</sup> In cases involving anterior, posterior, or lateral extension, transcranial or expanded endonasal approaches may be considered. Importantly, the expanded endonasal approach is part of the armamentarium of a few and should only be considered by surgeons with considerable expertise and exposure to such an approach.<sup>5</sup>

The microscope and endoscope are two tools which offer different benefits to the surgeon in gaining access via the nasal corridor. The microscope offers magnification and additional three-dimensional viewing

whereas the endoscope widens the surgeon's field of view.<sup>5</sup> Overall, the approach allows minimal brain trauma due to a lack of brain retraction and no visible scars (besides what may be harvested for a nasal mucosa fat graft).

After appropriate preparation with oxymetazoline pledgets and sterilization with betadine solution, the procedure begins. A speculum is used to visualize the turbinates and nasal septum. Upon identification, an incision is made through the posterior portion of the nasal septum and the septum if fractured and deviated. A diamond-tipped drill is used to remove bone of sphenoid ostia, portions of dorsum sella, and sella turcica before encountering dura. Also used are Kerrison rongeurs, and occasionally, the ultrasonic aspirator. The dura is incised in a cruciate fashion and the pituitary gland is encountered.

Care must be taken during the entire procedure to maintain proper orientation

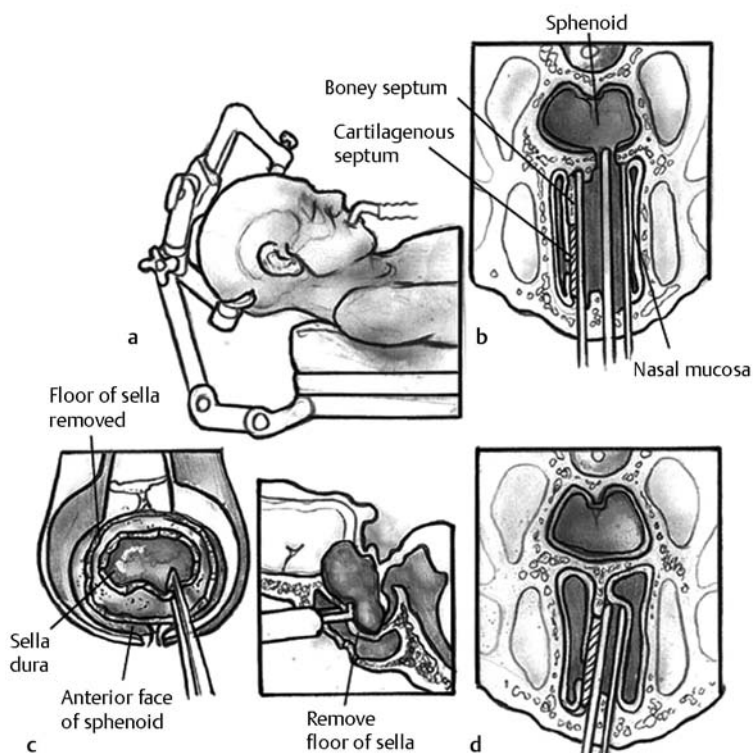


**Fig. 6.6** Craniotomy fascial exposure. Elevation of the temporalis muscle with a periosteal is seen in (a). (b) Temporalis muscle and relation to temporalis fascia is seen. 1. Superficial temporal line, 2. Vascularized pericranial flap, 3. Temporal fascia, 4. Skin, galea, and connective tissue, 5. Superficial temporal fat pad upper half, 6. Superficial temporal artery, 7. Craniotomy outline, 8. Muscle cuff remnant. (Reproduced from Nader R, Gragnaniello C, Berta S et al, *Neurosurgery Tricks of the Trade: Cranial*, 1st edition, ©2013, Thieme Publishers, New York.)

(► Fig. 6.7).<sup>16</sup> Identifying the opticocarotid recess provides a lateral landmark by which you need to exhibit extreme caution. Carotid injury mandates judicious packing with pro-coagulant adjuncts, cotton pads, and gentle pressure.<sup>6</sup> Distinguishing normal gland from

tumor is also essential for a successful outcome. The normal pituitary gland strongly enhances on contrasted studies and should be delineated from tumor. If the infundibulum is deviated towards a side, the pituitary gland will often be mobilized with it.<sup>16</sup>





**Fig. 6.7** Endonasal transsphenoidal approach. (a) Positioning of the patient with head slightly flexed. (b) Axial view of structures traversed in reaching the sphenoid sinus. (c) Endoscopic view of sphenoid and sella dura. Sagittal view noting entry into sella with outlined floor; note the clivus posteriorly. (d) Axial view again demonstrating structures traversed, including into ethmoidal sinus. (Reproduced from Connolly E, McKhann II G, Huang J et al, *Fundamentals of Operative Techniques in Neurosurgery*, 2nd edition, ©2010, Thieme Publishers, New York.)

### 6.8.6 Decompressive Hemisraniectomy

Decompressive hemicraniectomy (DHC) is a last resort procedure for control of refractory ICPs. DHC may be done emergently in traumatic cases, urgently for prevention of

secondary damages caused by malignant edema post-ischemic stroke, or even prophylactically after evacuation of hematomas where postoperative elevated ICPs are expected. The craniotomy is similar to that from frontotemporal approaches but is larger.



Patients are positioned supine with an ipsilateral shoulder roll and contralateral head rotation; care must be taken to prevent kinking or compression of jugular veins which will prevent venous drainage and further increase ICP. Especially in traumatic cases, manipulation of the head for positioning should be done with cervical spine precautions. Use of pins depends on surgeon preference and whether concomitant skull fractures are present.

A generous question mark skin incision is taken from the zygomatic arch far posteriorly and curving forward a few centimeters lateral to the superior sagittal sinus (which is often slightly eccentric to the right rather than at a true midline) and coursing towards the hairline (► Fig. 6.8).<sup>16</sup> The dissection is taken through the subcutaneous tissue and temporalis with anterior retraction and Raney clips for hemostasis on the scalp edges. A large craniotomy is taken with three burr holes and followed by a temporal craniectomy using rongeurs to decompress the middle fossa floor.

Various techniques are used for dural opening; in many cases, a stellate opening is used for maximum decompression. Dural substitutes are often placed over the opening with the dural flaps placed over. This is followed by watertight galeal and then skin closure due to relative exposure of the underlying brain.<sup>6</sup>

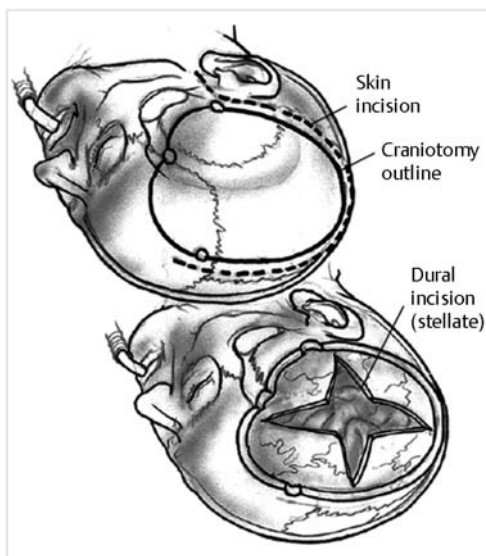
### 6.8.7 Craniotomy for Aneurysm

Many aneurysms are approached using a pterional craniotomy. The degree of head rotation provides a corridor to aneurysms, with larger degrees of rotation used for anterior communicating aneurysms and lesser rotation for posterior communicating aneurysms. For any aneurysms, angiography utilizing the digital subtraction technique is useful for preoperative understanding of aneurysm morphology and

position. Narrow-necked aneurysms are amenable to endovascular treatment; yet, clipping remains an option for more difficult aneurysms. Lumbar drains or EVDs are useful adjuncts for intraoperative fluid diversion control in these cases.

A pterional craniotomy is carried out as described in previous sections and a C-shaped dural incision is made. For middle cerebral artery (MCA) aneurysms, the Sylvian fissure is split and depending on the location splitting either occurs distal to proximal (lateral transsylvian) or proximal to distal (medial transsylvian). The lateral transsylvian approach is most preferred for MCA aneurysms; however, since exposure occurs distal to proximal, the aneurysm will first be realized before gaining proximal control and awareness of the internal carotid and early branches. A distal MCA branch is often identified and followed down to its more proximal branches. In the medial transsylvian approach, early identification of the internal carotid and optic nerve allows sharp dissection of arachnoid membranes in optic and carotid cisterns allowing relaxation of overlying brain. A superior temporal gyrus approach is usually reserved for cases of a ruptured MCA aneurysm with associated temporal hematomas requiring evacuation for brain relaxation before clipping may occur.<sup>6</sup> In any case, clipping requires complete visualization of the aneurysm neck and adjacent structures to ensure no extra-aneurysmal vessels are clipped causing ischemia. Prior to permanent clipping, temporary clips are often placed on feeding vessels for proximal control while manipulating and examining an aneurysm and its neck. Temporary clips are removed after permanent clipping is complete.<sup>6</sup> Use of intraoperative indocyanine green angiography is a common technique to confirm aneurysm closure and patency of adjacent vessels.<sup>19</sup>

Increased head rotation when positioning allows a corridor to anterior communicating aneurysm. Due to the midline nature



**Fig. 6.8** Dural incision in decompressive hemicraniectomy. Stellate dural incision is one method of opening this outer membrane during decompressive hemicraniectomy. (Reproduced from Connolly E, McKhann II G, Huang J et al, *Fundamentals of Operative Techniques in Neurosurgery*, 2nd edition, ©2010, Thieme Publishers, New York.)

of these lesions, it is preferred to approach from the patient's nondominant hemisphere. On the other hand, posterior communicating aneurysms are best approached with decreased head rotation. After eventually splitting the Sylvian fissure, the internal carotid is tracked deeper, towards the optic chiasm, to visualize the origin of the posterior communicating artery.

## 6.9 Spinal Approaches

### 6.9.1 Level Localization

Integral to any spinal procedure is confirming the appropriate level. Localization is confirmed in a variety of ways across institutions and surgeons. Fluoroscopy is the primary method and may be used before or after the incision is made. A number of landmarks are used, including visualization of the sacrum, counting ribs, and using the unique C2 vertebra. Care must be taken for anatomical variations. Lumbarization of the

S1 vertebra may give the appearance of six lumbar vertebral levels whereas sacralization of L5 may give the appearance of four. The latter is more common but overall rates of lumbosacral abnormalities range from 2.3 to 14.6%.<sup>20,21</sup>

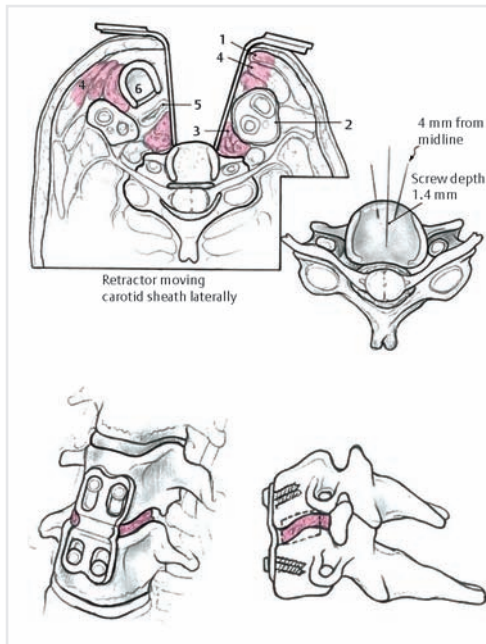
### 6.9.2 Anterior Cervical Discectomy and Fusion

ACDF is a commonly performed procedure for cervical radiculopathy secondary to disc compression. As mentioned previously, patients are placed supine and a transverse incision is made in a pre-existing neck crease to minimize visibility of an unsightly scar. Anatomical landmarks facilitate proper placement of the incision; the angle of the mandible approximates C2, hyoid bone approximates C3-C4, thyroid cartilage approximates C4-C5, cricothyroid membrane approximates C5-C6, and C6-C7 is often two finger breadths above the clavicle.<sup>22</sup>

The initial superficial fascial dissection involves splitting the platysma, retracting trachea and esophagus medially, retracting sternocleidomastoid laterally, and identifying the location of the carotid so that the sheath containing artery, jugular vein, and vagal nerve are retracted laterally. Care may also be taken to identify superior and inferior thyroid vessels and ligate if necessary.

Once superficial dissection is complete, attention is paid to the deep dissection. The prevertebral fascia is incised and longus colli muscles are retracted (► Fig. 6.9).<sup>4</sup> The anterior longitudinal ligament will be exposed. Care must be taken at the deep lateral margins since the sympathetic chain and also vertebral arteries lie in proximity. At this juncture, spinal levels are radiographically confirmed.

After the disc space is exposed and localization is confirmed, the discectomy takes place. A number of different techniques exist for disc removal. Often, the annulus fibrosus is incised and disc components are removed with curettes and rongeurs until the posterior longitudinal ligament is identified. The ligament may be incised and proper inspection, including foraminotomies, may be completed to ensure adequate decompression. Appropriate graft or cage construct is inserted in the disc space and an anterior plate is placed. Meticulous hemostasis prevents complications, including retropharyngeal hematoma, and the surgical site is closed. Patients should be monitored closely postoperatively, especially for development of retropharyngeal edema which may compromise the airway and require reintubation.



**Fig. 6.9** Anterior cervical discectomy and fusion. Number of structures can be seen after applying the self-retaining tractor displacing the longus colli muscle. 1. Sternocleidomastoid muscle, 2. Carotid sheath, 3. Longus colli, 4. Omohyoid muscle, 5. Esophagus, 6. Trachea. Image below notes completed ACDF in coronal and sagittal planes. (Reproduced from Nader R, Berta S, Gragnaniello C et al, *Neurosurgery Tricks of the Trade: Spine and Peripheral Nerves*, 1st edition, ©2014, Thieme Publishers, New York.)

### 6.9.3 Laminectomy/ Laminotomy

Laminectomy is the core operative technique in the spinal neurosurgeon's arsenal. Indications range from posterior decompression to complex posterior spinal approaches for discectomy, tumor, abscess, and more. Specific details of positioning and approach vary depending on the location of the laminectomy. Cervical cases will have the patient's head secured in three-point fixation and many will obtain baseline MEPs and SSEPs prior for ease of intraoperative monitoring; these measures are not routinely taken in lumbar laminectomies.

Cervically, C2 (bifid) and C7 (vertebra prominens) spinous processes are usually most prominent and serve as useful landmarks when planning the skin incision. Care is taken to keep the exposure medial to the facet joints since their compromise may produce instability. There are varying techniques for removal of lamina, including use of a small burr drill or Kerrison punches.

Planning the incision in the lumbar region can be done with fluoroscopy or, simply, with palpation for anterior superior iliac crests which provide an approximation for the L4–L5 interspace. After incision, subcutaneous fat will be met and dissected away exposing thoracolumbar fascia. Midline or paramedian (if desiring to preserve interspinous ligament) incision through the fascia is performed next. Fluoroscopic localization is done at this juncture. After dissection and exposure of the spinous process and medial aspect of the facets, bone cutters and/or rongeurs are used to remove the spinous process. Similarly to the cervical spine, a drilling burr or Kerrison can be used to thin out and remove the lamina and underlying ligamentum flavum. The laminectomy can be widened and, when complete, a ball-tipped probe is used to palpate neural foramina and ensure adequate decompression. Depending on

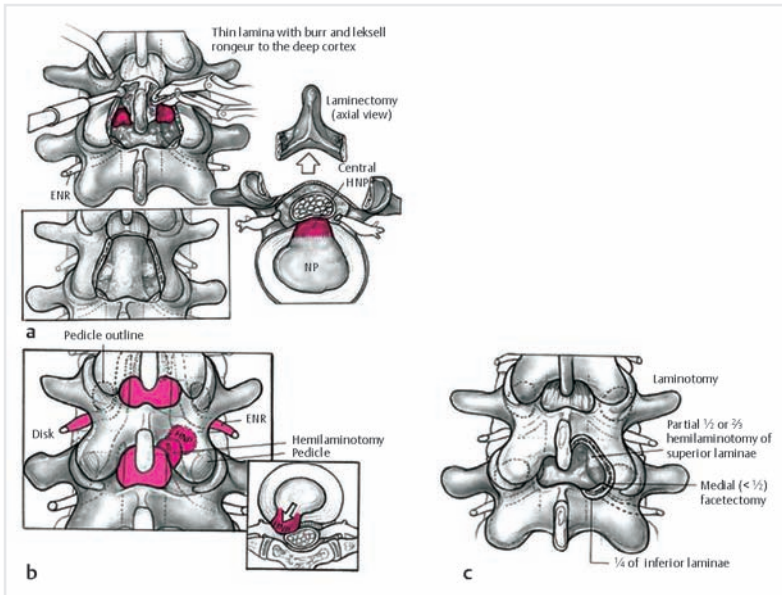
indication, the extent of the decompression may vary to range from spinous process preservation with laminotomy or hemilaminectomy to full laminectomies (► Fig. 6.10).<sup>4</sup> Tight closure of the different tissue layers, including deep and superficial fascia, is vital. In cases where the dura is violated, a watertight closure is necessary.<sup>6</sup>

### 6.9.4 Lumbar Interbody Fusion

There are a variety of types of lumbar interbody fusion. Most common is the transforaminal lumbar interbody fusion (TLIF) which is done for a range of pathologies and new approaches continue to be developed (► Fig. 6.11).<sup>4</sup> Lumbar instability, progressive spondylolisthesis, scoliosis, and symptomatic spinal stenosis with significant back pain are among some indications. Preoperatively, flexion-extension radiographs are helpful in determining the degree of instability. As with other spinal procedures SSEPs, MEPs, and fluoroscopy may be useful adjuncts. TLIF may also be done minimally invasively through a tubing system.

The procedure is carried out similarly to the initial steps of a laminectomy. Afterwards, a facetectomy with removal of the pars is completed to expose the neural elements and the region of ultimate pedicle screw placement. Prior to pedicle screw insertion, a small incision into the annulus fibrosus is made, followed by a discectomy. The annulectomy is made off the median which allows the TLIF to have the benefit of limited retraction of the neural elements. A graft for fusion is then inserted into the disk space and pedicle screws with rods are placed.<sup>6</sup>

Multiple variations exist. Posterior lumbar interbody fusion (PLIF) is theoretically similar to a TLIF; however, the approach extends through the midline and requires retraction of the thecal sac and nerve roots to gain access to the disc space.



**Fig. 6.10** Laminectomy/laminotomy. Laminectomy for central disc herniation is seen in (a) where preservation of the facets and pars interarticularis is essential. (b) Laminotomy bony removal for lateral disc herniation, seen in inset. (c) Medial facetectomy is seen with associated laminotomy. Care is taken to minimize the amount of facet removed to preserve joint stability. (Reproduced from Nader R, Berta S, Gragnaniello C et al, *Neurosurgery Tricks of the Trade: Spine and Peripheral Nerves*, 1st edition, ©2014, Thieme Publishers, New York.)

Other iterations include the anterior lumbar interbody fusion (ALIF) and lateral lumbar interbody fusion (LLIF). The latter forgoes the need to retract musculature of the back or abdomen and starts with an incision placed at the flank.

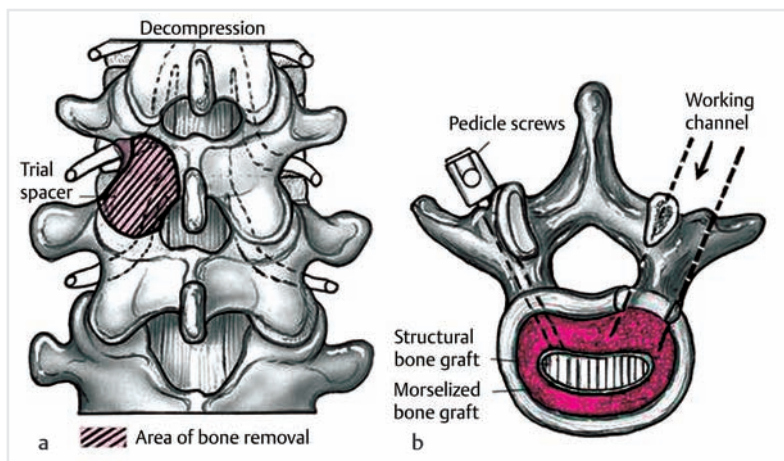
## 6.10 Pediatric

### 6.10.1 Ventriculoperitoneal Shunt

Ventriculoperitoneal shunts (VPS) are one of the most common operations completed

by the pediatric neurosurgeon. VPS is indicated for hydrocephalus cases of varying etiologies and often require revision. The patient is positioned supine with the head turned left (for a right-sided shunt) and the scalp, neck, clavicle, and abdomen are sterilely prepared. There are a wide variety of shunt valves available, including fixed, adjustable, and anti-siphon; the decision is based on the patient's age, pathology, and the surgeon's preference. The distal location of the shunt also varies with options including the pleural and atrial spaces as well.

Proximal shunt catheters can be inserted via a number of trajectories, including



**Fig. 6.11** Transforaminal lumbar interbody fusion. (a) Bony removal for TLIF is shown in image to left with removal of facet joint. The relationship to exiting and traversing nerve roots is seen. (b) Axial view of working channel for TLIF. (Reproduced from Nader R, Berta S, Gragnaniello C et al, *Neurosurgery Tricks of the Trade: Spine and Peripheral Nerves*, 1st edition, ©2014, Thieme Publishers, New York.)

frontal or occipital. There are a variety of points based on bony landmarks for placement of a shunt (► Table 6.2). Kocher's point is most commonly used in adult shunts; however in pediatrics, placement may vary based on the surgeon's judgment. Frontal shunts are measured similarly to EVDs and require a second releasing incision posterior to the ear. The advantage of posterior shunts is that a single parieto-occipital incision is made and a small burr hole is placed. For either approach, a pocket in the subcutaneous space is created for the reservoir and valve. The large tunneler is passed from the cranial to abdominal incision with care taken not to plunge into deeper spaces; structures at direct risk during tunneling are the carotid and jugular vasculature as well as lung apices (making pneumothorax a possible complication). The distal catheter is passed after the tunneled path is made. A one-way

valve is connected to the proximal end of the distal catheter to ensure flow directed cranially to abdominal. Attention is then redirected to the cranial burr where a small dural incision is made and a catheter is passed into the ventricle. Care is taken to secure the depth and position of the catheter, CSF flow is confirmed, and the distal end of the proximal catheter can be connected to the valve reservoir. Next, distal flow is confirmed from the abdominal catheter before feeding it into the peritoneal cavity. Closure at both incisions is carried out in multiple layers to reduce the risk of CSF fistulas forming.<sup>6</sup>

Depending on the institution, VPS may be completed with the assistance of a general surgeon for the abdominal exposure with or without laparoscopy. A small abdominal incision is made with sharp dissection of fascial layers, muscle is conservatively split, and the peritoneum is

**Table 6.2** Cranial landmarks for adult and pediatric shunt placement

| Point                       | Landmarks                                                                                                                                                                                      | Direction and length                                                                                                                                                              |
|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dandy's point (occipital)   | 2 cm lateral to midline and 3 cm above inion; approximately location of intersection between lamboid suture and midpupillary line                                                              | Perpendicular to cortex, slightly cephalic, and approximately 4–5 cm                                                                                                              |
| Frazier's point (occipital) | 3–4 cm lateral to midline and 6 cm above inion                                                                                                                                                 | Perpendicular to cortex, approximately 4–5 cm                                                                                                                                     |
| Keen's point (parietal)     | 2.5–3.0 cm posterior to ear and 2.5–3.0 cm above the ear                                                                                                                                       | Perpendicular to cortex, approximately 4–5 cm                                                                                                                                     |
| Kocher's point (frontal)    | 3.0 cm lateral to midline (approximately parallel to the midpupillary line) and 1 cm anterior to the coronal suture. Often measured as 11 cm posterior from nasion and 3 cm lateral to midline | Trajectory towards ipsilateral medial canthus (coronal plane) and towards tragus of ear (sagittal plane) to approximately 6.5 cm to 3rd ventricle and 4–5 cm to lateral ventricle |

carefully incised to reveal the abdominal cavity. Lifting the peritoneum with mosquito clamps helps ensure no direct bowel injury.

## 6.11 Functional

### 6.11.1 Deep Brain Stimulation

Deep brain stimulation (DBS) is gaining increased utilization and indications for a variety of conditions, especially movement disorders such as Parkinson disease, dystonia, and essential tremor. Patients are positioned in a stereotactic frame with local rather than general anesthesia. Depending on the patient's specific symptom profile, one of multiple targets may receive DBS electrodes including the subthalamic nucleus (STN), globus pallidus internal segment (GPi), and ventralis intermedius nucleus of the thalamus (Vim). Possibly most important in DBS is understanding

coordinate placement and calculation of coordinates. Coordinates are calibrated to several midline structures including the anterior and posterior commissures, Sylvian aqueduct, septum pellucidum junction with splenium of corpus callosum, and interpeduncular point.

Small incisions are made anterior to the coronal suture to allow placement of a lateral burr hole. The microelectrode recording center is prepared and these are inserted via guide tubes using the determined coordinates. Extreme care is taken to avoid ventricular entry since excessive loss of CSF causes brain relaxation which distorts coordinates. When electrodes are inserted, the recordings are verified to those expected for the distinct target and then are locked in place. After electrode placement is complete, the second phase is to place the DBS generator. Generators are often placed in a pocket at the infraclavicular space. A tunneler is used to pass the cable between electrode and generator.<sup>6</sup>



## Pearls



- When tunneling an EVD using a trocar, travel medially. In cases where there are refractory elevated ICPs, the drain would not be in the way of your incision site.
- The farther an EVD is tunneled from Kocher's point, the lower the risk of an infection.
- For interbody fusions, additional methods exist for measuring spinopevic parameters including preoperative planning applications.
- Intraoperative MRI is becoming a more readily available tool in functional procedures, including magnetic resonance-guided laser-induced thermal therapy for obliteration of recurrent brain metastasis.<sup>23</sup>
- *The Neurosurgical Instrument Guide* provides an additional resource for a description of the common tools used in neurosurgery.

3. Failure to complete which of the following while placing an external ventricular drain has the potential to lead to the MOST SEVERE complication?
  - a) Accidentally throwing away the capping red nipple
  - b) Tunneling the EVD too short a distance
  - c) Measuring the ventricular catheter to 7.5 cm
  - d) Accidentally stitching through the EVD while securing it
4. Which structure listed below is retracted laterally during an ACDF?
  - a) Sternocleidomastoid muscle
  - b) Carotid artery
  - c) Esophagus
  - d) Trachea
5. Where, in relation to skull landmarks, is a keyhole burr hole placed?
  - a) Half the distance of a line connecting the bregma and inion
  - b) Pterion (Intersection of frontal, parietal, temporal, and sphenoid bones)
  - c) Within 1 cm of anterior tragus and 1 cm above zygomatic arch
  - d) Intersection of zygoma, superior temporal line, and superior orbital ridge
6. The intercrystal line, a horizontal line between the most superior point of both iliac crests, approximates what lumbar spinal level?
  - a) L1–L2
  - b) L2–L3
  - c) L3–L4
  - d) L4–L5
  - e) L5–S1
7. When using Mayfield three-point fixation for pinning, where should the two-pins generally be placed?
  - a) Superior temporal line
  - b) Frontal sinus

## 6.12 Top Hits

### 6.12.1 Questions

1. Which of the following is NOT part of the appropriate management of intraoperative air embolism?
  - a) Copiously irrigating operative field
  - b) Elevating the head of the bed
  - c) Aspiration of air from right atrium using central venous pressure catheter
  - d) Lowering the head of the bed
  - e) Compressing jugular vein
2. Which of the following structures is NOT directly at risk of harm during a pterional craniotomy?
  - a) Frontalis branch of facial nerve
  - b) STA
  - c) Supraorbital nerve
  - d) Zygoma



- c) The dependent position of the head
  - d) Vertex
8. Which of the following is NOT employed in standard positioning for a pterional craniotomy?
    - a) Ipsilateral shoulder roll
    - b) Neck extension 10–15°
    - c) Maxillary eminence as highest part of operative field
    - d) Thorax elevation 10–15°
    - e) Contralateral head rotation 75°
  9. Which of the following is NOT a routine mechanism of perioperative peripheral nerve injury?
    - a) Stretch
    - b) Shear
    - c) Ischemia
    - d) Compression
  10. Resection of which of the following during a laminectomy will lead to instability?
    - a) Lateral two-third of facet
    - b) Medial one-third of facet
    - c) Lamina
    - d) Spinous process
    - e) Ligamentum flavum

incision. Sensitive structures include the STA, frontalis branch of facial nerve, and supraorbital nerve. The location of the former two may be estimated given knowledge of the zygoma.

3. **c.** Measuring the catheter to greater than 7.0 cm runs the risk of placing a catheter too deep and injuring essential neural and vascular structures. The additional choices all represent poor outcomes but are not nearly as severe. Throwing away the cap necessitates reopening an additional package. Tunneling the catheter a short distance increases infection risk. Stitching through the EVD mandates replacement of the EVD as overdrainage and infection are further risks.
4. **a.** The sternocleidomastoid is identified and typically retracted laterally. The remaining options are classically retracted medially.
5. **d.** Keyhole burrs are placed at the intersection of the zygoma, superior temporal line, and supraorbital ridge.
6. **d.** L4–L5. Studies have demonstrated that the level localized by palpation may vary based on gender and body habitus.
7. **c.** The arm with two-pins should be placed in the most dependent portion of the head in its final position. This is done to reduce risk of slipping of the head out of the Mayfield due to gravity. The pins can be placed at the superior temporal line but this is not always the case. Care should be taken to avoid placement of the pins in the frontal sinus.
8. **e.** Rotating the head 75° risks kinking of jugular veins, elevation of ICPs, and prevents appropriate brain relaxation during the approach. For any procedure which necessitates rotation of the head greater than 30°, an ipsilateral shoulder roll is helpful to reduce muscular tension and allow additional rotation without compromising venous

## 6.12.2 Answers

1. **b.** Elevating the head of bed is not a part of the appropriate management of air embolism, it will rather make the issue worse. The appropriate management includes irrigating the field copiously, packing off veins from further bleeding and air entry, lowering the head of the bed, compressing the jugular vein if possible, and aspirating air using a central venous pressure catheter.
2. **d.** The zygoma is not at direct risk during a pterional craniotomy. The zygoma may be used as a landmark in determining the lowest extent of the

outflow. Typically, the most rotation needed in a pterional craniotomy is approximately 60° for reach anterior fossa lesions.

9. **b.** Shear is not a routine method of perioperative peripheral nerve injury. The remaining mechanisms of stretch, compression, and ischemia are classically involved in perioperative peripheral nerve deficits.
10. **a.** Resection of the lateral portion of the facet joint may cause instability of the posterior column of the spinal column. Up to one-third of the medial facet can be removed without compromising vertebral stability. Lamina, spinous process, and ligamentum flavum are frequently removed during a laminectomy.

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## 7 Neurocritical Care

Xiaoran Zhang, Lori Shutter

### 7.1 Introduction

Care of neurosurgical patients does not stop at the end of an operation. These patients are often some of the sickest patient in the hospital and knowledge of neurocritical care is crucial to ensuring good outcome.

### 7.2 Respiratory Physiology

Respiration describes the body's ability to oxygenate and ventilate. The definition of respiratory failure is therefore the inability of the respiratory system to meet the oxygenation and ventilation requirements of the patient.<sup>1</sup> Furthermore, respiratory failure is divided into two types with type 1 being hypoxemic ( $pO_2 < 60$  mmHg) and type 2 being hypercapnic ( $pCO_2 > 50$  mmHg). The respiratory system can be divided into four interconnecting components: (1) the central nervous system (CNS), (2) airway, (3) alveoli, and (4) thorax. Failure in one or more components can lead to acute respiratory failure.

The CNS components include chemoreceptors responsible for sensing oxygen and carbon dioxide in blood, the respiratory center in the brainstem responsible for respiratory drive, and CNS efferents responsible for transmitting signals from the brainstem to the muscles that carry out the movements necessary for ventilation. CNS respiratory failure secondary to changes in respiratory drive or ability of CNS efferents to transmit signal are commonly seen in the neurological intensive care unit (NICU). Dampened respiratory drive secondary to medication effects can be seen in cases of excessive use of opioids, sedatives, and medications associated with CNS depression. Hemorrhagic and

ischemic strokes, infection, and mass lesions in the medulla can also dampen respiratory drive. It is important to note that mechanical compression from pontine herniation is also a cause of decreased respiratory drive. Demyelinating diseases and high cervical spine trauma can lead to the inability of CNS efferents to transmit signals from the respiratory center, leading to respiratory paralysis.

The airway includes the oropharynx, trachea, and bronchi. Mechanical or soft tissue obstruction in any segment can quickly lead to respiratory failure. Patients with diminished mental status or pathologies involving the lower cranial nerves can be at risk of airway compromise and respiratory failure due to either inability to protect the airway from saliva/vomitus, or experience obstruction of the airway by soft tissue in the oropharynx. Optimal gas exchange is dependent on unobstructed air flow through the pulmonary system and adequate blood flow to the pulmonary vasculature (perfusion). Common causes to impaired gas exchange include processes both intrinsic and extrinsic to the lung. Intrinsic pulmonary processes, such as pneumonia, pulmonary edema, and acute respiratory distress syndrome, can lead to decreased ventilation. Extrinsic processes, such as pulmonary artery embolism from either thrombus or fat, can lead to poor perfusion.<sup>2</sup> Components of the thorax include the muscles necessary for breathing, the chest wall, and pleural space, which are responsible for the mechanical movements of respiration. Demyelinating disorders, cervical spinal cord injuries, neuromuscular conditions (e.g., myasthenia gravis, Guillain-Barre syndrome, and amyotrophic lateral sclerosis), or traumatic injuries can prevent the normal movement of muscles

necessary for respiration. Injuries to the chest wall including rib fractures can lead to significant pain and poor respiratory effort. Pneumo- and hemothoraces can prevent the normal expansion of lung. Patients with morbid obesity can have impaired respiratory mechanics and chronically retain carbon dioxide, which places them at a higher risk of type 2 respiratory failure perioperatively.

## 7.2.1 Acute Respiratory Distress Syndrome

Acute respiratory distress syndrome (ARDS) is an important cause of acute respiratory failure. As many as 35% of NICU patients have some form of ARDS.<sup>3</sup> It is characterized by widespread inflammation of the lungs facilitated by infiltration and accumulation of neutrophils which leads to breakdown of endothelial and epithelial barriers resulting in extravascular accumulation of edema and subsequent impaired gas exchange. ARDS is clinically defined as an acute (< 7 days) onset of respiratory distress with radiographic evidence of bilateral pulmonary infiltrates on chest CT or X-ray.<sup>4,5</sup> Mild ARDS is defined as  $\text{PaO}_2/\text{FiO}_2$  of 200–300 with associated mortality of 27%. Moderated ARDS is  $\text{PaO}_2/\text{FiO}_2$  of 100–200 with associated mortality of 35%. Severe ARDS is  $\text{PaO}_2/\text{FiO}_2$  of less than 100 with associated mortality of 45%. The exact pathogenesis of ARDS is not well understood; however, development of ARDS is known to be associated with pathologies commonly seen in the NICU setting such as sepsis, severe trauma, blood transfusions, pneumonia, and aspiration pneumonitis.<sup>6</sup> Treatment of ARDS consists mainly of supportive therapy. Low volume ventilation with a target tidal volume of no higher than 6 mL/kg in ideal body weight has been shown as the most important intervention at improving outcomes.<sup>7</sup> Intermittent supine to prone

positional change can also potentially lead to improved outcomes. Studies have shown that aggressive diuresis or corticosteroid therapy does not have a role in the management of ARDS.

## 7.2.2 Ventilator Basics

Patients who are suffering from acute respiratory failure that is refractory to non-invasive methods of ventilation undergo intubation with an endotracheal tube for mechanical ventilation. The position of the endotracheal tube is generally described by the distance from the tip of the tube to the teeth. Placement of the tube is confirmed by end-tidal carbon dioxide color change and auscultation of the lungs, with final confirmation and determination of tube position done by chest X-ray. Ideally, the tip of the tube is positioned between 5 and 7 cm above the carina for adults. The endotracheal tube is connected to the ventilator through a series of plastic tubing called “the circuit”. The ventilator has several variables that can be set to tailor when and how a breath is delivered. Ventilation mode dictates the threshold for when a breath is delivered. The most common modes include continuous mandatory ventilation (CMV), assist control (AC), and pressure support (PSV). Under CMV, a breath is delivered at fixed time intervals (i.e., every 5 s). CMV is generally reserved for patients who are unable to initiate their own breaths either due to several neurologic injury or deep sedation. Under AC, a breath is delivered at a fixed time interval unless the patient initiates a breath at which point the ventilator will help the patient breathe a sufficient volume. AC is the most commonly used setting in the NICU as it allows the patients to breathe on their own as much as possible with “safety” programmed to ensure proper ventilation regardless of patient effort. Under PSV, the patient initiates the breath and controls the

volume with the ventilator only providing some additional positive pressure. PSV is typically used in patients who are candidates for extubating and serves as a test to determine whether they are able to independently initiate breaths with sufficient volume and with only minimal positive pressure support. Important settings to know on a ventilator include tidal volume ( $V_t$ ), respiratory rate (RR),  $FiO_2$ , and positive end expiratory pressure (PEEP).  $V_t$  is how much air a patient is taking in per breath, typically the setting is 5–8 mL/kg of ideal body weight. RR is typically set at 12–14 breaths per minute.  $FiO_2$  is the concentration of oxygen being delivered to the patient; typically start at 100% and decrease as tolerated. PEEP is the positive pressure being delivered to the patient, typically start at PEEP of 5–7 cm  $H_2O$ . It is important to note that the circuit itself will require a PEEP of 5 cm  $H_2O$  to overcome, so PEEP is never less than 5 cm  $H_2O$ .

## 7.3 Shock

Shock is acute failure in tissue perfusion across multiple organ systems. It is classically divided into four categories based on etiology and physiologic characteristics including preload, cardiac output, and afterload.

### 7.3.1 Hypovolemic Shock

This is defined as the loss of effective intravascular volume secondary to inadequate intake, excessive loss, or a mixture of both. In neurosurgical patients, common causes include blood loss secondary to trauma or surgery, cerebral salt wasting (CSW), or diabetes insipidus (DI). Hypovolemic shock classically presents with tachycardia and tachypnea. It is characterized by decreased preload, decreased cardiac output, and increased afterload. Treatment requires volume resuscitation.

### 7.3.2 Cardiogenic Shock

Cardiogenic shock is failure of tissue perfusion secondary to decreased cardiac output. In neurosurgical patients, common causes include myocardial infarction and stress cardiomyopathy, both of which are associated with aneurysmal subarachnoid hemorrhage (SAH). Classical presentation includes symptoms of fluid overload such as pulmonary edema. It is characterized by increased preload, decreased cardiac output, and increased afterload. Treatment options are limited to supportive therapy, diuresis, and afterload reduction.

### 7.3.3 Distributive Shock

There is failure of vascular autoregulation leading to inadequate distribution of blood. This is most commonly seen in neurosurgery in the setting of systemic vasodilation secondary to sepsis or neurogenic shock. It is important to note that neurogenic shock from spinal trauma can also have elements of cardiogenic shock, as it may involve decreased sympathetic drive. Common symptoms include hypotension and poor systemic oxygenation in the setting of adequate volume status and cardiac function. Preload and cardiac output can both be either normal or increased, afterload is always decreased. In neurogenic shock, other symptoms include bradycardia and hypothermia. Treatment primarily consists of adequate resuscitation and vasoactive agents.

### 7.3.4 Obstructive Shock

This is characterized by mechanical obstruction to blood flow through cardiac chambers. Most important causes of obstructive shock in neurosurgical patients include postoperative venous thrombosis, tension pneumothorax from central line placement, and air embolus from surgeries

in sitting position or involving dural venous sinuses. Presentation includes profound hypotension and hypoxia in the setting of normal to high preload, decreased cardiac output, and increased afterload. Treatment requires adequate oxygenation, proper positioning, removal of obstruction via thrombectomy, or chest tube placement.

## 7.4 Fluid and Electrolytes

### 7.4.1 Hyponatremia

Hyponatremia is defined as serum sodium of less than 135 mEq/L. Symptoms of hyponatremia include lethargy, confusion, coma, and seizure. The differential for hyponatremia in neurosurgical patients most commonly includes syndrome of inappropriate antidiuretic hormone secretion (SIADH) and CSW. SIADH, as its name suggests, involves the inappropriate secretion of antidiuretic hormone (ADH) in the absence of its normal physiologic trigger, serum hyperosmolality. It is classically seen in the setting of lung neoplasm. Neurosurgical causes of SIADH includes meningitis, traumatic brain injury (TBI), intracranial hypertension, SAH, and neoplastic processes. Other causes include medication side effects, most notably carbamazepine. Diagnosis of SIADH is made with the criteria of hyponatremia ( $< 134$  mEq/L), high urine sodium ( $> 18$  mEq/L), and low serum osmolality ( $< 280$  mOsm/L). Definite diagnosis is through a water-load test. Treatment of acute SIADH is fluid restriction to typically less than 1 L/day. CSW is the renal loss of sodium secondary to an intracranial process. The exact mechanism of CSW is unclear. In neurosurgical patients, CSW is most commonly seen in patients with SAH and TBI. Diagnosis of CSW is made with the criteria of hyponatremia ( $< 134$  mEq/L), high urine output, high urine sodium ( $> 40$  mEq/L, and an

elevated urine osmolality ( $> 100$  mOsm/kg and often  $> 300$  mOsm/kg). Treatment of CSW differs significantly from SIADH as it is treated with fluid repletion and usage of fludrocortisone to promote renal sodium reabsorption. Although the efficacy of enteric sodium repletion strategies is controversial, sodium chloride tablets and Gatorade are commonly used as an adjunct treatment for hyponatremia.

The determination must be made between SIADH and CSW prior to treatment as they entail very different approaches. Patients with SIADH are fluid neutral or overloaded and thus treatment is with fluid restriction, given fluid will serve to exacerbate symptoms of fluid overload and further worsen hyponatremia. Patients with CSW are fluid depleted or “dry.” The treatment is then fluid resuscitation with the goal of at least maintaining an even intake and output. Fludrocortisone is a mineralocorticoid that can be used to increase renal reabsorption of sodium. Fluid restriction in SAH patients with CSW can be dangerous due to the risk of worsening vasospasm.

Correction of hyponatremia should be no faster than 1.3 mEq/h and no more than 8 mEq in 24 h and 18 mEq in 48 h.

Overly quick correction can lead to central pontine myelinolysis, which can produce quadriplegia, pseudobulbar palsy, and cranial nerve abnormalities.

### 7.4.2 Hypernatremia

Hypernatremia is defined as serum sodium of greater than 150 mEq/L. DI is the most common cause of hypernatremia in neurosurgical patients. In patients with DI, there is an abnormally low levels of serum ADH

which results in excessive loss of free water through urination and increasing serum sodium. Common causes of DI in neurosurgical population includes TBI, neoplastic (primarily pituitary region lesions), meningitis, and autoimmune causes. Manipulation of the pituitary gland during transphenoidal surgeries can lead to either permanent or temporary DI depending on the degree of injury to the posterior pituitary gland and pituitary stalk. A unique phenomenon known as the “triphasic response” is sometimes seen in patients after pituitary surgery where patient initially presents with symptoms of DI, followed by a period of normalization prior to going back into DI. The theory behind the triphasic response is that the initial injury causes lack of ADH secretion promoting the patient to go into DI. Over the next 48 hours, apoptosis of injured ADH secreting cells can cause a sudden release of ADH leading to normalization or even overcorrection of serum sodium. After all the ADH has been utilized, the patient again goes back into DI. Diagnosis of DI is made with urine output greater than 250 mL/h, serum sodium of greater than 140 mEq/L, and urine osmolality of less than 200 mOsm/L. Definitive diagnosis is made with water deprivation test. DI is treated with desmopressin.

## 7.5 Cerebral Metabolism and Perfusion

Cerebral blood flow (CBF) is a measurement of the volume of blood (mL) that passes through a fixed amount of tissue (g) in a given amount of time (min). Normal CBF is estimated to be 40–60 mL/100 g/min. When CBF drops to 20–30 mL/100 g/min, slowing can be seen on an electroencephalogram (EEG), and disturbances of consciousness occur. CBF of less than 20 mL/100 g/min leads to electrical failure

on the cellular level corresponding with severely suppressed EEG and loss of consciousness. Cellular ionic pumps begin to fail at CBF of 10–12 mL/100 g/min which leads to cellular swelling and cytotoxic edema that can be seen on imaging. Complete failure of cellular metabolism and irreversible brain damage occurs at CBF less than 10 mL/100 g/min.<sup>8</sup>

The driving force of CBF is cerebral perfusion pressure (CPP), which is the difference in pressure between arterial inflow and venous outflow. Arterial inflow pressure is the mean arterial pressure (MAP). Venous outflow pressure correlates closely with intracranial pressure (ICP), thus ICP is often used as a surrogate. In short, CPP can be mathematically described as<sup>9</sup>:



$$\text{CPP} = \text{MAP} - \text{ICP}$$

An important concept in cerebral perfusion and metabolism is cerebral autoregulation, which describes the ability of cerebral vasculature to regulate its own blood flow through either relaxation or constriction in response to metabolic or pressure cues in order to maintain blood flow to provide brain oxygenation. One of the most important metabolic cues is carbon dioxide, to which the cerebral vasculature is very sensitive.<sup>10</sup> It is estimated that a change of 1 mmHg of PaCO<sub>2</sub> results in a 4% change in CBF. This property is taken advantage of in situations where a temporary reduction in ICP is desired. Cerebral autoregulation is only effective within a set regulatory plateau. At CPP below the plateau, there is passive collapse of blood vessels. At CPP above the plateau, there is segmental dilatation of blood vessels with breakdown of the blood brain barrier.

A good understanding of cerebral metabolism and cerebral autoregulation is crucial in management of SAH patients. The clinical course of a SAH patient battling vasospasm

frequently pushes the boundary of cerebral autoregulation. The pathophysiology of SAH will be discussed in further detail in the vascular chapter see section 12.2.

## 7.5.1 Intracranial Pressure Monitoring

The importance of ICP lies in its relationship with CPP. As previously discussed, CPP is the difference between MAP and ICP, and thus persistently elevated ICP can lead to decreased CPP with resultant cerebral hypoperfusion and neurologic injury.



The concept of ICP is best explained by the classic Monro-Kellie Hypothesis which states that the human cranium is a fixed space occupied by three major components, brain parenchyma, blood, and cerebrospinal fluid (CSF), and an increase in any of the components or the introduction of a new mass lesion can lead to an elevation in ICP.

Lesions that cause increased ICP can be divided based on which component is affected. Common lesions that can cause an increase in ICP include mass lesions such as subdural or epidural hematomas, neoplasm, abscess, and intraparenchymal hemorrhages; cerebral edema from trauma, infarction, or inflammation; and hydrocephalus.

There are many methods of continuous ICP monitoring, the gold standard of which is through an external ventricular drain (EVD) as it directly transduces the fluid pressure inside the ventricular system. Other monitoring modalities involve placement of monitoring devices such as fiberoptic transducers or piezoresistive sensors in the epidural space, subdural

space, or brain parenchyma. In addition to direct transduction of ICP, an EVD offers the added advantage of allowing for therapeutic drainage of cerebrospinal fluid. When compared to other modalities, EVD placement is more invasive and associated with risks of catheter tract hemorrhage and infections that can lead to ventriculitis.<sup>11,12</sup> In patients who have difficult-to-correct coagulopathy and pathology that is unlikely to require CSF diversion, indirect methods of measuring ICP can be considered.

## 7.6 Hematology and Coagulation

Regardless of whether it is a lumbar puncture or a deformity correction surgery, it is critically important to confirm that the patient can tolerate a procedure from the hematological and coagulation standpoint prior to starting. Typical preprocedure laboratory tests include hemoglobin, platelet count, international normalized ratio (INR), and partial thromboplastin time (PTT). If the patient is on antiplatelet medications (i.e., aspirin, clopidogrel), platelet function assays may also be routinely sent. For patients undergoing a procedure with small expected blood loss, a hemoglobin of 7.0 g/dL is typically considered the minimal threshold prior to transfusion with packed red blood cells (pRBC). A unit of pRBC (~350 mL) will on average increase hemoglobin by 1.0 g/dL. A platelet count of 100,000/ $\mu$ L is the preprocedural minimum for neurosurgical patients. Platelet concentrates are usually administered as a pool of 6 units. In the average adult, each of these platelet concentrates will increase the platelet count by 5,000–10,000/ $\mu$ L. As such an entire pool may increase the platelet count by



30,000–50,000/ $\mu\text{L}$ . Platelet administration in patients who are on antiplatelet medications is controversial and the practices are widely different. At our institution, prior to a procedure, we do not typically transfuse patients who take aspirin, but we will transfuse patients on clopidogrel with a positive response assay because in our experience, clopidogrel use is associated with more profound intraoperative blood loss. INR is a functional measurement of the extrinsic coagulation pathway with a typical cutoff of between 1.2 and 1.4 and PTT is the measure of the intrinsic pathway with a cutoff of 40 seconds. Increased INR can be due to a variety of factors such as medication effect (warfarin, direct oral anticoagulants [DOACs]), poor nutrition, poor liver synthetic function, and certain disease states. Reversal of increased INR is discussed in detail in Cranial chapter (Chapter 8).

### 7.6.1 Disseminated Intravascular Coagulation

Disseminated intravascular coagulation (DIC) is a dangerous phenomenon where there is abnormal generation of microthrombi that can lead to organ dysfunction, and at the same time, there is significantly increased risk of bleeding due to consumption of coagulation factors and platelets by the abnormal thrombi formation. DIC often presents as a manifestation of underlying disease processes. In neurosurgical patients, the most common disease processes that can lead to DIC include sepsis, severe multisystem trauma, and in patients who required significant amounts of blood products to replace either intraoperative or traumatic losses. In these high-risk patients, frequent laboratory testing and repletion of coagulation components is important. At our institution,

we perform laboratory testing every 6 hours for hemoglobin, hematocrit, platelet count, INR, PTT, and fibrinogen. Prompt transfusion of pRBC, platelets, fresh frozen plasma (INR/PTT), and cryoprecipitate (fibrinogen) based on suboptimal laboratory results can potentially prevent catastrophic hemorrhages.

### 7.6.2 Venous Thromboembolism

Venous thromboembolism is a dreaded and possibly life-threatening complication that is not uncommon in postoperative patients. As the name suggests, deep vein thrombosis (DVT) is defined as the formation of blood clots in one of the deep veins. Pulmonary embolism (PE) is the most clinically significant complication of DVT, which occurs when a piece of the clot breaks off and travels to the pulmonary circulation leading to increased ventilatory dead space and difficulty with gas exchange. PE manifests clinically in the form of tachycardia, tachypnea, and oxygen desaturation. A helical chest CT angiogram is the most valuable tool for diagnosis of PEs. PE treatments primarily consist of supportive therapy with anticoagulation in the form of heparin drip, therapeutic low molecular weight heparin (LMWH; i.e., lovenox), warfarin, or DOAC. Common neurosurgical conditions that increase the risk for developing DVTs include neoplasm, immobility, and multisystem trauma. In these patients, DVT prophylaxis is extremely important. Typical prophylaxis consists of sequential compression devices, subcutaneous heparin or prophylactic lovenox, and improving mobility, especially ambulation. It is important to note that therapeutic LMWH can be dangerous in postoperative neurosurgical patients as it cannot be titrated which can lead to potentially fatal bleeding events.

## Pearls



- In managing critically ill neurosurgical patients, ABC (airway, breathing, and circulation) come before the neurological system.
- Always remember there are noninvasive interventions for elevated ICPs and they should be utilized prior to invasive interventions.
- In managing patients with suspected DI, close monitoring is necessary to prevent rapid shifts in serum sodium from triphasic response.

## 7.7 Top Hits

### 7.7.1 Questions

1. A 37-year-old female, on postoperative day one from endoscopic endonasal resection of pituitary adenoma, is complaining of polydipsia and polyuria. What you do suspect? How do you work it up?
2. How is CPP mathematically calculated?
3. A 52-year-old male is brought to the emergency department after being involved in a high velocity motor vehicle collision. On arrival, his heart rate is 42, blood pressure is 82/45 mmHg, and temperature is 35°C. His chest X-ray is negative for pneumothorax. His trauma FAST evaluation was negative for intraabdominal hemorrhage. He has 0/5 strength in bilateral lower extremities. What is going on? How do you manage this?
4. A 22-year-old male presented 3 days ago as a polytrauma with severe TBI and splenic laceration requiring large volume of pRBC transfusion. He suddenly develops increased ventilator requirements. What is your diagnosis? How do you manage this condition?
5. What is the Monro-Kellie Hypothesis?

### 7.7.2 Answers

1. Polydipsia and polyuria in patients who had recently undergone transphenoidal surgery should immediately make one concerned for DI. Workup of DI includes testing serum sodium ( $> 140$  mEq/L) and urine osmolality ( $< 200$  mOsm), and measuring urine output ( $> 250$  cc/h).
2.  $CPP = MAP - ICP$ .
3. Presentation of bradycardia and hypotension in the setting of suspected spine trauma is concerning for neurogenic shock. This patient should be managed with vasopressors and intravenous fluid.
4. This patient has multiple risk factors for developing ARDS such as trauma and significant blood transfusion. Management of ARDS is supportive therapy with low volume ventilation, and diuresis.
5. The Monro-Kellie hypothesis states that the human cranium is a fixed space occupied by three major components, brain parenchyma, blood, and CSF, and an increase in any of the components or the introduction of a new mass lesion can lead to an elevation in ICP.

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# 8 Traumatic Brain Injury

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## 8.1 Introduction

The Centers for Disease Control and Prevention reported that in 2013, there were at least 2.8 million emergency department visits, hospitalization, or deaths related to traumatic brain injury (TBI).<sup>1</sup> To put this in perspective, every hour, there are an average of 204 TBI-related emergency department visits, 33 TBI-related hospitalizations; and 6 TBI-related deaths.<sup>1</sup> Overall, TBIs contribute to 30% of all injury-related deaths.<sup>1</sup> The range of TBI spans from mild to life-threatening and the subsequent treatment ranges from observation and medical optimization to emergent surgical intervention. Understanding TBI is critical to effectively evaluate and treat these patients.

## 8.2 Classification of Head Injury

### 8.2.1 Examination to Assess Head Injury

The Glasgow Coma Scale (GCS) serves as an initial way to assess the severity of head injury (► Table 8.1). It is composed of three components: motor (6 points), verbal

(5 points), and eye response (4 points) for a minimum score of 3 and maximum score of 15. There is a separate way to assess pediatric patients using the GCS score dependent on age (► Table 8.2; see section 14.4, chapter 14). Based on the GCS, the severity of TBI can be estimated (► Table 8.3).

The common phrase “less than 8, then intubate” speaks more to the inability for the patient to protect his/her airway.

In fact, 56–60% of patients with GCS score less than or equal to 8 have one or more other organ systems injured.<sup>2</sup> Furthermore, 4–5% have associated spine fractures. GCS can be affected by factors other than neurological injury including pharmacologic, respiratory compromise, and metabolic abnormalities. Re-evaluation once underlying issues are addressed is essential for accurate prediction of prognosis.

### 8.2.2 Recommendations for Imaging

In patients with minor head injury, the decision to obtain CT imaging can be difficult

**Table 8.1** Adult Glasgow Coma Scale

| Response | 1 point     | 2 points                         | 3 points                       | 4 points                | 5 points              | 6 points         |
|----------|-------------|----------------------------------|--------------------------------|-------------------------|-----------------------|------------------|
| Eye      | No response | Open to pain                     | Open to voice                  | Open spontaneously      |                       |                  |
| Verbal   | No response | Incomprehensible sounds          | Incoherent words               | Disoriented or confused | Appropriate responses |                  |
| Motor    | No response | Extensor (decerebrate) posturing | Flexor (decorticate) posturing | Withdraws from pain     | Localizes to pain     | Follows commands |

**Table 8.2** Pediatric Glasgow Coma Scale

| Response | Age       | 1 point     | 2 points                         | 3 points                                     | 4 points                | 5 points                     | 6 points    |
|----------|-----------|-------------|----------------------------------|----------------------------------------------|-------------------------|------------------------------|-------------|
| Eye      | < 1 year  | No response | Open to pain                     | Open to shouting                             | Open spontaneously      |                              |             |
|          | > 1 year  | No response | Open to pain                     | Open to command                              | Open spontaneously      |                              |             |
| Verbal   | < 2 years | No response | Grunts, agitated, restless       | Persistent inappropriate crying or screaming | Cries and consolable    | Smiles or coos appropriately |             |
|          | 2–5 years | No response | Grunts                           | Persistent crying and screaming              | Inappropriate words     | Appropriate word phrases     |             |
|          | > 5 years | No response | Incomprehensible sounds          | Inappropriate words                          | Disoriented or confused | Oriented                     |             |
| Motor    |           | No response | Extensor (decerebrate) posturing | Flexor (decorticate) posturing               | Withdrawal              | Localizes to pain            | Spontaneous |

**Table 8.3** Traumatic brain injury grading

| Category | Criteria  |
|----------|-----------|
| Mild     | GCS 13–15 |
| Moderate | GCS 9–12  |
| Severe   | GCS 3–8   |

Abbreviations: GCS, Glasgow Coma Scale.

compared to ordering CT imaging on a patient with clear neurological deficit. There are two major published recommendations to aid in decision making: the Canadian Head CT rule and the New Orleans criteria.

### Canadian CT Head Rule

- Applies to patients with GCS 13–15 with witnessed loss of consciousness (LOC), amnesia, or disorientation.
- High risk of need for intervention:
  - GCS scores less than 15 at 2 hours after initial injury.
  - Suspected open or depressed skull fracture.
  - Any sign of basilar skull fracture (raccoon sign, otorrhea, rhinorrhea, Battle's sign, hemotympanum etc).
  - More than one episode of emesis.
  - Age 65 years or older.

- Medium risk for brain injury on CT:
  - Amnesia before injury for more than 30 minutes.
  - Dangerous mechanism including pedestrian struck, ejection from vehicle, fall from height over 3 feet, or fall down more than five stairs.

## New Orleans Criteria

CT is recommended for patients with minor head injury (GCS 15) with any one of the following findings:

1. Headache.
2. Vomiting.
3. Age more than 60 years.
4. Drug or alcohol intoxication.
5. Persistent anterograde amnesia.
6. Visible trauma above the clavicle.
7. Seizure.

## 8.2.3 Imaging to Modalities

### Computed Tomography

Non-contrast CT scans of the brain can also be used to predict mortality using the Marshall Grade (►Table 8.4). Predicted

mortality increases with the presence of an intracranial lesion, edema causing compression of the cisterns, midline shift (MLS) more than 5 mm, and volume of the lesion more than 25 mL. Contrasted scans are often not indicated in most trauma situations unless there is suspicion for significant brain edema (visible on non-contrasted scan) secondary to suspected neoplasm or suspected altered sensorium from infectious epidural collection.

### X-rays

Skull X-rays may be helpful in certain situations such as penetrating injuries. However, X-ray has low sensitivity for detecting intracranial abnormalities (roughly 25%).<sup>3</sup> If a CT cannot be obtained, then X-rays can be used to identify pneumocephalus, skull fractures, pineal shift, and air-fluid levels.

### Magnetic Resonance Imaging

MRI is usually not used for acute head injuries given its lower availability on an acute basis, contraindication in critical patients who may not be able to tolerate lying

**Table 8.4** Marshall Grade to predict mortality<sup>2</sup>

| Category                          | Cisterns             | Midline shift        | Intracerebral hemorrhage | Mortality |
|-----------------------------------|----------------------|----------------------|--------------------------|-----------|
| Diffuse injury I                  | No visible pathology | No visible pathology | No visible pathology     | 9.6%      |
| Diffuse injury II                 | No pathology         | < 5 mm               | Lesion densities present | 13.5%     |
| Diffuse injury III (swelling)     | Compressed or absent | < 5 mm               | Lesion densities < 25 mL | 34%       |
| Diffuse injury IV (midline shift) |                      | > 5 mm               | Lesion densities > 25 mL | 56.2%     |
| Evacuated mass lesion             |                      |                      | Evacuated                | 38.8%     |
| Nonevacuated                      |                      |                      |                          | 52.8%     |

flat or undergoing a longer scan, and unchanged sensitivity in detecting surgical lesions.<sup>4</sup> MRI scans do have utility after the patient is stabilized in order to detect evidence of diffuse axonal injury (DAI, although clinical correlation is key in making this diagnosis), hypoxic injury, or punctate hemorrhages not seen on CT.

## 8.2.4 Brain Injury

Brain injury secondary to trauma occurs from an initial mechanical impact to the brain, sometimes called primary injury or impact damage. However, secondary injury also occurs due to alterations in a variety of cerebral physiological process, including metabolic crisis and ischemia, release of inflammatory cytokines and cytotoxins, membrane breakdown, excitotoxicity, and neurotransmission derangements.<sup>5,6</sup> Ischemia is thought to be the most important factor leading to secondary damage. The brain is dependent on cerebral blood flow and reduction in oxygen leads to tissue damage in a physiologically predictable process. Normal, healthy brain that is able to maintain autoregulation can tolerate a cortical flow reduction to 20 mL/100 g/min. However, below 20 mL/100g/min, loss of consciousness and coma ensue.<sup>7,8,9,10,11</sup> When this flow reduces below 18 mL/100 g/min, energy dependent ion pumps are unable to maintain ionic gradients across the neuronal cell wall and stops functioning. This can lead to anaerobic metabolism and begins to generate lactic acid. At 10 mL/100 g/min, the cell membrane loses stability and there is a massive influx of calcium leading to irreversible damage. On pathology, there is karyorrhexis, or loss of nuclear definition, along with vacuolation of perineuronal astrocytic processes and swelling of the mitochondria, Golgi and intracellular cytoplasmic vesicles. When flow is 15–18 mL/100g/min for more than 30 minutes, selective neuronal loss may occur.<sup>12,13</sup>



Hippocampal neurons in the cornu ammonis (CA1) and CA3 layers, cerebellar granular cells, and larger cortical neurons are most susceptible to selective neuronal loss.

When flow is 10 mL/100 g/min or less for more than 60–90 minutes, infarction occurs. This dependence on cerebral blood flow for tissue integrity makes it less surprising that a single episode of hypotension with systolic blood pressure (SBP) less than 90 leads to a 150% increase in mortality for TBI patients.<sup>14</sup>

## 8.2.5 Hemorrhage Types

There are various types of hemorrhages depending on etiology, mechanism, and sometimes age. They vary in both appearance and location, which can provide insight into the type of hemorrhage and subsequently, the management of the hemorrhage (► Table 8.5).

### Epidural Hemorrhages

Epidural hemorrhages (EDHs) are classically caused by rupture of the middle meningeal artery with an overlying fracture of the temporoparietal bone. However, this is actually only the case in approximately one-third of adults and one-fifth of children.<sup>15</sup> EDHs can also be due to bleeding from the middle meningeal vein or dural sinus. EDHs are more common in young adult males aged 20–30 years. Additionally, skull fractures have been found in 95% of patients with EDH. The classic presentation is a brief loss of consciousness after the traumatic event, followed by a lucid interval, then rapid deterioration over several hours. Almost half of patients will present with a classic “lucid interval” and 27% will present neurologically intact.<sup>16,17</sup>

**Table 8.5** Types of hemorrhages

| Type of hemorrhage          | Appearance                                                                                                       | Location                                                                    | Etiology                                                                                           | Associations                                                                                                        |
|-----------------------------|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| Epidural hemorrhage         | Lens or biconvex                                                                                                 | Does not cross suture lines because of dural attachment                     | Arterial bleeding, often the middle meningeal artery                                               | Skull fracture often overlies EDH because high impact                                                               |
| Subdural hemorrhage         | Crescent shaped                                                                                                  | Does not cross midline or tentorium                                         | Venous bleeding, often due to bridging veins                                                       | Elderly patients have atrophy of the brain leading to increased susceptibility of bridging veins                    |
| Subarachnoid hemorrhage     | Hyperdensity along sulci or in cisterns                                                                          | Convexity, Sylvian fissure; Inter-hemi-spheric, cisternal                   | Arterial                                                                                           | If basilar (starfish appearance), a ruptured aneurysm must be ruled out                                             |
| Intraparenchymal hemorrhage | Circular or ovoid                                                                                                | 1. Basal ganglia<br>2. Lobar<br>3. Cerebellar                               | Mechanical tearing of vessel, injury to vessel leading to permeability and subsequent hemorrhage   | Severe impact, poor nutritional status                                                                              |
| Contusion                   | Hyperdense blood; May be stippled or multiple; May be mixed density (both hyperdense blood and hypotenuse areas) | May be in any location; Lobar common, especially frontal and temporal lobes | “Bruising” from acceleration/ deceleration, direct force trajectories, shear and rotational forces | “Contrecoup” injuries may occur opposite to the site of impact                                                      |
| Intraventricular hemorrhage | Blood within ventricle                                                                                           | Lateral, 3 <sup>rd</sup> , and/or 4 <sup>th</sup> ventricle                 | In trauma, often secondary from extension from parenchymal or subarachnoid                         | Can be isolated or an extension of parenchymal or subarachnoid hemorrhage; Isolated more common in elderly patients |



In adults, over 90% of EDHs occur secondary to traffic accidents, falls, and assaults. In pediatric patients, a 10% drop in hematocrit should elevate suspicion for an EDH. In pediatrics, falls account for approximately half of EDHs, while traffic accidents account for another one-third.<sup>15</sup> Symptoms include obtundation, contralateral hemiparesis (unless Kernohan's notch phenomenon occurs), and ipsilateral pupil dilatation (up to 44%).<sup>17,18</sup> EDH is present in up to 4% of TBI patients, and almost 10% will present in a coma.<sup>19,20,21</sup> The single most important prognostic factor is the GCS score at time of presentation. If GCS is 6–8, mortality is 9% whereas with GCS 3–5, mortality increases to 36%.<sup>20</sup> Patients with no pupillary findings have a poor outcome in 30% of cases, one fixed pupil have a poor outcome in 35% of cases, and bilaterally fixed pupils have a poor outcome in 50%.<sup>22</sup> Other poor prognostic factors are associated traumatic subarachnoid hemorrhage (tSAH), greater than 50 mL in volume, effacement of basal cisterns, and MLS more than 1 cm.<sup>22,23</sup>

If an EDH is diagnosed and treated within a few hours, mortality is estimated to be between 5 and 12%.<sup>24</sup> More specifically, for patients that require operative evacuation, one study found that all patients with evacuation completed after 70 minutes from the onset of pupillary dilation died.<sup>25</sup> Death is often secondary to uncal herniation causing injury to the midbrain leading to respiratory arrest. Management ranges from observing closely to emergent surgery.

## Surgical Indications

1. Signs of local mass effect (symptomatic EDH).
2. Acute asymptomatic EDH more than 30 cm<sup>3</sup>, thickness more than 15 mm, or more than 5 mm midline shift on initial CT regardless of GCS.<sup>18,23,26,27,28</sup>
3. Signs of herniation<sup>23,25,29</sup>
  - a) Increased drowsiness, pupillary changes, hemiparesis.

4. Cardiorespiratory abnormalities.
5. Anisocoria and GCS less than 9.

## Subdural Hemorrhages

Subdural hemorrhages (SDHs) are the most common traumatic intracranial lesions and occur in up to 29% of TBI patients.<sup>30</sup> Younger patients most commonly presents after a motor vehicle accident and older patients most commonly present after a fall. Patients commonly present obtunded and up to half present with pupillary abnormalities.<sup>22,31,32,33</sup> They can arise from injury or tearing of bridging veins in the subdural space, or bleeding from parenchymal injuries. SDHs are often associated with damage to the actual underlying brain parenchyma; therefore, although evacuation may be lifesaving, removal does not ensure a good outcome. Regardless of GCS score at presentation, mortality is between 40 and 60% whereas mortality for patients who present in a coma is 57–68%.<sup>30</sup>

There have been a multitude of studies looking at morbidity and mortality based on the thickness of the SDH, degree of midline shift, presenting GCS score, and age.<sup>34,35,36,37</sup> Not surprisingly, larger-sized SDHs, greater degrees of associated MLS, lower presentation GCS scores, and higher ages at presentation are all associated with increased mortality and poorer outcome.<sup>34,35,36,37</sup> As with epidural hematomas, earlier evacuation in operative patients is associated with better outcome. Evacuation within 2–4 hours of clinical decline is associated with improved morbidity and mortality.<sup>17,29,38</sup>

Kernohan's notch phenomenon is when the brainstem shifts away from the mass and may cause compression of the opposite cerebral peduncle on the tentorial notch.<sup>39</sup> This can cause a false localizing sign and lead to ipsilateral hemiparesis.

## Surgical Indications

1. SDH thickness greater than 1 cm or MLS greater than 5 mm regardless of GCS<sup>35,36</sup>
2. GCS less than 9, lack of ability to localize on motor response should undergo intracranial pressure (ICP) monitoring.<sup>37</sup>
3. GCS less than 9 with thickness less than 1 cm and midline shift less than 5 mm should undergo surgical evacuation if the GCS decreases by 2 points, there is an abnormal pupillary examination, or there is sustained ICP elevation above 20 mmHg despite medical therapies.

## Subarachnoid Hemorrhages

Traumatic SAH occurs in 12–53% of TBIs.<sup>40,41,42</sup> It is caused most often by bleeding from cortical arteries, veins, and capillaries but can also rarely be secondary to bleeding from the rupture of bridging veins or traumatic aneurysms.<sup>40,43</sup> Its presence increases mortality by twofold. The two main explanations for this are that either tSAH is an indicator of a greater severity of injury or because of subsequent vasospasm and ischemia.<sup>42,43</sup> Prognosis of TBI patients with tSAH is related to admission GCS and other associated hemorrhages.<sup>40</sup>

## Intraparenchymal Hemorrhages

Intraparenchymal hemorrhages (IPH) occur from various mechanisms: tearing of deeper vessels from impact injury, or vascular disturbances secondary to trauma resulting in vasothrombosis and vasoparalysis which leads to perivascular edema and subsequently to perivascular hemorrhage.<sup>45</sup> Additionally, poor nutritional status after trauma can lead to

increased permeability of vessel walls causing increased hemorrhage.<sup>45</sup> Up to 38% of patients with traumatic IPH may have an increase in size of the lesion.<sup>46</sup> The presence of SAH, SDH, and higher initial volumes (11% risk per cm<sup>3</sup>) have been associated with progressive IPH enlargement.<sup>46</sup> Surgical intervention for IPH can be done for hematoma evacuation, cerebral decompression, or both.

## Surgical Indications

1. Progressive deterioration of neurological examination localizable to the lesion, medically refractory intracranial hypertension, signs of mass effect on CT such as edema, MLS, or compression of the ventricles/cisterns.<sup>47,48,49,50,51</sup>
2. Any lesion with a volume more than 30 cm<sup>3</sup> or MLS more than 5 mm.<sup>52</sup>

## Contusions

Contusions are caused by a variety of mechanisms and forces, including direct linear force, rotational and shear forces, and sudden deceleration of the head. They may occur in a coup-contrecoup pattern and often occur at the frontal, temporal, and occipital poles as well as the basilar aspects of the frontal and temporal lobes because of impact against the inside of the skull and its bony prominences on the floor of the anterior and temporal fossae. They typically evolve over time and may enlarge or be associated with progressive edema, which may cause mass effect issues and require urgent surgical decompression in cases of herniation. Sometimes contusions develop in a delayed fashion in patients with severe TBI (GCS ≤ 8). These delayed contusions occur in approximately 10% of patients usually within 72 hours of the traumatic event.<sup>53,54</sup> Mortality is high for these patients and ranges from 50 to 75%.<sup>55</sup>

## Surgical Indications

1. Progressive deterioration of neurological examination localizable to the lesion, medically refractory intracranial hypertension, signs of mass effect on CT such as edema, MLS, or compression of the ventricles/cisterns.<sup>47,48,49</sup>
2. GCS 6–8 with frontal or temporal contusions more than 20 cm<sup>3</sup> with MLS more than 5 mm or cisternal compression.<sup>48</sup>
3. Any lesion more than 50 cc in volume.<sup>48</sup>

## Intraventricular Hemorrhages

Intraventricular hemorrhage (IVH) is found in 1.5–5.7% of patients with blunt head trauma and present in almost 10% of patients with severe TBI.<sup>56,57</sup> IVH may occur from extension of parenchymal hemorrhages, redistribution of subarachnoid hemorrhage, or may occur in isolation, especially in the presence of coagulopathy.<sup>56,58</sup> Traumatic IVH is associated with poor outcome and high mortality.<sup>56,57</sup> Presence of hemorrhage in all four ventricles portends worsened outcome and may be associated with diffuse axonal injury.<sup>56</sup> Acute hydrocephalus is relatively rare after traumatic IVH.<sup>56</sup>

## 8.2.6 History and Physical

The following key points should be gleaned from the history, which often must be obtained from family members, friends, and first responders at the scene:

- History of present illness: Time of onset, time of acute decline.
- Anticoagulation and antiplatelet medications, dosage, indications, time last taken, time, and result of last therapeutic blood level as applicable.
- Physical examination: Focal neurological deficit.

- Imaging: Time of last scan (if transferred).
- Important laboratory values: Arterial blood gas (ABG), complete metabolic panel, especially sodium, glucose, and creatinine; complete blood count (CBC), especially hemoglobin, hematocrit, and platelet count; partial thromboplastin time (PTT), prothrombin time (PT) / international normalized ratio (INR); possibly platelet assays; urinalysis; serum alcohol level; and toxicology screen.

## 8.2.7 Initial Assessment

The initial assessment of a trauma patient is essential to avoid missing any critical injuries. The “ABCDE” method of assessment precedes any imaging or neurological exam. In other words, in a patient who is unable to protect their airway, intubation takes precedent over a neurological examination or obtaining imaging to determine whether they have a potential head injury.

## Resuscitation (A B C D E)

- Airway: Ask the patient a question such as “What is your name?” If they are able to verbalize a response, this means their airway is patent. If they do not verbalize a response then apply noxious stimulation. If they are able to verbalize a response (including guttural sounds such as a groan) then their airway is patent.
- Breathing: Listen with a stethoscope to both lungs. Unequal breath sounds may indicate a traumatic injury such as a pneumothorax or hemothorax.
- Circulation: Palpate for pulses in bilateral radial, femoral, posterior tibial, and dorsalis pedis arteries. The ability to palpate the pulse at certain regions is an indicator of blood pressure, and asymmetry may indicate a proximal arterial injury secondary to trauma.
- Disability: cursory examination of the patient overall to look for any gross

traumatic injury such as an open long bone fracture.

- Exposure: Remove any clothing the patient may have on to avoid continued exposure to any potential toxins and cover the patient to prevent hypothermia.

## Physical Examination

- Vitals (Cushing's reflex)
- GCS
- Laceration
  - Is there an underlying open skull fracture?
  - Is the wound contaminated?
- Basal skull fracture
  - Battle's sign: Postauricular ecchymoses (around the mastoid air sinuses).
  - Raccoon sign: Periorbital ecchymoses.
  - Hemotympanum.
  - Otorrhea, rhinorrhea.

## 8.3 Monitoring

### 8.3.1 Intracranial Pressure

Sustained elevated ICP can be devastating. Less than 3% of patients with a GCS of 14 or 15 later deteriorate into coma, so monitoring is generally not used in this group. Of note, however, in TBI patients with GCS greater than 8, intracranial hypertension has been found to develop in over 50% of patients with an abnormal head CT compared to 13% of TBI patients with GCS less than 8 with a normal head CT. Parenchymal monitors have extremely low complication rates and can be used for longer periods of time without infectious risk.

### Surgical Indications

1. Patients with a GCS score 3–8 or patients unable to localize on the motor component of the GCS with an intracranial lesion on head CT.

2. Patients with GCS score 9 to 12 with concerning mass lesions on CT should be considered for monitoring.
3. Monitoring should be considered in patients with a normal head CT with any two of the following—age greater than 40 years, SBP less than 90 mmHg, unilateral or bilateral posturing (unable to localize).<sup>30</sup>

### 8.3.2 External Ventricular Drains

External ventricular drains (EVD) may be used for both ICP monitoring and to drain cerebrospinal fluid (CSF) to reduce ICP.<sup>59</sup> Indications include those delineated above plus intracranial hypertension resistant to medical management or upon initiation of monitoring with radiographic signs of cerebral edema and mass effect. Studies suggest that continuous drainage, instead of intermittent drainage, is more effective at lowering ICP.<sup>60</sup> <sup>61</sup> However, continuous open drainage precludes accurate ICP measurements via a fluid-coupled measurement mechanism alone, so either a combination catheter or multiple catheters can be used. The use of antimicrobial-impregnated catheters in comparison to standard catheters, has been shown to reduce infection rates associated with EVD use.<sup>62,63</sup> While EVD has the added benefit of therapeutic CSF drainage, the complication rates, particularly for infection, are higher than those of parenchymal monitors.

## 8.4 ICP Treatment

Normal ICP is generally considered to be less than 20 to 25 mmHg; and treatment is often initiated in the setting of TBI to keep ICP less than 20 mmHg. As previously mentioned, a single incidence of SBP less than 90 mmHg is associated with a doubling of mortality. Another important predictor of poor outcome is the duration of time that ICP is elevated more than 20 mmHg.

Cerebral perfusion factor (CPP) is defined as the difference between the mean arterial pressure (MAP) and ICP. Therefore, with an increase in ICP, the CPP decreases unless a concomitant increase in BP occurs, and thereby deleterious reductions in cerebral blood flow to the brain may occur.

Management of TBI therefore requires a detailed understanding of these relationships as well as the dynamic states of individual patients over time.

When cerebral autoregulation is lost, increases in BP may produce unsafe elevations in ICP.

As previously noted, monitoring of ICP can include parenchymal ICP monitoring, external ventricular drainage, or both. Parenchymal ICP monitoring shows superior accuracy compared to subdural, sub-arachnoid, and epidural monitors. Numeric drift may occur affecting the accuracy after one week but this is often minor. EVDs are the most accurate instruments to measure ICPs due to the fluid coupled mechanism. However, accuracy may be affected by the presence of hemorrhage in the ventricle and concomitant catheter occlusion. As noted, EVDs also offer the advantage of being able to treat ICPs via drainage of CSF.<sup>64</sup> Overall, complications related to monitors are low. Significant infections are exceedingly rare especially with the use of antibiotic-impregnated catheters and incidence of hematomas actually requiring surgical intervention is less than 1%.<sup>64,65,66</sup>

### 8.4.1 Decompressive Craniotomy/Craniectomy

Decompressive craniectomy (DC) is often utilized to reduce dangerously elevated ICP when medical management has failed, or in conjunction with evacuation of mass lesions when cerebral edema is severe. The presence

of severe midline shift (especially if out of proportion to the thickness of a subdural hematoma), effacement of cisterns, and the presence of other significant lesions are indications that a bone flap may need to be left out after craniotomy and should prompt a large exposure. Both mortality and improved outcomes at 6 months based on the Glasgow Outcome Scale-Extended (GOS-E) after DC have been shown, with even greater improvements at 12 months, but at least some studies have shown that the proportion of debilitated survivors may be increased, so patient selection is critical.<sup>50,67</sup>

Key studies for further reading are the DECRA and RESCUEicp trials.

Decompressive craniectomies should measure at least 15 cm in diameter to improve both neurologic outcome and mortality.<sup>68,69</sup>

### 8.4.2 Antiepileptic Management

Post-traumatic seizures occur in up to 42% up to 3 years after TBI. Patients most at risk for developing seizures are those with hematomas, depressed skull fractures, and GCS score less than 10.<sup>70,71,72</sup> Early post-traumatic seizures are defined as a seizure that occurs within the first 7 days after a TBI. These occur in up to 25% of patients. Preventing early seizures reduces the change of epilepsy.<sup>71</sup> Additionally, seizures can cause elevated ICPs, reduce cerebral oxygenation, result in hemodynamic instability, and further damage an already fragile brain.

Phenytoin has been found to be effective in reducing early post-traumatic seizures, but not late post-traumatic seizures.

Thus, it is not recommended to maintain antiepileptics beyond the first 7 days after injury as a prophylactic measure (as opposed to using for the treatment of ongoing seizures).<sup>73</sup> While valproic acid and phenytoin, they were approximately equally effective, however valproic acid was associated with a higher mortality rate so is not usually employed in this setting.<sup>74</sup>

## 8.5 Anticoagulation

### 8.5.1 Prophylactic Anticoagulation

Patients with TBI have a high incidence of deep vein thrombosis (DVT) without any prophylactic treatment with estimates ranging from 33–54%.<sup>75</sup> The risk of developing a DVT decreases to 25% in those treated with sequential compression devices (SCDs).<sup>76</sup> Factors that increase the risk of DVT are extracranial injuries, increasing age, subarachnoid hemorrhage, Injury Severity Score greater than 15, and increased severity of TBI.<sup>75,77</sup> Chemical prophylaxis such as heparin or enoxaparin, can decrease the risk of DVT, but may carry the risk of worsening intracranial hemorrhage.<sup>78,79,80,81,82,83</sup> There is no consensus/convincing evidence in the literature regarding the appropriate medication, dosage, and timing for initiating DVT prophylaxis.

### 8.5.2 Reversal of Prior Anticoagulation Agents

Regular use of aspirin and use of warfarin are independent predictors of death after spontaneous intracerebral hemorrhage.<sup>84</sup> Patients who regularly use aspirin have a mortality rate over 40% and patients on warfarin have mortality rates up to 68%.<sup>84</sup> While little data exists on outcome after TBI in patients on antithrombotic medications, emerging literature shows similar patterns. Whether hemorrhages actually expand with

aspirin use, despite increased mortality, is not proven.<sup>84,85</sup> A recent multicenter, randomized controlled clinical trial showed that platelet transfusion actually leads to worsened outcomes and thus is not recommended as a routine matter.<sup>85</sup> However, platelet transfusion may be required prior to or during the conduct of intracranial procedures or operations to provide some functioning circulating platelets to aid in clot formation and coagulopathy management. Conversely, reversal of warfarin is routinely employed in the acute management of traumatic hemorrhages (►Table 8.6).<sup>86</sup> Warfarin (vitamin K antagonist) can be reversed with fresh frozen plasma and/or prothrombin complex concentrate (PCC) which contains coagulation factors II, VII, IX, and X.<sup>87</sup> Vitamin K must also be given, and it is imperative that serial laboratory tests be performed as initial reversal may not be durable. The reversal of warfarin with PCC is 4–5 times faster in comparison to administration of fresh frozen plasma, and may be better tolerated in elderly patients or those with congestive heart failure due to the smaller volumes required.<sup>87</sup> With the advent of new agents such as rivaroxaban (factor Xa inhibitor) and dabigatran (thrombin inhibitor) management becomes more difficult.<sup>88</sup> These agents do not reliably reverse with standard methods. Theoretically, PCC should be able to reverse both rivaroxaban and dabigatran.<sup>88</sup> However, in a study in healthy subjects, PCC administration only reversed the effect of rivaroxaban, but not dabigatran.<sup>88</sup> Idarucizumab, is a humanized monoclonal antibody that has been developed to reverse dabigatran and has recently been approved for clinical use but has not been studied in detail in the TBI population.<sup>89</sup>

### 8.5.3 Skull Fractures

Skull fractures are a strong predictive factor for the presence of underlying intracranial hemorrhage.<sup>90,91</sup> However, they may occur in isolation with no significant brain injury.

**Table 8.6** Anticoagulation agents and reversal

| Anticoagulation agent | Mechanism of action  | Reversal agent                    | Mechanism of action           | Half-life                                                                              |
|-----------------------|----------------------|-----------------------------------|-------------------------------|----------------------------------------------------------------------------------------|
| Warfarin              | Vitamin K antagonist | Fresh frozen plasma and vitamin K | All coagulation factors       | Limiting factor is factor VII (4–6 h)                                                  |
|                       |                      | Prothrombin complex concentrate   | Factors II, VII, IX, and X    | Factor II (60–72 h)<br>Factor VII (4–6 h)<br>Factor IX (16–20 h)<br>Factor X (40–45 h) |
| Rivaroxaban           | Factor Xa inhibitor  | Prothrombin complex concentrate   | Factors II, VII, IX, and X    | Factor II (60–72 h)<br>Factor VII (4–6 h)<br>Factor IX (16–20 h)<br>Factor X (40–45 h) |
| Dabigatran            | Thrombin inhibitor   | Idarucizumab                      | Humanized monoclonal antibody | 10–13 h                                                                                |

Underlying pneumocephalus may indicate a basal skull fracture or open fracture. Closed, linear, nondisplaced skull fractures generally do not require surgical intervention but overnight observation may be warranted. Open depressed skull fractures are managed operatively. Fractures involving the frontal sinus often require surgical treatment, especially if the nasofrontal ducts are involved, pneumocephalus suggesting dural lacerations are present, or if they are comminuted and involving the posterior wall and cribriform plate.

### 8.5.4 Basal Skull Fractures

Basal skull fractures are usually extensions of fractures from the cranial vault. They occur in 12–20% of patients after trauma. Basal skull fractures are characterized by several signs on physical examination; raccoon eyes (periorbital ecchymoses), Battle's sign (postauricular ecchymosis), CSF rhinorrhea/otorrhea, hemotympanum, or epistaxis. Cranial nerve (CN) injury can also be indicative of a skull base fracture. Temporal bone

fractures may result in a CN VII and/or CN VIII palsy, anterior basal skull fracture may result in CN I or CN II palsy, and clival fracture (highly lethal) may result in CN VI injury. If a basal skull fracture is suspected or diagnosed, certain precautions must be taken to prevent further complications.

Nasotracheal intubation or insertion of nasogastric tubes must be avoided in case of accidental intracranial violation. This has been associated with mortality in 64% of cases.<sup>92,93</sup>

About 3% of patients will have a CSF leak after trauma. To avoid unnecessary increased ICP, the patient should avoid nose blowing and the use of straws. A bowel regimen (including scheduled stool softeners and laxatives as needed) to avoid Valsalva maneuvers during bowel movements should be implemented as well. Cough suppressants should be employed as needed and physical activity involving straining that could lead to a Valsalva maneuver

should be avoided. The patient's head of bed (HOB) should be elevated to approximately 30° at all times. On subjective questioning, it is important to ask about the presence of a salty or metallic taste at the back of the mouth or if any nasal drip is occurring. Rhinorrhea and otorrhea generally consist of clear, thin, water-like fluid, but may also be pink or blood-tinged if associated fractures or soft tissue injuries exist. Examination of the pillow case for CSF may also be helpful if the patient is unable to communicate this information. The benefit of prophylactic antibiotics is debated.<sup>94</sup> If there is mass effect or underlying hematoma, operative intervention is indicated. Otherwise, conservative management of CSF leak associated with basilar skull fractures (as distinguished from frontal sinus fractures) with bed rest (with HOB elevation) and observation for CSF leak is appropriate. If the CSF leak persists, a lumbar drain can be placed for a period of sustained CSF diversion. If this is not sufficient to stop the CSF leak, then craniotomy or endoscopic approach for a dural repair can be undertaken. If, despite all, a persistent CSF leak occurs, a shunt may be indicated late in the course.

### 8.5.5 Pediatric Skull Fractures

A linear, nondisplaced skull fracture in an infant also does not usually require surgical intervention but there are other considerations that must be undertaken. In infants, the connective tissue overlying the skull fracture more easily expands and given the baseline low circulatory volume, a significant amount of blood may be lost into the overlying cephalohematoma. In addition to physical examination of the cephalohematoma, hematocrit should be measured on presentation and the next day. In addition, the possibility of nonaccidental trauma should be assessed, especially if there is underlying intracranial hemorrhage. If

nonaccidental trauma is suspected, a skeletal survey (X-ray imaging) and MRI of the neuroaxis (brain, cervical, thoracic, and lumbar spine) may be warranted. Although the majority of linear skull fractures are nonoperative, the development of a growing skull fracture (post-traumatic leptomeningeal cyst) is a possibility. These are exceedingly rare and only occur in 0.5–0.6% of skull fractures.<sup>95</sup> They almost always occur in patients less than a year of age and require both a widely separated fracture and a dural tear. If they do occur, it is usually within 6 months of injury and present as a scalp mass. Treatment of a growing skull fracture is repair of the dural defect.

### 8.5.6 Depressed Skull Fractures

Depressed skull fractures are often open, and are associated with infection rates of up to 11% and epilepsy in up to 15%.<sup>30,91</sup> Depressed skull fractures account for 6% of adult skull fractures and 90% are open. The most common location is parietal, followed by temporal, frontal, and occipital. Mortality from injuries in which a depressed skull fracture is present are estimated to be as high as 19%.<sup>30</sup> Surgical indications for elevation of depressed skull fractures include depression greater than the thickness of the skull or beyond the inner table, pneumocephalus indicating a dural laceration in the face of an open fracture, neurologic deficit related to compression of underlying brain tissue, CSF leak, gross contamination, or frontal sinus involvement, with cosmesis occasionally playing a role. A relative but not absolute contraindication to surgery is location of a skull fracture overlying a venous sinus. The surgical decision-making follows the same indications as noted above, with special care being required upon elevating the fracture fragments; the surgeon should be prepared for venous sinus repair and control of venous bleeding prior to opening. Depressed skull fractures



in the pediatric population are most common in the frontal and parietal region. One-third are closed and closed fractures tend to occur more often in younger children because of thin calvaria. Indications for surgery in simple depressed skull fracture in the pediatric population are evidences of dural penetration, persistent cosmetic defect, or focal neurologic deficit. In newborns, a green-stick type of fracture called a “ping-pong ball” fracture can occur where there is a focal indentation of the skull producing a concavity. Without any focal deficit, temporoparietal ping-pong ball fractures usually do not require surgical intervention as the deformity will usually correct as the skull grows. Surgical indications include an associated neurologic deficit, radiographic evidence of intraparenchymal bone fragments, signs of increased ICP from related injuries, growing skull fracture, or CSF leak. Surgery involves opening the cranium adjacent to the depression and pushing out the deformity.

## 8.6 Penetrating Trauma

### 8.6.1 Gunshot Wounds

Gunshot wounds to the head are the most lethal type of head injury and over 90% in some series were fatal.<sup>96,97</sup> Injury from gunshot wounds comes from direct injury to scalp and facial soft tissue, depressed skull fragments and bullet fragments which may injure vasculature, and direct injury to brain tissue from the bullet and from shock waves (blast) secondary to the force from the bullet. On physical examination, in addition to a neurological examination, it is important to note the appearance and location of entry and exit wounds, presence of gunpowder stippling, presence of bone fragments and brain matter in soft tissue, nasal or oral cavities, or external auditory canals, as well as the status of the tympanic membranes. A non-contrast CT is needed to identify the

bullet tract, intracranial hemorrhage patterns, status of cisterns, midline shift, and cerebral edema CT imaging also helps identify skull fractures as well as bullet and bone fragment locations CT angiography is helpful in identifying vascular injuries and should be done at the time of presentation if feasible. Formal angiography may also be required upon presentation. ICP may be elevated so HOB should be elevated and mannitol administered if no hypotension is present. An antiepileptic (phenytoin) should be administered. The decision to operate and indications to do so are controversial. Level of consciousness is the most important prognostic factor.<sup>97</sup> Path, trajectory, type of gun, and caliber of the bullet are also important for prognosis and surgical decision-making.



For penetrating non-missile injuries that are not bullets, the foreign body should not be removed until the patient is in the operating room if possible. If there is an identical object available to compare, it can be helpful in planning for extrication.

Intracranial hemorrhage on CT is also a poor prognostic factor. Suicide attempts are more likely to be fatal. The goals of surgery are debridement of devitalized tissue, evacuation of hematomas, removal of accessible bone fragments, removal of accessible bullet fragments, obtaining hemostasis, dural closure, repair of depressed skull fractures, and decompression of edematous hemispheres. While surgery is not done strictly for forensic purposes (identification of entry/exit wounds, retrieval of bullet fragment), if surgery performed, evacuated bullet fragments should be submitted to the proper authorities. Delayed imaging with angiography should be done to rule out traumatic pseudoaneurysm, generally at 7–14 days post-injury and possibly also later. These are more likely for trajectories

involving major vascular anatomy, such as the anterior and middle cerebral artery complexes, but may occur in distal branches.

Trajectories that cross midline at the level of the ventricles, involve the basal ganglia or zona fatalis (suprachiasmatic region), include the posterior fossa or brainstem, or involve multiple lobes have poorer prognoses.

The protruding object should be stabilized as best as possible during transportation. CT angiography is warranted if the object passes through a region concerning for vascular injury, near the dural sinuses or there is evidence of arterial bleeding. Perioperative antibiotics and tetanus administration are appropriate in these patients, and more prolonged antibiotics may be necessary if organic material (e.g., tree branches or sticks) are involved.

### Pearls

- In TBI, primary injury occurs from impact and secondary injury occurs due to a variety of pathophysiological processes resulting from that impact.
- EDHs requiring surgery must be done emergently to reduce mortality.
- Apart from mass effect, SDHs are often associated with damage to the underlying brain parenchyma, which can explain morbidity despite timely evacuation.
- Contusions are caused by a variety of mechanical forces to the brain, including acceleration/deceleration, rotational torque, and brain contact with the skull, especially the bony prominences at the skull base.
- Decompressive craniectomies should be large enough to adequately decompress the hemisphere and extend to the middle (temporal) fossa floor to be effective at improving both neurologic morbidity and mortality.

## 8.7 Top Hits

### 8.7.1 Questions

1. What kind of hemorrhage crosses suture lines?
  - a) Subdural hemorrhage
  - b) Epidural hemorrhage
  - c) Subarachnoid hemorrhage
  - d) All of the above
  - e) None of the above
2. What is the most important prognostic factor in the GCS?
  - a) Eye component
  - b) Voice component
  - c) Movement component
  - d) All are equally important
3. Which of the following meets operative criteria for a subdural hemorrhage?
  - a) 3 mm thickness, 3 mm midline shift
  - b) 8 mm thickness, 3 mm midline shift
  - c) 3 mm thickness, 8 mm midline shift
  - d) 8 mm thickness, 8 mm midline shift
  - e) All of the above
  - f) c and d
4. Which of the following are operative indications for skull fractures?
  - a) Open fracture
  - b) Depression of the skull fracture below the level of the inner table
  - c) Associated intracranial hemorrhage
  - d) Fracture over the venous sinus
  - e) b and c
  - f) a, b and c
  - g) All of the above
5. What kind of hemorrhage would you expect in a person who has a "lucid interval"?
  - a) Subdural hemorrhage
  - b) Epidural hemorrhage

- c) Subarachnoid hemorrhage  
d) All of the above  
e) None of the above
6. An elderly individual presents with confusion after falling 1 week ago, what kind of hemorrhage do they probably have?  
a) Subdural hemorrhage  
b) Epidural hemorrhage  
c) Subarachnoid hemorrhage  
d) All of the above  
e) None of the above
7. A child is hit in the pterional region with a baseball, what vessel is most likely to be at risk for rupture causing hemorrhage?  
a) Carotid artery  
b) Internal jugular vein  
c) Middle meningeal artery  
d) Bridging veins  
e) None of the above
8. What structure is being compressed in a person who presents with a "blown" pupil?  
a) Cranial nerve I  
b) Cranial nerve II  
c) Cranial nerve III  
d) Cranial nerve IV  
e) Cranial nerve VI
9. A baby presents with bilateral acute on chronic subdurals, what other imaging should be obtained?  
a) Abdominal ultrasound  
b) Chest XR  
c) MRI brain  
d) Skeletal survey

- over the tentorium. Epidurals can cross the midline and the tentorium.
2. c. The motor component is the most important prognostic factor in GCS.
3. f. c (3 mm thickness, 8 mm midline shift) and d (8 mm thickness, 8 mm midline shift).

| Type of hemorrhage          | Criteria for operation                                                                                                            |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| Subdural hemorrhage         | > 1cm thickness or > 0.5 cm midline shift                                                                                         |
| Epidural hemorrhage         | > 30 cm <sup>3</sup> volum (volume is calculated by $\frac{1}{2} \times \text{length} \times \text{width} \times \text{height}$ ) |
| Intraparenchymal hemorrhage | > 30 cm <sup>3</sup> volume                                                                                                       |

4. f. a (open fracture), b (depression of the skull fracture 12 mm in thickness) and c (associated intracranial hemorrhage).
5. b. Epidural hemorrhages often have a lucid interval because of the lower likelihood of underlying brain injury.

| Operative Indications                                                                                                                                                                                                                                                                                                | Contraindications                                                                                                                         |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>Open fracture</li> <li>Depression of the fracture greater than the thickness of the calvarium or below the inner table</li> <li>Cosmetic</li> <li>Gross contamination</li> <li>Intracranial hemorrhage</li> <li>Dural violation</li> <li>Frontal sinus involvement</li> </ul> | <ul style="list-style-type: none"> <li>Fractures over venous sinuses may be relative contraindications depending upon location</li> </ul> |

## 8.7.2 Answers

1. a. SDHs will cross the suture lines but not the midline over the convexity (secondary to the sagittal sinus). While they can cross the tentorium, it is more common to see blood layered

- Rapid deterioration ensues due to the often arterial nature of the bleeding. Lucid intervals can occur in other types of injury as well.
6. a. Possibly from an acute on chronic or chronic subdural. Tearing of the bridging veins causes subdural hemorrhages.
7. c. The middle meningeal artery is at risk. This will cause an epidural hemorrhage.
8. c. Uncal herniation causing compression of CN III.
9. d. There should be a high suspicion of nonaccidental trauma (abuse). A skeletal survey will help make this determination.

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# 9 Spinal Trauma

Katherine E Wagner, Jamie Ullman

## 9.1 Introduction

Traumatic injuries to the spinal column and cord can be seen following motor vehicle crashes, violence, sports, and even falls. These patients should be evaluated promptly by the trauma team and spine surgeon. The basic tenets of resuscitation apply; airway, breathing, and circulation should be evaluated first, as part of the standard primary survey. An evaluation of rectal tone is an essential part of the assessment of neurological function in patients with potential spinal trauma. Furthermore, patients may have concomitant head trauma, long bone fractures, and internal injuries. During the initial postinjury period, patients are generally kept in a hard cervical collar until it is “cleared,” clinically and/or radiographically.

## 9.2 Examination

The American Spinal Injury Association (ASIA) scale, outlined in ► Table 9.1, is a useful tool in the acute setting, and is ideally performed within 72 hours of the injury. Sometimes, patients with devastating injuries show signs of improvement after 24–72 hours, so the most meaningful score is obtained later.<sup>1</sup>

## 9.3 Imaging

The decision to image a patient’s spine depends on their level of wakefulness and ability to participate in a neurological examination.

Awake patients with *no neurological symptoms* or neck pain, *no distracting injuries* with a full, painless range of motion at the neck do *not* require immobilization or imaging.

**Table 9.1** American Spinal Injury Association grading system

| Grade | Description                                                                                                                                               |
|-------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| A     | Complete injury: No sensory or motor function preserved below the injury, including the sacral elements S4-S5                                             |
| B     | Incomplete injury: Sensory, but not motor, function preserved below the neurological level                                                                |
| C     | Incomplete injury: Motor function is preserved below the neurological level. More than half of the key muscles below the level have < 3 out of 5 strength |
| D     | Incomplete: Motor function is preserved below the neurological level. More than half of the key muscles below the level have ≥ 3 out of 5 strength        |
| E     | Normal motor and sensory function                                                                                                                         |

These guidelines stem from the National Emergency X-Radiography Utilization Study (NEXUS) results.<sup>2</sup> Criteria for imaging a patient with suspected blunt vascular injury are described later.

Awake patients with neurological symptoms should remain in a collar and get a cervical CT scan. If the CT is negative but the patient continues to have symptoms, including pain or numbness, an MRI with short inversion time inversion recovery (STIR) sequences should be obtained within 48 hours to evaluate the disc spaces, cord, and ligaments. If that is unremarkable, flexion/extension X-rays are next. If no injury or instability is



found, the collar can be used for comfort. Patients who cannot safely enter the MRI machine (i.e., they have incompatible hardware) can be evaluated with flexion/extension films.<sup>2</sup>

Obtunded patients should have a CT scan of the neuroaxis as part of their trauma workup and pan-scan.

One school of thought suggests obtaining an MRI of the cervical spine within 48 hours if there is a need to remove the collar. However, others have suggested that clearance based on careful review of CT scan alone is sufficient in an obtunded trauma patient.

## 9.4 Shock

Patients can present in hemorrhagic shock from other injuries, or in frank spinal shock with spinal cord injury (SCI) above T1.

Avoiding hypoxia and hypotension is crucial in minimizing secondary injury to the spinal cord.

Elevating the mean arterial pressure to 85–90 mmHg with monitoring in an intensive care unit can result in better outcomes.<sup>3</sup> Of note, return of the bulbocavernosus reflex indicates complete SCI as opposed to just spinal shock.

## 9.5 Steroids

There is no Class I evidence supporting the use of steroids like methylprednisolone in patients with SCI. Animal models with very early administration of steroids suggest a potential benefit. However, the National Acute Spinal Cord Injury Studies (NASCIS)

I, II, and III do not demonstrate convincingly sustained improvements in patient outcomes after administration.<sup>4,5</sup> There is strong evidence linking steroids to gastrointestinal hemorrhages<sup>4</sup> and wound infections.<sup>5</sup>

## 9.6 Immobilization

Cervical collars may be hard (e.g., Aspen or Miami J) or soft.

- Soft collars do not limit motion but can be useful after surgery for comfort.
- The compressed foam Philadelphia collar may be utilized by emergency medical technicians to limit motion in the cervical spine.

The sterno-occipital-mandibular immobilization device (SOMI brace) has an anterior piece, rigid shoulder supports, and removable mandibular support.

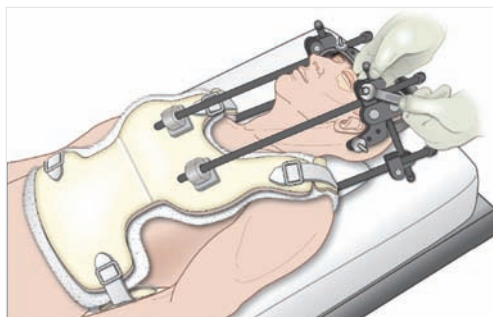
- The SOMI can help limit motion at the craniocervical junction, help maintain alignment, and minimize motion in the lower cervical spine and cervicothoracic junction.<sup>6</sup>
- The Minerva brace, a cervicothoracic orthosis, is a similar device in the market.

The halo vest offers another form for rigid fixation of the occipital cervical junction (► Fig. 9.1).<sup>6,7</sup>

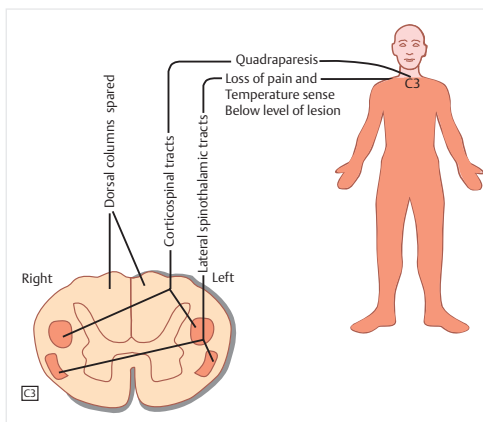
- The pins need to torque to 8 lb at 24 and 48 hours after placement.
- Excessive tightening can penetrate or fracture the skull.<sup>7</sup>

“Snaking” or excessive motion of the lower cervical spine is a potential issue with the halo vest.

Thoracolumbosacral and lumbosacral orthoses (TLSO/LSO) minimize movement of the torso.



**Fig. 9.1** Placement of the Halo. (Reproduced from Ullman J, Raksin P, Atlas of Emergency Neurosurgery, 1st edition, ©2015, Thieme Publishers, New York.)



**Fig. 9.2** Anterior cord syndrome. (Reproduced from Alberstone C, Benzel E, Najm I et al, Anatomic Basis of Neurologic Diagnosis, 1st edition, ©2009, Thieme Publishers, New York.)

## 9.7 Spinal Cord Syndromes

These result from incomplete injuries to the cord.

### 9.7.1 Anterior Cord Syndrome

- Mechanism: Cord infarction in areas supplied by the anterior spinal artery (► Fig. 9.2).
- Deficit: Sudden-onset paraplegia or quadriplegia; loss of pain and

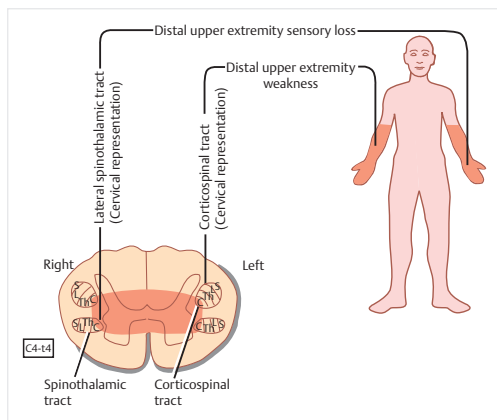
temperature below the level of the lesion, and preserved posterior column function.

- Outcomes: Poor prognosis; most patients have no or minimal improvement in their deficits.<sup>8</sup>

### 9.7.2 Central Cord Syndrome

It is the most common spinal cord syndrome (► Fig. 9.3).<sup>9</sup>

- Mechanism: Neck extension
  - Usually occurs in patients with bony spurs, thickened ligaments, or herniated discs who suffer



**Fig. 9.3** Central cord syndrome. (Reproduced from Alberstone C, Benzel E, Najm I et al, *Anatomic Basis of Neurologic Diagnosis*, 1st edition, ©2009, Thieme Publishers, New York.)

hyperextension from a fall or motor vehicle accident (MVA).

- Bimodal distribution: Younger patients with congenital stenosis and severe traumas and older patients with degenerative stenosis and even minor traumas.<sup>9,10</sup>
- The long tract fibers in the center of the cord may swell and, since they are located in a watershed vascular territory, may suffer temporary ischemia.
- Deficit: Greater motor deficits in the upper extremities than the lower, distal more than proximal. Sensory findings may vary, and some patients become frankly myelopathic.
- Outcomes: Prognosis is guarded. Lower extremity and bowel/bladder function can recover, while upper extremity function is variable.<sup>9,10</sup>
- There is controversy about the timing of treatment.<sup>9</sup>
  - Some advocate laminectomy and possible fusion on the same admission, while others will do the case electively after the patient has some physical therapy/rehabilitation.
  - If the patient deteriorates, urgent surgery is warranted.
  - Steroid use is also controversial.

### 9.7.3 Posterior Cord Syndrome

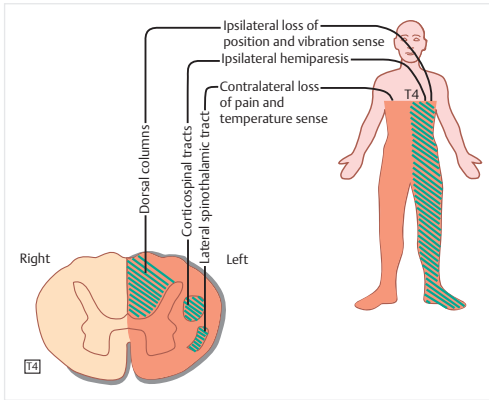
- Mechanism: Can result from injury to the posterior spinal artery.
- Deficit: Results in pain and paresthesias.
- Relatively rare.

### 9.7.4 Brown-Séquard Syndrome (► Fig. 9.4)

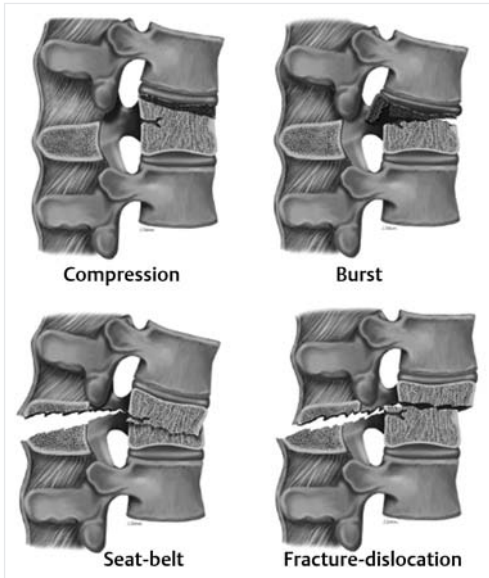
- Mechanism: Cord hemisection, often traumatic.<sup>11</sup>
- Deficit: Ipsilateral motor paralysis; loss of proprioception, vibration sense with contralateral loss of pain and temperature.
- Outcomes: Variable prognosis.

## 9.8 Spinal Column Model

White and Panjabi put forward the concept of spinal stability as the ability of the spine to limit movements under normal, physiological conditions to prevent injury to or irritation of the spinal cord and nerve roots and prevent deformity and mechanical pain. Francis Denis proposed the widely used three-column model for evaluating spine



**Fig. 9.4** Brown-Séquard syndrome. (Reproduced from Alberstone C, Benzel E, Najm I et al, *Anatomic Basis of Neurologic Diagnosis*, 1st edition, ©2009, Thieme Publishers, New York.)



**Fig. 9.5** The Denis classification spinal columns—anterior, middle, and posterior, and major spinal fractures. (Reproduced from Jallo J, Vaccaro A, *Neurotrauma and Critical Care of the Spine*, 1st edition, ©2008, Thieme Publishers, New York.)

trauma (► Fig. 9.5).<sup>12,13,14,15</sup> His model was designed for the thoracic and lumbar spine, but can be applied to the lower cervical spine as well. Fractures involving one column are generally stable; fractures involving two or three columns are considered unstable and may require surgery.<sup>12,13,14,15</sup> Denis also

outlined five types of fractures seen in the thoracolumbar region (refer to thoracolumbar injury section).

- The anterior column: Anterior longitudinal ligament (ALL), anterior two-thirds of the vertebral body and disc, including the annulus fibrosus.

- The middle column: Remaining posterior third of the vertebral body and disc, including the annulus fibrosus, posterior longitudinal ligament (PLL).
- The posterior column: Structures posterior to the PLL; pedicle, facet joints, ligamentum flavum, interspinous ligaments.

The rest of this chapter outlines various spinal injuries and their management.

## 9.9 Cervical Spine

Paramedics generally perform spinal immobilization and place a cervical collar on patients who may have a spinal column injury. Up to 25% of SCIs occur after the trauma, secondary to the way the patient is handled and transported.<sup>3</sup> Spinal immobilization is contraindicated in penetrating trauma (i.e., gunshots, stabblings), as it has increased morbidity and mortality with higher risk of increased intracranial pressure, pressure sores, and aspiration.<sup>3</sup>

Injuries at or above C3 can produce bulbar-cervical dissociation.

These patients die unless cardiopulmonary resuscitation is started shortly after injury. Survivors are quadriplegic and ventilator dependent.

## 9.10 Cervical Injuries

### 9.10.1 Blunt Cerebrovascular Injuries

- Blunt-force trauma to the head, face, or neck or high-speed deceleration to the thorax can cause blunt cerebrovascular injuries (BCVI).
- Injuries to the carotid and/or vertebral arteries may present as devastating

strokes. There is still controversy about which patients should be screened.

The Denver criteria (below) can be used to determine which patients should undergo CT angiogram of the head and neck.

- The criteria are divided into signs and symptoms of a BCVI and risk factors. Patients with any of these should be considered for CTA.
- Treatment is generally anticoagulation or antiplatelet therapy.<sup>16,17</sup>
  - Signs and symptoms: Focal neurological deficit, especially with an examination inconsistent with patient's CT head; stroke on CT head; arterial hemorrhage, expanding hematoma; cervical bruit.
  - Risk factors: Le Forte II or III fractures; basilar skull fractures involving carotid canal; cervical spine fractures, especially those involving transverse foramen; diffuse axonal injury with Glasgow Coma Scale less than 6 or anoxic brain injury with hanging or near hanging mechanism.

### 9.10.2 Atlanto-occipital Dislocation

- Generally seen in high-energy traumas, more common in children.<sup>18</sup>
- Presentation can vary from minimal neurological findings to bulbar-cervical dislocation causing respiratory arrest and death.<sup>18</sup>
- Type I injuries: The occiput is displaced anteriorly to atlas.
- Type II injuries: The occiput is distracted away from the atlas.
- Type III injuries: The occiput is displaced posteriorly to atlas.

- Radiographic Measurement: Distraction via a cervical collar or traction is contraindicated.<sup>18</sup>
  - *Powers ratio* is defined as the distance from the tip of the basion to the posterior arch of C1 divided by the distance from the opisthion to the anterior arch of C1. Normal is a ratio < 1.
  - *Basion-Dens Interval* (BDI): normal < 12 mm on plain radiographs.
- A halo orthosis may be used to immobilize the neck, especially before definitive surgery; some authors state all patients require a posterior occipital-cervical fusion.<sup>18</sup>
- Patients with incomplete injuries may improve with stabilization.

### 9.10.3 Occipital Condyle Fractures

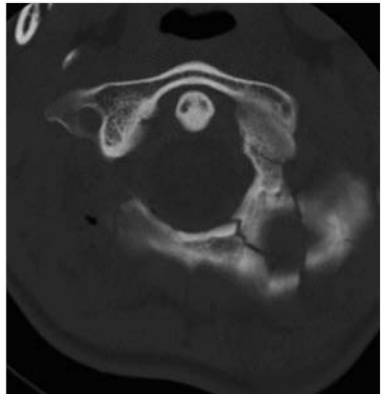
- Patients have head trauma and skull fractures (► Fig. 9.6).

Look for condyle fractures in trauma patients with lower cranial nerve palsies (usually cranial nerve [CN] XII; CN VI, IX, and X can also be affected).

- Persistent neck pain, or reduced mobility in the upper cervical spine.
- Displaced bone fragments may compress the brainstem.
- Evaluate for rotatory subluxation and concomitant traumatic brain injury.<sup>19,20</sup>
- There are two major classification schemes for these fractures (► Table 9.2).

### 9.10.4 Atlanto-axial Dislocation

- Refers to loss of stability between atlas and axis (C1 and C2).
- Increased atlanto-dens interval.



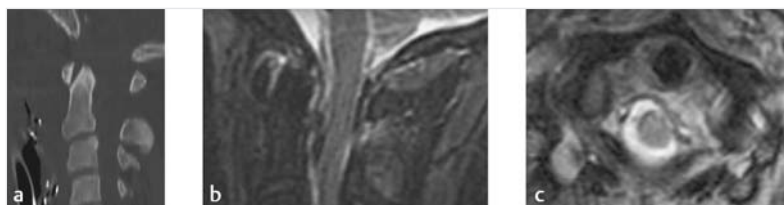
**Fig. 9.6** CT scan with fracture of the occipital condyle and basilar skull. (Reproduced from Jallo J, Vaccaro A, Neurotrauma and Critical Care of the Spine, 1st edition, ©2008, Thieme Publishers, New York.)

- Normal in Adults < 2–3 mm, Children < 5 mm
- Can be traumatic or secondary to certain diseases. ► Fig. 9.7 shows an injury causing atlanto-axial dislocation. The transverse ligament is now just attached to a bone fragment as the result of a comminuted C1 fracture. The C1 lateral mass is displaced and the spine is unstable.
  - Associated conditions include Down Syndrome, Morquio Syndrome, and rheumatoid arthritis.<sup>21</sup>
  - A purely traumatic atlanto-axial dislocation in the absence of another predisposing risk factor is rare—evaluate patients with the above conditions carefully, and rule out these conditions in patients with unexplained deficits localizing to the high cervical cord.<sup>21</sup>
  - Treatments include cervical traction and posterior fusion with or without a transoral odontoidectomy.

**Table 9.2** Classifications for evaluating occipital condylar fractures

|                        | Type | Description                                         | Stability | Treatment                 |
|------------------------|------|-----------------------------------------------------|-----------|---------------------------|
| Anderson and Montesano | I    | Comminuted; no/minimal displacement                 | Stable    | Collar                    |
|                        | II   | Direct trauma and associated basilar skull fracture | Stable    |                           |
|                        | III  | Avulsion fracture involving the alar ligament       | Unstable  | Halo or surgical fixation |
| Tuli et al             | 1    | Nondisplaced                                        | Stable    | Collar                    |
|                        | 2A   | Displaced, ligaments intact                         | Stable    |                           |
|                        | 2B   | Displaced, with craniocervical instability          | Unstable  | Halo or surgical fixation |

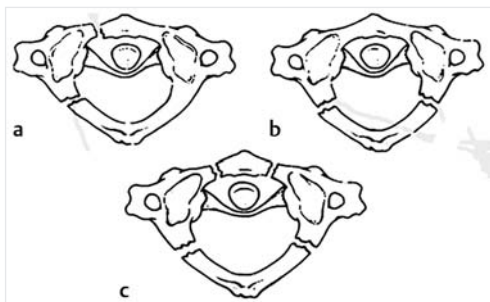
Source: Adapted from Oskouian R, Shaffrey C, Neurotrauma and Critical Care of the Spine, ©2009, Thieme Publishers, New York.



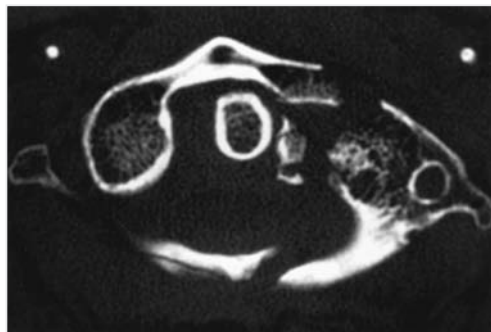
**Fig. 9.7** Anterior atlanto-occipital dislocation. **(a)** Dissociation of the bony elements. **(b)** Decreased basion-dens interval resulting from a posterior ligamentous complex injury. **(c)** Epidural hematoma. (Reproduced from Jallo J, Vaccaro A, Neurotrauma and Critical Care of the Spine, 1st edition, ©2008, Thieme Publishers, New York.)

## 9.11 C1 Fractures

- Isolated C1 fractures do not usually result in deficits unless they are not properly managed (► Fig. 9.8 and ► Fig. 9.9).<sup>19</sup>
- Evaluate the integrity of the transverse ligament.
- A Jefferson fracture is a C1 burst fracture, classically with fractures in both anterior and both posterior arches (► Fig. 9.8).<sup>19</sup>
  - Associated with diving head first into shallow water (i.e., axial loading onto the head).
  - If the transverse ligament is intact, the cervical spine should be immobilized for 10–12 weeks (► Fig. 9.9). If it is NOT intact, a C1–C2 fusion or halo fixation for 12 weeks is advised.
- The Rule of Spence can help determine the stability of the transverse ligament. The left and right C1 lateral masses



**Fig. 9.8** Common C1 fractures. (a) Lateral mass fracture. (b) Posterior arch fracture. (c) Classic Jefferson fracture. (Reproduced from Jallo J, Vaccaro A, Neurotrauma and Critical Care of the Spine, 1st edition, ©2008, Thieme Publishers, New York.)



**Fig. 9.9** Comminuted C1 lateral mass fracture and associated atlanto-axial instability. The attachment of the transverse ligament to the spinal column has been injured. (Reproduced from Bambakidis N, Dickman C, Spetzler R et al, Surgery of the Craniovertebral Junction, 2nd edition, ©2012, Thieme Publishers, New York.)

generally do not overhang C2. If the sum of the overhang of the left and right C1 lateral masses is greater than 7 mm, the transverse ligament may be injured, and should be evaluated with a treatment algorithm for isolated atlas fractures is shown in ► Fig. 9.10.<sup>19</sup>

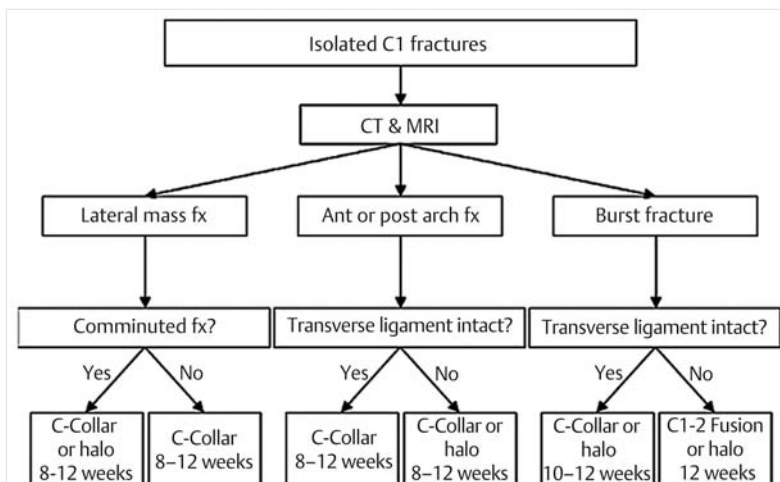
- They are generally stable and treated with a collar, unless atlanto-occipital dislocation is present. Then options include surgery or immobilization with a halo or collar.

### 9.11.1 Odontoid (Dens) Fractures

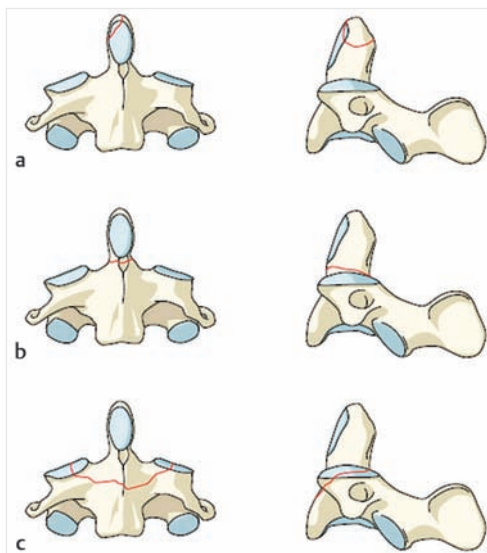
- Most common C2 (axis) fractures; make up 7–14% of traumatic cervical spine injuries.
- Often present with high cervical pain; mechanism of injury can vary.<sup>19,20</sup>
- Type I fractures involve the tip of the dens (► Fig. 9.11).

Type II fractures occur where the odontoid meets the vertebral body. These are the most common odontoid fractures and have a high rate of nonunion. These are generally unstable and treated with surgery or immobilization. If comminuted fragments are present, the fracture is unstable and surgery should be considered.





**Fig. 9.10** Management of isolated C1 fractures. (Reproduced from Jallo J, Vaccaro A, Neurotrauma and Critical Care of the Spine, 1st edition, ©2008, Thieme Publishers, New York.)



**Fig. 9.11** Dens fracture types (a) Type I. (b) Type II. (c) Type III. (Reproduced from Chapman J, Dettori J, Norvell D, Spine Classifications and Severity Measures, 1st edition, ©2009, Thieme Publishers, New York.)

- Type III fractures go through the vertebral body and are generally stable. Treat with a cervical collar unless there are other injuries rendering the spine unstable.

### 9.11.2 Hangman's Fractures

- Vertical or oblique fractures through the C2 pars interarticularis, disconnecting the posterior arch from the vertebral body as shown in ►Fig. 9.12.<sup>22</sup>
- Usually caused by hyperextension (MVA or diving injury); the posterior C1 ring and C2-C3 disc should also be evaluated for injury.
- Most isolated fractures can be managed with a collar; displaced, isolated fractures can be managed with a halo brace.
- Surgery may be indicated if the C2-C3 facets are locked or the patient has other injuries rendering the spine unstable.

### 9.11.3 Other C2 Fractures

- Isolated, nondisplaced fractures of the C2 lamina, vertebral body, and facets are generally stable and heal in a collar.<sup>22</sup>

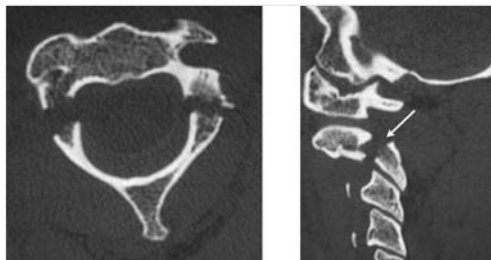
- C2 fractures seen in combination with C1 fractures require careful evaluation for spinal stability.

### 9.11.4 Subaxial Cervical Spine Injuries

- The most commonly injured level is C5-C6.<sup>19</sup>
- The three kinds of injuries are compression, flexion/extension/distraction, and rotation (►Table 9.3).
- The table includes bony (fracture) and ligamentous (whiplash) injuries.  
►Fig. 9.13 shows a severe fracture-dislocation injury.

### 9.11.5 Jumped Facets

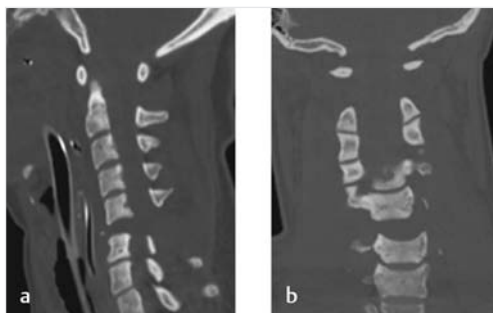
- Jumped facets can result in severe injury to the spinal cord and nerve roots.<sup>19</sup>
- The facets may be perched or frankly locked depending on the severity of injury.
- Unilateral injuries can occur when the spine is rotated. Bilateral injuries usually result from flexion or extension that disrupts the posterior ligaments.  
►Fig. 9.14 shows perched and locked facet injuries in the cervical spine.



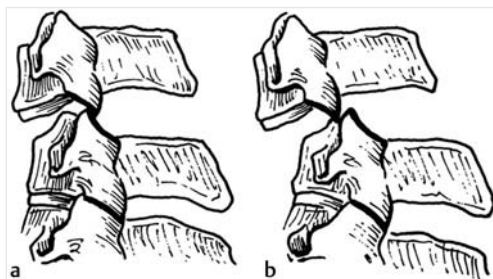
**Fig. 9.12** Hangman's fracture involving the bilateral C2 pars. (Reproduced from Meyers S, *Differential Diagnosis in Neuroimaging: Spine*, 1st edition, ©2016, Thieme Publishers, New York.)

**Table 9.3** Classification of cervical injuries

|                                                      | Injury                                                                                                                                                                                               | Mechanism                                                                     | Stability and Treatment                                                                                                      |
|------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| Compression                                          | Anterior compression (wedge fracture)                                                                                                                                                                | Axial loading<br>+/- flexion/extension                                        | Stable.<br>Generally heal with external immobilization                                                                       |
|                                                      | Comminuted fracture (burst fracture)                                                                                                                                                                 | Axial loading<br>+/- flexion                                                  | Generally unstable.<br>Treat with fusion, and decompression if needed                                                        |
|                                                      | Teardrop fracture                                                                                                                                                                                    | Hyperflexion-compression                                                      | Unstable—evaluate disc space and ligaments on MRI.<br>Treat with fusion, decompress if needed                                |
| Flexion/Extension/Distractio                         | <b>These injuries below are unstable if the PLL/posterior annulus fails AND there is anterolisthesis, facet malalignment, end plate angulation &gt; 10 degrees, or vertebral segment distraction</b> |                                                                               |                                                                                                                              |
|                                                      | Whiplash with neurologic injury                                                                                                                                                                      | Flexion/extension                                                             | Stable.<br>Management is controversial and can include collar and physical therapy                                           |
|                                                      | Severe whiplash (sprain)                                                                                                                                                                             | Flexion/extension                                                             | Re-evaluate integrity of posterior ligaments; treat with collar, physical therapy                                            |
|                                                      | Bilateral facet fracture-dislocation                                                                                                                                                                 | Distraction + flexion/extension with failure of posterior ligamentous complex | Unstable: Closed or open reduction and internal fixation/fusion.<br>Evaluate for herniated discs with MRI                    |
|                                                      | Unilateral facet fracture                                                                                                                                                                            | Lateral flexion + rotation                                                    | Stable if there is no significant subluxation, dislocation, or kyphosis.<br>Treat with collar                                |
|                                                      | Fracture separation of articular pillar                                                                                                                                                              | Extension, compression, + rotation                                            | Evaluate for other injuries to determine if stable.<br>Treatments include collar, halo, surgery.                             |
|                                                      | Unilateral dislocation                                                                                                                                                                               | Lateral flexion + rotation                                                    | A perched facet is unstable.<br>Evaluate for nerve root and cord injury.<br>Treatments include reduction and halo or fusion. |
| Abbreviations: PLL, posterior longitudinal ligament. |                                                                                                                                                                                                      |                                                                               |                                                                                                                              |



**Fig. 9.13** Fracture-dislocation injury at C5–C6. (Reproduced from Fehlings M, Vaccaro A, Boakye M et al, *Essentials of Spinal Cord Injury, Basic Research to Clinical Practice*, 1st edition, ©2012, Thieme Publishers, New York.)



**Fig. 9.14** (a) Perched. (b) Locked facets. (Reproduced from Benzel E, *Biomechanics of Spine Stabilization*, 3rd edition, ©2015, Thieme Publishers, New York.)

- The bony injury needs to be reduced.
  - Unilateral injuries may be reduced in traction and then a halo or surgical fusion.
  - Closed traction is controversial in bilateral injuries. Generally, patients will need surgery, with either an anterior or posterior approach and intraoperative reduction.
  - Some surgeons prefer to get an MRI before reduction, to evaluate for disc herniations.<sup>19</sup>

## 9.12 Additional Principles for Cervical Trauma

- Unless atlanto-occipital dislocation is present (i.e., the transverse ligament is torn in its midportion) most isolated

ligamentous injuries can be managed with a cervical collar alone. Follow-up in 4–6 weeks and evaluate range of motion and cervical tenderness.

- Patients with rheumatoid arthritis, Down syndrome, ankylosing spondylitis, and other conditions predisposing them to cervical instability require imaging and careful examination following trauma.
- Patients with hardware from previous cervical spine surgery need careful evaluation. X-rays, CT, and CT myelograms are useful imaging options. MRI is necessary to evaluate the spinal cord, but evaluation of the bones may be limited by artifact.
- Plain radiographs will not show the C7–T1 disc space and facets well; if there is concern for a junctional injury CT and/or MRI are necessary.

## 9.13 Thoracic Injuries

- The spinal cord generally ends at L1-L2, with the cauda equina filling the distal canal.
- Significant force is needed to fracture the thoracic vertebrae. However, the canal is narrow and thus the cord vulnerable to injury from retropulsed or dislodged fragments.<sup>19</sup>
- Lesions above this level can result in complete or incomplete paraplegia and bowel/bladder problems with typical upper motor neuron findings.
- Injuries below may involve different nerve roots and show lower motor neuron findings.
- Conus medullaris syndrome can occur with T12-L1 injury. Damage to the sacral nerve roots results in bowel and bladder problems. Some of the lumbar nerve roots may be intact.
- The three-column approach to evaluating spinal stability is discussed below in the next section and useful for evaluating these injuries.

## 9.14 Thoracolumbar and Lumbar Spine Injuries

Along with his three-column model for determining spinal stability, Denis classified spine injuries into minor injuries—articulating process, transverse process, spinous process, and pars interarticularis fractures, and major injuries—compression, burst, seat-belt type fractures, and fracture-dislocations.<sup>12,13,14,15</sup> These terms can be used for thoracic and lumbar spinal injuries, and the major injuries are shown in ► Fig. 9.5.

- Minor injuries are generally stable, but patients should be evaluated for other injuries.

- Compression fractures and burst fractures *may* be stable, depending on the integrity of the ligaments.
- Seat-belt type injuries and fracture dislocations are generally unstable.

The Spine Trauma Group put forth the Thoracolumbar Injury Classification and Severity Score (TLICS) to help guide treatment. See ► Table 9.4 below.

Patients with a TLICS score of less than 4 can usually be treated nonoperatively; score equal to 4 may be treated operatively or nonoperatively; a score of greater than 4 usually warrants operative management.<sup>23,24</sup>

**Table 9.4** The Thoracolumbar Injury Classification and Severity scoring system

### Thoracolumbar Injury Classification and Severity (TLICS) Score

|                               |                                                                                                                                                       |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Morphology                    | Compression: 1 point<br>Burst: 2 points<br>Translation/rotation: 3 points<br>Distraction: 4 points                                                    |
| Posterior ligamentous complex | Intact: 0 point<br>Suspected or indeterminate injury: 2 points<br>Injured: 3 points                                                                   |
| Neurologic involvement        | Intact: 0 point<br>Nerve roots: 2 points<br>Cord/conus medullaris (incomplete): 3 points<br>Cord/conus (complete): 2 points<br>Cauda equina: 3 points |

### 9.14.1 Compression Fractures

- Occur when the anterior column fails.
- The middle column is intact, so it can serve as a hinge.
- The posterior column may fail, depending on the forces involved.
- Injuries involving more than one column may be unstable.

### 9.14.2 Burst Fractures

Denis also broke thoracolumbar burst fractures into five categories, shown in ►Table 9.5. Purely bony injuries can be managed conservatively in select cases; however, patients who cannot or will not tolerate a brace may get better results with surgery. In two level injuries, the bone or disc of the middle column is injured. These patients may require surgery.

### 9.14.3 Seatbelt Type Injuries

- In a seatbelt type injury, the middle and posterior columns fail when the patient is severely flexed.
- Patients usually present as restrained occupants in a MVA. The anterior column acts like a hinge, and may be injured as well.
- The spine is unstable in flexion.
- One level injuries may present as a Chance fracture, which is a fracture through the vertebral body and neural arch, or as a disruption of the disc and PLL.

### 9.14.4 Fracture Dislocations

- These occur when all three columns fail.
- The mechanism of injury can vary—compression, tension, rotation, or shear.
- Most of these injuries require surgery.<sup>23</sup>

**Table 9.5** Denis classification of burst fractures<sup>11,12,13,14</sup>

| Type | Elements involved                                                                                                           | Typical cause(s) and site(s)                                  |
|------|-----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| A    | Fracture of both endplates without kyphosis. Bone may be retropulsed into the canal                                         | Pure axial load; usually lumbar spine                         |
| B    | Fracture of superior endplate<br>Most common                                                                                | Axial load and flexion; usually thoracolumbar junction        |
| C    | Fracture of the inferior endplate                                                                                           | Axial load and flexion; no particular sites commonly involved |
| D    | Burst rotation fracture with comminution of the vertebral body, possible laminar fractures, and bone retropulsed into canal | Axial load and rotation; mid-lumbar spine                     |
| E    | Burst lateral flexion with fractured posterior wall of the vertebral body and extrusion towards the side of the flexion     | Axial load and lateral flexion                                |

## 9.15 Sacral Fractures

These are less common and are often caused by shear forces.<sup>24</sup> They can injure sacral roots, plexus, and affect pelvic and spinopelvic stability. Injuries below S2 should not affect ambulation, but may be unstable and cause pain that improves after surgical fixation. More medial fractures have higher instances of neurologic injury and worse outcomes.

► Fig. 9.15 outlines the three zones into which Denis divided the sacrum.

- Zone 1: Lateral to the neural foramina.
- Zone 2: Through the neural foramina.
- Zone 3: Central canal.

Roy and Camille also presented another schematic to evaluate Zone 3 fractures. It was later modified by Strange-Vognsen and Lebech, as in ► Fig. 9.16.



**Fig. 9.15** The Denis classification of sacral fractures. (Reproduced from Vialle L, AOSpine Masters Series, Volume 6: Thoracolumbar Spine Trauma, 1st edition, ©2015, Thieme Publishers, New York.)

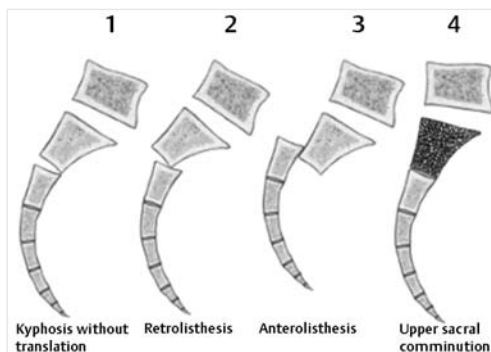
### Pearls

- Remember the ABCs of resuscitation. Look for life-threatening injuries in patients with significant spine injuries. Patients in spinal and/or hemorrhagic shock need aggressive treatment and careful monitoring. Avoid hypotension in patients with spinal cord injuries.
- Make sure to perform a thorough neurological examination on any patient with suspected spine trauma. These findings will guide your decision to image the patient.
- Take extra caution when evaluating patients with spinal hardware or conditions predisposing them to cord compression and serious neurological injury.
- There are a multitude of conditions that make individuals more susceptible to major spine injury from a seemingly trivial injury. When a patient presents with an injury that seems out of proportion to the mechanism, obtain imaging promptly and consider these and other predisposing conditions.

## 9.16 Top Hits

### 9.16.1 Questions

1. An elderly man with a history of untreated cervical stenosis falls down the stairs and immediately complains of numbness and tingling in his hands and weak grip. What is the most likely diagnosis?
  - a) Unilateral jumped facet
  - b) Central cord syndrome
  - c) Atlanto-axial subluxation
  - d) Compression fracture of the C6 vertebra



**Fig. 9.16** Further classification of Denis type 3 sacral fractures. (Reproduced from Vialle L, AOSpine Masters Series, Volume 6: Thoracolumbar Spine Trauma, 1st edition, ©2015, Thieme Publishers, New York.)

2. A 25-year-old man is extricated from a burning vehicle and arrives to the hospital unconscious, intubated, and with a cervical collar in place. Initial CT head and cervical spine are negative. His injuries include lower extremity fractures requiring orthopedic surgery and a pneumothorax requiring a chest tube. He is stabilized, extubated, and awake and alert 2 days later. What is the best way to assess the need for his cervical collar?
  - a) Confrontational examination only
  - b) Flexion-extension films only
  - c) Confrontational examination and MRI
  - d) Repeat CT
3. Which of the following injuries will most likely require operative intervention?
  - a) A unilateral facet fracture at C4-C5 with intact ligaments on MRI
  - b) Unilateral transverse process fractures at L2 and L3
  - c) An isolated C7 superior endplate fracture
  - d) Bilateral facet fractures at C4-C5

## 9.16.2 Answers

1. **b.** This is a classic presentation of central cord syndrome. Patients present with distal greater than proximal deficits, and many have pre-existing cervical stenosis.
2. **c.** The patient cannot undergo a confrontational examination alone, as he has other painful injuries. Any pain on confrontation may indicate ligamentous injury, which can be confirmed or ruled out on an MRI at this point.
3. **d.** Bilateral facet fractures result in an unstable spine and the patient will need instrumentation to restore stability.

## References

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# 10 Spine

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## 10.1 Introduction

Nontraumatic spine diseases affect millions of people around the world. These can include common age-related degenerative diseases of the cervical, thoracic, and lumbar spines which may present with pain, functional deficiencies, and/or neurological symptoms. Other pathologies include vascular, neoplastic, and/or infectious lesions which can lead to pain from instability or can compress the neural elements leading to symptoms of spinal cord or nerve root compression. In the present chapter, we have provided an overview of these various conditions and outlined their pathophysiology, clinical and radiographic presentations, available treatment options, and clinical outcomes.

## 10.2 Cervical Spine Degenerative Disease

Degenerative conditions of the cervical spine are prevalent and affect nearly two-thirds of the population at some time during their lifetime leading to neck pain and neurological symptoms in a subset of these patients.<sup>1</sup> The baseline prevalence of radiographically-determined cervical disc degeneration, for example, has been previously reported to be 21.7%.<sup>2</sup> While most degenerative conditions of the cervical spine follow a benign clinical course, they can also result in compression of the neural elements leading to myelopathy and/or radiculopathy in addition to local mechanical neck pain.

## 10.3 Degenerative Cervical Myelopathy

Nontraumatic degenerative cervical myelopathy is the most common cause of spinal cord pathology among the elderly and it is estimated to have a prevalence of 605 per million individuals in North America alone.<sup>3,4</sup> These degenerative changes can be subdivided into osteoarthritic (spondylotic) and nonosteoarthritic changes though both types can ultimately lead to symptomatic spinal cord compression or myelopathy. The various subtypes of degenerative cervical myelopathy are considered in the sections below.

### 10.3.1 Cervical Osteoarthritis

### Degenerative Disc Disease

The intervertebral disc, which is an avascular fibrocartilaginous structure,<sup>5</sup> is comprised of an outer annulus fibrosus and the inner nucleus pulposus both of which contain poorly vascularized cells. The former contains fibrocyte-like cells and the latter contains chondrocyte-like cells. Proteoglycans and collagen fibers comprise the extracellular matrix (ECM) in which these cells are suspended. The disc structure allows for the radial redistribution of compressive forces that would otherwise be transmitted longitudinally. However, over time, with excessive or repetitive use, trauma, and/or the influence of genetic or environmental factors, disc degeneration can occur.<sup>4</sup> Guio et al have reported that compromised diffusion of

substances through the intervertebral disc, including oxygen and nutrients, is a central mechanism by which cell death and disc degeneration occur.<sup>5</sup> This degenerative process can lead to a redistribution of forces within the vertebral column, increased stress on the annulus fibrosis, a decrease in intervertebral disc height, disc protrusion or herniation, and osteophyte development.<sup>6</sup>

## Cervical Disc Herniation

### Pathology

Cervical disc herniation occurs when the nucleus pulposus either protrudes (deforms, but does not rupture through the annulus) or extrudes (ruptures through) the annulus fibrosis. This can lead to cervical radiculopathy (due to nerve impingement at the level of the neuroforamen) and/or myelopathy (due to spinal cord compression).<sup>7</sup>



Disc herniations can be classified as either soft or hard, with the latter referring to cases involving osteophytes (calcified bone spurs). Computed tomography (CT) imaging may be warranted in cases whereby a calcified disc is suspected.

Disc herniations with osteophytes are commonly referred to as disc/osteophyte complexes. The intervertebral disc level most commonly affected is C5–C6 followed by C4–C5 and C6–C7.<sup>8</sup>

### Diagnosis

Several imaging modalities can be used for the diagnosis of cervical disc herniations:

- Plain film radiographs: Useful in cases where the index of suspicion is high for associated spondylolisthesis or cervical

fractures and/or dislocations. These can also be used to assess spinal stability by utilizing dynamic flexion and extension images which can provide information about the spine that could not be achieved by the advanced neuroimaging studies that are obtained in a motionless state.

- Magnetic Resonance (MR): is the single most useful test. Not only does an MR supply important anatomical information in cases involving degenerative diseases of the spine, but it is particularly useful in diagnosing inflammatory, infectious, or neoplastic conditions of the cervical spine. It is the imaging modality of choice for delineation of neural elements and for detecting intrinsic diseases of the spine and spinal cord.<sup>9</sup>
    - Key findings include loss of signal intensity of the nucleus pulposus on T2-weighted scans, migration of the disc into the spinal canal with compression of the thecal sac or nerve roots, and narrowing of the intervertebral disc space.<sup>10</sup>
  - CT myelography: Useful for diagnosis of associated spondylosis and/or ligamentous degeneration (including calcification and/or ossification of these structures).
    - There are numerous situations where MRI cannot be performed due to implantation of devices which are not MR-compatible, and in these scenarios, CT-myelography may be the best option to delineate intraspinal structures.
- Symptoms consistent with a herniated cervical disc may include neck pain, arm pain, numbness, tingling, and weakness in the upper extremities. Arm pain in patients with cervical radiculopathy (resulting from disc compression of a cervical nerve root) typically follows a dermatomal distribution.<sup>7</sup> One should be aware of the possibility of position-dependent symptomatic relief in the context of cervical radiculopathy

(i.e., pain that is relieved from holding the arm up on the ipsilateral side of the compressed cervical nerve root and from leaning the head away from the side of neural compression; both of these maneuvers may increase the foraminal surface area and lessen radicular pain symptoms). Cervical myelopathy, on the other hand, can present with ataxia, gait disturbance, bowel and bladder dysfunction, difficulty with fine motor movements, and/or uncoordinated lower and upper extremity movements.<sup>7,11</sup>

A thorough history should be obtained and a detailed musculoskeletal physical examination should be performed in all patients. This includes an assessment of gait, range of motion of the cervical spine, sensation in the dermatomes of the upper and lower extremities, motor strength, reflexes, and cranial nerves. In addition, nerve entrapment syndromes (such as carpal tunnel syndrome) and motor neuron diseases should be ruled out. Findings on physical examination which would support the diagnosis of cervical myelopathy include positive pathological reflexes such as Babinski's and Hoffman's signs as well as the presence of ankle clonus, hyperreflexia of the deep tendon reflexes, and increased muscle tone in the lower extremities.<sup>7,12</sup>

## Treatment

Treatment for cervical disc herniations can involve the use of both nonoperative and operative modalities. In patients presenting with cervical radiculopathy, a nonoperative treatment regimen may be attempted for up to 6 weeks. These employ the use of:<sup>7,13,14,15</sup>

- Anti-inflammatory medications.
- Transforaminal corticosteroid injections.
- Physical therapy.
- Cranioskeletal traction.

However, in patients with persistent radiculopathy, progressive symptomatology, worsened neurological status, or

myelopathy, surgical intervention is usually indicated. Both anterior and posterior approaches have been successfully utilized for removal of the herniated disc and decompression of associated compressed foramina. For herniated cervical discs, an anterior cervical discectomy and fusion (ACDF), is the most commonly performed surgical intervention at this time.<sup>16,17</sup> The 10-year results from a recent prospective study on long-term clinical outcomes following ACDF noted self-reported success rates between 85 and 95%. Alternatively, a cervical arthroplasty can be performed via an anterior approach. An arthroplasty replaces the natural disc with an artificial disc. The 7-year data presented at the Cervical Spine Research Society (CSRS) annual meeting, in 2017, demonstrated excellent long-term performance of arthroplasty devices.<sup>18,19</sup> Of particular importance with arthroplasty is that there needs to be no significant posterior element degenerative disease to achieve the best outcome, and as a result, younger patients tend to be more optimal candidates for arthroplasty surgeries. Posterior decompression has a long track record of success and may or may not be associated with a fusion procedure.<sup>20,21,22,23</sup> Considerations regarding a posterior surgical vector include a perceived approach-related morbidity from the muscular dissection and limited access in cases involving central disc herniations. The results from the Cervical Spondylotic Myelopathy Surgical (CSM-S) trial, which randomized patients to either ventral or dorsal surgery for the management of CSM, will help to better elucidate the effect of surgical approach on patient outcomes, in the near future.<sup>24</sup>

Complications of anterior cervical surgery can include dysphagia, recurrent laryngeal nerve palsy with resultant voice hoarseness, cerebrospinal fluid (CSF) leaks, vascular injury, and postoperative hematomas, which can lead to airway compromise

if not identified and decompressed in a timely manner. Of note, neurosurgeons should also be aware of the potential for the development of adjacent segment disease. This is defined as degeneration of the disc adjacent to an operated level presumably due to an increased load on the neighboring vertebrae.<sup>25</sup>

## Osteophytosis

### Pathology

Due to an increase in mechanical stress on vertebral endplates following degeneration of intervertebral discs, bone spurs (osteophytes) can form along the ventral aspect of the spinal canal resulting in compression of the spinal cord and/or nerve roots.<sup>9</sup> This process is considered a reactive response to segment hypermobility, thus increasing the stability of adjacent vertebrae in the short term, by increasing the surface area of the vertebral endplates.<sup>9,26,27</sup> Simultaneous hypertrophy of the uncinate processes of the subaxial (C3–C7) vertebrae can lead to further stenosis of the intervertebral foramina, which then presents as radiculopathy.<sup>28</sup> It is important to note that osteophytosis typically occur in patients with pre-existing cervical joint degeneration and degenerative disc disease (DDD).

### Diagnosis

CT scan imaging is important for evaluating a patient with suspected spondylosis secondary to osteophyte formation, as it has a higher sensitivity for the detection and delineation of bony structures as compared to MRI or plain radiography. For best evaluations of the foraminal region in cases of disc/osteophyte complex formation, combining a myelogram with a postmyelogram CT scan provides optimal visualization of the neural foramen.

### Treatment

Operative intervention is indicated in patients with progressive clinical myelopathy and radiographic evidence of spinal cord compression or canal stenosis.<sup>29</sup> Early decompression and osteophyte resection can be performed from both anterior and posterior approaches, although there is a risk of injury to the cord from either approach which must be assessed prior to surgery.<sup>29</sup>

## Facet Joint Degeneration

### Pathology

Osteoarthritis of the facet joints (or zygapophyseal facet joints) is commonly seen in older adults.<sup>30</sup> Macroscopic changes include pitting and eventual erosion of the articular cartilaginous surface, fibrosis of the joint capsule, remodeling of the subchondral bone, and osteophyte formation. Cervical DDD can result in a significant increase in the transmission of force across the facet joints due to a decrease in the load-bearing capacity of the disc, leading to eventual facet joint hypertrophy and instability.<sup>31,32,33</sup> Not surprisingly, facet joint osteoarthritis is often detected at the vertebral levels in which evidence of DDD is present. Facet joint hypertrophy can also occur in the context of an age-related decrease in the paraspinal muscle mass which further destabilizes the vertebral column.<sup>34</sup> Spondylolisthesis and degenerative scoliosis are both associated with facet joint osteoarthritis. In the former condition, cartilaginous degradation and osteophyte formation are believed to be the primary mechanisms by which facet joint subluxation occurs resulting in displacement of the adjacent vertebrae.<sup>35</sup>

### Diagnosis

Radiographic signs of facet joint degeneration include (but are not limited to):

hypertrophy of the articular processes, facet joint narrowing, and osteophyte and subchondral cyst formation.<sup>32</sup> CT imaging is the modality of choice for the evaluation of bony pathologies, while MRI is particularly valuable for assessing compression of the neural elements. It is important to note that the radiographic findings of facet joint osteoarthritis do not always correlate with a presentation of neck pain. This may be partly due to the heterogeneity in the criterion used for diagnosing facet joint degeneration on imaging studies.<sup>36</sup> In the cervical spine, radiographic findings consistent with osteoarthritis of the facet joints are most commonly seen at the C3–C5 levels, with a previous study finding the prevalence of cervical facet joint osteoarthritis to be 57% in adults who were 65 years or older.<sup>32</sup>

The clinical presentation of cervical facet joint arthropathy consists of localized neck pain with or without radiation to the upper limbs. Mid-cervical and lower-cervical facet joint arthropathy can present with pain in the posterior scapular region with radiation to the shoulder girdle. Conversely, upper cervical facet joint arthropathy can present with pain in the occipital region and/or headaches.<sup>32,37,38</sup> Herniated discs, fracture-dislocations, neoplasms, and/or spinal stenosis should be ruled out on physical examination and diagnostic workup, as potential etiologies in symptomatic patients.

## Treatment

It is important to carefully evaluate the facet joint morphology when considering surgical treatment options. If significant degeneration of the facets has occurred, a disc arthroplasty procedure is contraindicated. This was an exclusion criteria in the original prospective arthroplasty clinical trials and it is important to avoid arthroplasty when facet disease is present.

## Ligamentous Degeneration

### Pathology

Degenerative cervical myelopathy can also result from age-related changes in the posterior longitudinal ligament (PLL), which is located dorsal to the vertebral body and ventral to the spinal cord. Degenerative changes can include hypertrophy, calcification, and/or ossification of the ligament. However, hypertrophy is believed to precede ossification, with both likely occurring under the influence of a combination of genetic, biomechanical, environmental, and systemic factors.<sup>39</sup>

Ossification of the PLL (OPLL) most commonly occurs within the cervical spine, and has a higher prevalence amongst men, the elderly, and in the Asian subpopulation.<sup>40</sup> The pathogenesis for the condition is not well understood but prior studies have suggested that initial PLL hypertrophy may be secondary to prolapse of the nucleus pulposus of the intervertebral disc.<sup>4</sup>

### Diagnosis

CT imaging has been found to have a better intrarater reliability for the diagnosis of OPLL in comparison to traditional radiography (► Fig. 10.1). MRI may be more useful than CT scanning for evaluating the extent of cord compression or foraminal stenosis in patients presenting with either myelopathy or radiculopathy, respectively. However, it is not as reliable for the diagnosis of a calcified PLL.<sup>41</sup>

While symptomatic presentation is rare in the early stages of OPLL, patients with advanced disease may present with serious neurological symptoms resulting from compression of the neural elements. Early symptoms may include pain, numbness or tingling in the hands, and dysesthesia. Myelopathic symptoms such as gait



**Fig. 10.1** (a) Sagittal computed tomography (CT) scan showing a segmental type ossification of the posterior longitudinal ligament (OPLL). (b) Axial CT scan showing OPLL. (Reproduced from Nader R, Berta S, Gragnaniello C, et al, *Neurosurgery Tricks of the Trade. Spine and Peripheral Nerves*, 1st edition, ©2014, Thieme Publishers, New York.)

disturbances and changes in fine motor skills and/or balance may also be observed.<sup>42</sup> The rate of symptom progression in a majority (80%) of patients is slow, although this may vary depending on the age of initial presentation. Presentation within the fourth decade of life or earlier, is more often associated with progressively symptomatic OPLL.<sup>42,43</sup> A prospective study on the natural history of OPLL has established that only a small fraction (17%) of patients who do not initially present with myelopathy, go on to develop myelopathic symptoms after 18 years of follow-up. Of note, more than 60% canal stenosis was found to be an important predictive risk factor for the development of myelopathy.<sup>44</sup>

## Treatment

Conservative (nonoperative) treatment regimen for the management of OPLL include:

- Administration of oral analgesics
- Physical therapy sessions.

Operative intervention is reserved for patients with progressive myelopathy and/or radiculopathy, and/or for patients who

do not respond to nonoperative regimen. Either anterior, posterior, or combined anterior-posterior (AP) surgical approaches can be utilized. The traditional criteria of performing anterior surgery whenever a kyphosis is present in the cervical spine has been challenged by some surgeons in the Asia-Pacific region. Due to excessive bleeding associated with anterior surgery in OPLL cases and the risk of dural injury with subsequent CSF leak or cord injury, many spine surgeons have transitioned to posterior approaches utilizing standard cervical laminectomy with fusion or laminoplasty in these OPLL surgeries. Combined AP approaches are often indicated in patients with significant kyphotic deformity on pre-operative imaging. Anterior approaches include:

- ACDF (single or multiple)
  - Often a thin layer of ossified ligament, which is adherent to the dura, is left “floating,” enabling decompression of the cord while minimizing the risk of a dural tear.
- Corpectomy and fusion
  - Corpectomies can be complicated by dural tears and CSF leaks.

- This increased risk of a CSF leak is due to the calcified PLL coapting with the underlying dura and eliminating a plane of dissection;
- When the calcified PLL is removed, oftentimes, the ventral dura is simultaneously resected.

Posterior surgical approaches include:

- Laminoplasty: This can be complicated by postoperative axial neck pain.
- Laminectomy: This can be complicated by postoperative kyphosis.
- Laminectomy and fusion.

Operative complications are more common in patients with OPLL than other types of cervical spine pathology with a recent review finding an overall surgical complication rate of 21.8%.<sup>45</sup>

## 10.4 Thoracic Spine Degenerative Disease

The thoracic spine, often referred to as the upper and/or middle back consists of 12 vertebrae (T1-T12). In contrast to the cervical and lumbar spine, each of the individual vertebrae in the thoracic spine articulate with the rib head facets, thereby limiting its mobility. The width of the thoracic intervertebral discs and the diameter of the spinal canal in the thoracic canal is reduced in comparison to both the cervical and lumbar spine. Despite its unique anatomy, symptomatic DDD is significantly less common in the thoracic spine, possibly due to the biomechanical advantage of splinting by the ribs; operations for herniated thoracic discs, for example, account for only 0.14–4% of all spinal disc excision operations.<sup>46</sup> These herniations are classified based on their location and can be either central, lateral, or centrolateral.

Like cases of cervical disc herniation, radiographic findings of thoracic disc herniation do not necessarily correlate with

symptomatic presentation. A previous study, for example, found that 37% of older adults (with no history of thoracic or lumbar pain or with a history of low-back pain only) had radiographic evidence of thoracic disc herniation on MRI.<sup>47</sup> The more widespread use of MRI has led to an increased level of detection of thoracic disc herniation which may or may not be symptomatic. This number may be lower when conventional radiography and/or CT is used for the initial imaging workup. Of note, thoracic disc herniation is more common in the lower thoracic spine (T8–T12), due to increased movement of this segment on flexion and extension, and decreased resistance to rotational forces.<sup>48</sup> Compression of the cord or nerve roots can result in myelopathy and radiculopathy, respectively. It is important to note that the thoracic spine's natural kyphosis and the presence of the dentate ligaments in the posterior spinal canal, increase the risk of ventral cord compression from protruding discs.<sup>48</sup> This is further complicated by the limited vascular anastomoses in the thoracic cord, particularly in the T3-T6 region (which is considered a watershed region), and which can lead to ischemia of the neural elements and subsequent myelopathy.

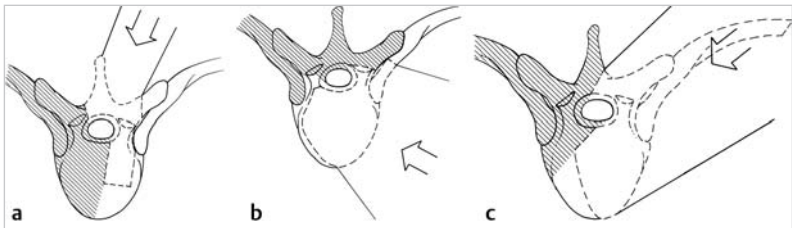
Clinical presentation can vary in severity depending on several factors including but not limited to: the extent of the herniation, the location of the herniated disc within the canal, the patient's comorbidities, etc. Presentation with pain is common and includes middle or lower back pain which radiates from the lower back to the abdomen, groin, lower limbs, and/or the anterior chest.<sup>48</sup> Possible differential diagnoses for upper and/or middle back pain can include cardiovascular, pulmonary, neoplastic, hepatobiliary, and/or gastrointestinal etiologies. As has been previously discussed, nonoperative treatment regimen



are indicated in patients without significant neurological deterioration, pain, and/or myelopathic symptoms.

Open and endoscopic surgical treatments are available for patients with progressive symptomatology from thoracic disc herniations. Indications for a transthoracic-transpleural (thoracotomy), posterolateral (transpedicular, transfacetal, or costotransversectomy), or lateral surgical approach, can vary (►Fig. 10.2). As the practice of performing a decompressive laminectomy, which is associated with high morbidity and mortality rates (approaching up to 50%), has been abandoned, clinical outcomes have generally improved.<sup>49</sup> Interestingly, a review by Mulier et al found that a higher rate of partial or total neurological recovery was achieved when a transthoracic (93%) approach was used rather than a posterolateral or lateral approach ( $p < 0.05$ ). However, this approach was also associated with a higher rate of pulmonary complications ( $p < 0.025$ ).<sup>50</sup> The morbidity of anterior approaches leading to prolonged postoperative pain, compared with certain posterior approaches, has led to an

increased recent popularity of posterior approaches for thoracic disc herniations. Minimally invasive thoracoscopic surgery may be performed for resection of single or bi-level thoracic lesions with prospective data finding a decreased length-of-stay in the hospital, a decreased complication rate and a decreased rate of morbidity in comparison to open approaches.<sup>51</sup> Nonetheless, for a variety of reasons, the endoscopic approach to thoracic disc removal has not caught on in the surgical community and has not received acceptance by the great majority of spine surgeons. This may be due to a significant learning curve for the approach which includes many cases of inadequate disc excision. Ultimately, the choice of approach should be based on the patient's overall health, the size of the disc, location of the herniation relative to the spinal canal, consistency of the disc (soft vs. calcified), and patient's individual spinal biomechanics.<sup>49</sup> Furthermore, the spine surgeon's level of comfort with the various surgical options available weighs into the choice of which approach will be offered.



**Fig. 10.2** Comparative operative views of (a) the anterolateral approaches (thoracotomy and thoracoscopy), (b) transpedicular approach, and (c) costotransversectomy approach. The only approaches that provide a view of the ventral dura are the thoracotomy and thoracoscopic approaches. Each approach has a blind area on the surface of the dura opposite the surgeon's line of view. (Reproduced from Dickman C, Rosenthal D, Perin N, *Thoracoscopic Spine Surgery*, 1st edition, ©1999, Thieme Publishers, New York.)

## 10.5 Lumbar Back Pain

Low back pain (LBP) is a frequently encountered clinical entity which places a significant socioeconomic burden on healthcare systems worldwide. A recent systematic review evaluating the epidemiology of LBP found a global point prevalence of 11.9%.<sup>48,52</sup> It is also the second most common cause of disability among adults in the United States with 80% of the population projected to experience an episode of LBP within their lifetime.<sup>53,54</sup> As a result of this condition, nearly 150 million work days are lost annually.<sup>55</sup> LBP is typically classified as being either acute (lasting less than 12 weeks) or chronic, with most acute cases completely resolving over time without surgical intervention. While specific diagnoses are not made in most cases of LBP, symptomatic improvement without medical intervention is often rapid, and can occur within 1 month. Differential diagnoses for LBP can include (but are not limited to): musculoskeletal pain (most common), degenerative diseases of the lumbar spine leading to either nerve root compression/radiculopathy or cord compression, fracture-dislocations, neoplasms, or infections (i.e., osteomyelitis). The latter three conditions may be discernable from a thorough history and physical examination. Compression of the L1-L5 nerve roots can lead to “sciatic” symptoms in addition to local LBP.

## 10.6 Spinal Neoplasms

The overall incidence of tumors in the spinal column is reported to be approximately 0.97 per 100,000.<sup>56</sup> Spinal neoplasms are termed intradural if they arise from inside the dura mater, and extradural if they arise from outside. Intradural tumors are further classified as intramedullary if they

involve the spinal cord and extramedullary if they do not.



The most common type of spinal neoplasm is spinal metastasis, which is most commonly extradural.

Primary spinal cord tumors, which originate from the neural elements, are predominantly benign (69%)<sup>57</sup> and their histologic types include meningiomas in 29%, nerve sheath tumors in 24%, and ependymomas in 23%.<sup>57</sup> Primary malignant spinal neoplasms are associated with a 64% overall 10-year survival.<sup>57</sup> Spinal neoplasms often present with back pain or neurological deficits of the lower and/or upper limbs with sparing of the head and face.<sup>58</sup> Primary spinal neoplasms, being far less common than metastases, may be misdiagnosed as degenerative spinal disease. The mainstay for diagnosis of spinal tumors is MRI, which enables an assessment of both the tumor and its relationship with the dura mater and neural elements. Treatment and outcome depend on the location and histology of each tumor.

### 10.6.1 Intradural Tumors

**Intramedullary Tumors:** Intradural intramedullary tumors are the rarest of adult spinal neoplasms.<sup>59</sup> Histologically, intradural intramedullary tumors are usually ependymomas (30–60%) or astrocytomas (30%),<sup>56,58</sup> with the rare occurrence of hemangioblastomas (2–8%)<sup>56</sup> and metastases (2%).<sup>60</sup> Intradural intramedullary tumors are more likely to occur in the longer spinal cord segments, with about half located in the thoracic spine and one-third in the lumbar segment.<sup>61,62</sup> Most intradural intramedullary tumors enhance on MR.<sup>63</sup>



Ependymomas are the most common tumors of the conus medullaris, are more common in adults than children, can metastasize through CSF seeding, are associated with cyst formation, and can be treated with surgical excision (because they are encapsulated).<sup>64</sup>

Myxopapillary ependymomas are the most common variant found in the conus medullaris and filum terminale regions.<sup>65</sup> Astrocytomas present more commonly in the 3<sup>rd</sup> to 5<sup>th</sup> decades of life and are more commonly low grade (grade 4 lesions are found in only 12% of cases).<sup>66</sup> The clinical picture of intradural intramedullary tumors does not provide enough information to distinguish them from other spinal neoplasms. MRI is the diagnostic imaging modality of choice. Asymptomatic tumors can be followed conservatively in some cases. However, symptomatic lesions should be treated as soon as possible. Debulking using microdissection, laser, or ultrasonic aspiration are all reasonable first-line treatment options, with ependymomas often providing good surgical planes for dissection.<sup>67</sup> The outcomes are directly associated with the extent of neurological deficit prior to surgery.<sup>68</sup>

**Extramedullary Tumors:** Intradural extramedullary tumors arise within the dura mater, but outside the spinal cord. The most common histologic types are nerve sheath tumors (neurofibromas and schwannomas most commonly and gangliogliomas and malignant nerve sheath tumors less commonly).<sup>69</sup>



Nerve sheath tumors have a characteristic MRI T1 “target lesion” pattern, with decreased signal centrally (Antoni A tissue) and increased signal peripherally (Antoni B tissue).<sup>70</sup>

Nerve sheath tumors undergo malignant transformation in approximately 2–6% of cases.<sup>71</sup> Recurrence is rare in sporadic tumors if complete resection is achieved.<sup>72</sup> Meningiomas are the second most common type of intradural extramedullary tumors. They are generally benign slow-growing tumors with a characteristic enhancing “dural tail” on contrast MRI studies.<sup>73</sup>

Meningiomas may recur in 2–7% of cases, depending on resection totality.<sup>74,75</sup>

## 10.6.2 Vertebral Body Metastases

The most common type of spinal neoplasms are epidural metastases (most commonly from the lung and breast) and they occur in 5–10% of all cancer patients.<sup>76</sup> Patients may present with localized pain from vertebral body destruction/fracture or acute symptoms of cord compression, which call for emergency management to preserve neural function. Metastases seed to the vertebral column in 85% of cases, the paravertebral tissues in 14% of cases, and to the epidural space rarely.<sup>77</sup> Most spinal metastases are located in the vertebral body.<sup>78</sup> After metastasizing, the tumor can grow posteriorly, eventually compressing the spinal cord. The thoracic segments are the most likely to be affected, followed by the lumbosacral and the cervical spine, but multiple metastatic segments are common, occurring in 20–35% of cases.<sup>79</sup> Symptoms involve back pain,<sup>79</sup> often worse in the recumbent position, motor weakness with hyperreflexia,<sup>80</sup> cord compression, and cauda equina syndrome.

Modern management of spinal metastases involves pain management, steroids, radiation therapy, and surgery. Surgical management in symptomatic patients is proven to result in better overall outcomes and an improvement in quality of life in comparison to use of radiotherapy alone.<sup>81,82</sup>

Spinal instability and neurologic function are key elements in the decision to operate. The Spine Instability Neoplastic Score (SINS) can aid in such referral decisions.<sup>83</sup> It evaluates:

- Tumor location (junctional: 3 points, cervical/lumbar: 2 points, thoracic: 1 point, sacral: 0 points).
- Increase in pain with loading of the spine and relief in recumbency (3 points if consistent, 1 point if occasional, 0 if no pain).
- Type of bone lesion (2 points for lytic, 1 point for mixed, 0 points for blastic).
- Spinal alignment (4 points for subluxation, 2 points for kyphoscoliosis, 0 points otherwise).
- Vertebral body collapse (3 points if > 50% collapse, 2 points if < 50% collapse, 1 point if no collapse but > 50% of vertebral body is involved, 0 points otherwise).
- Involvement of the posterolateral spinal elements (3 points if bilateral, 1 point if unilateral, 0 point if not). The total score ranges from 0–18.

Spinal Instability Neoplastic Score (SINS) 0–6 is considered stable, 7–12 is potentially unstable, and 13–18 is unstable. A patient with a score more than 7 should be assessed by a spinal surgeon.

## 10.7 Spinal Vascular Disorders

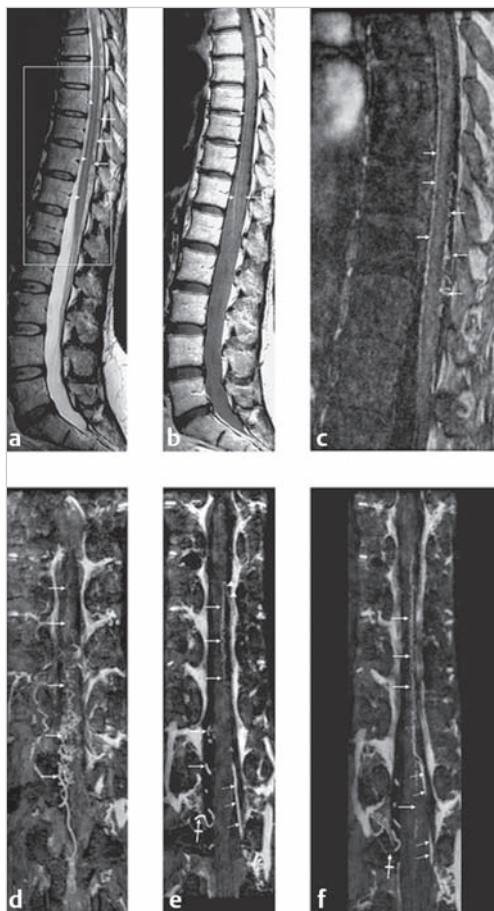
The spinal cord contains vessels interwoven with its neuronal and glial elements. Disruption of the vasculature can be seen with vascular malformations, including malformations (AVMs), dural arteriovenous fistulas (AVFs), cavernomas, hemangiomas and, rarely, aneurysms.

### 10.7.1 Vascular Malformations

Spinal AVMs and dural AVFs are the most common spinal vascular malformations. The gold standard for imaging in these cases is spinal cord angiography, which is often indicated following screening with MRA. Anson and Spetzler<sup>65</sup> classically classified spinal vascular malformations into four types.

Type I is the dural AVF, which is the most common type and accounts for 70–80% of spinal vascular disorders.<sup>84,85</sup> It is a direct fistulous connection between a radiculomeningeal artery and a radicular vein.<sup>86</sup>

Anatomically, the fistula is usually located along the dural root sleeve. Type I dural AVFs are classified as “low flow”, because of the low-pressure gradient typically involved. They rarely bleed but they do cause venous congestion with subsequent edema and ischemia of the cord. Symptoms include low back pain, radiculopathy and bladder symptoms, or cauda equina syndrome. The lesion can be managed with both endovascular or open surgical treatment or a combination of both, with excellent results. The optimal strategy is dependent on the anatomy of the malformation.<sup>87</sup> Type II vascular malformations are called glomus AVMs and consist of an intramedullary nidus of tightly packed vessels, usually supplied by the anterior and/or posterior spinal circulation.<sup>88</sup> Type III malformations are juvenile intramedullary and extramedullary AVMs, and Type IV are AVFs of the pia matter, where a spinal artery and a spinal vein communicate without a capillary network.<sup>88</sup> Types II, III and IV are classified as “high-flow” malformations (► Fig. 10.3). They present acutely following hemorrhage in 75% of cases and have a



**Fig. 10.3** Spinal dural arteriovenous fistula. **(a)** Sagittal T2-weighted image. **(b)** Contrast-enhanced sagittal T1-weighted image. **(c)** Sagittal high-resolution magnetic resonance angiography (MRA), maximum intensity projection (MIP) reconstruction. **(d)** Coronal high-resolution MRA, MIP reconstruction (slice 1). **(e)** Coronal high-resolution MRA, MIP reconstruction (slice 2). **(f)** Coronal high-resolution MRA, MIP reconstruction (slice 3). (Reproduced from Forsting M, Jansen O, MR Neuroimaging: Brain, Spine, Peripheral Nerves, 1st edition, ©2016, Thieme Publishers, New York.)

worse prognosis than Type I lesions.<sup>86</sup> Due to their intramedullary location, high-flow malformations are usually treated endovascularly while asymptomatic patients can be followed conservatively.<sup>87</sup>

### 10.7.2 Cavernomas

Intramedullary spinal cavernomas account for 5–12% of all spinal vascular pathologies.<sup>89, 90, 91</sup> Only 3–5% of central nervous system (CNS) cavernomas are located in the

spinal cord.<sup>92</sup> These lesions may present with acute intraparenchymal hemorrhage, or with progressive neurological decline following multiple microhemorrhages.<sup>93</sup>

For cavernomas, the imaging modality of choice is MRI and it typically reveals a hyperintense T2 lesion (so called popcorn lesion), surrounded by a hypointense rim.

Surgical resection is the primary treatment modality for symptomatic spinal cavernomas.<sup>94,95,96</sup> However, conservative treatment is sometimes utilized in cases where a single bleed is followed by complete resolution of symptoms.

## 10.8 Spinal Deformity

The spine receives rotational and translational forces along its axial, coronal, and sagittal axes. According to this biomechanical paradigm, rotational forces are applied to the vertebrae when loads are carried eccentrically, causing shearing, compression, and distraction, and leading to degeneration and deformity in the sagittal, coronal, or axial planes.<sup>97</sup> The normal spinal column consists of a cervical lordosis, a thoracic kyphosis, a lumbar lordosis and a sacral angulation, which must neutralize each other so that the head and trunk are located over the pelvis ensuring optimal load distribution and balance.

In clinical practice, standing 36-inch AP and lateral long films, with the hips and knees extended, are used to evaluate spinal deformity. Commonly used measurements include sagittal balance and the Cobb angle.

To determine sagittal spinal alignment on a lateral X-ray, a plumb line (line vertical to the floor) is dropped from the center of the C7 vertebra and should pass through L1 and the posterior aspect of the L5/S1 disc space.

The Scoliosis Research Society has defined normal sagittal balance as the plumb line from C7 passing within 2 cm anterior or posterior to the sacral promontory (S1).<sup>98,99</sup> Deviation of the line more than 2 cm anteriorly is considered positive sagittal malalignment, while deviation

more than 2 cm posteriorly is negative sagittal malalignment.

After determining sagittal balance, the lateral long X-ray should be used to evaluate angulation for each spine segment.

- The Cobb angle is the angle between intersecting lines drawn perpendicular to the top of the rostral vertebra and the bottom of the caudal vertebra (along the endplates) of the measured segment. Cervical lordosis has historically been accepted as normal at  $40 \pm 9.7^\circ$ , thoracic kyphosis at  $20\text{--}50^\circ$  and lumbar lordosis at  $31\text{--}79^\circ$ .<sup>100,101</sup>

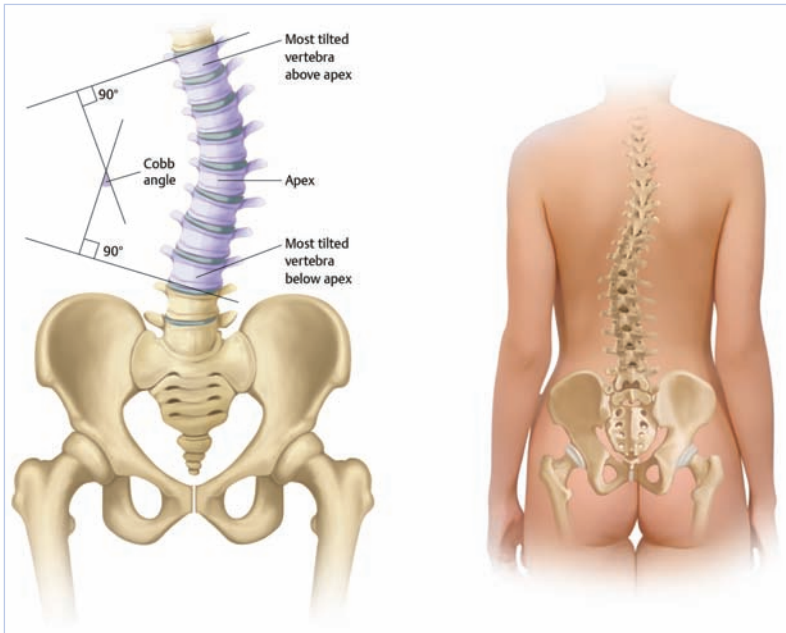
This accounts for the commonly accepted “40–50–60” rule for cervical, thoracic and lumbar angulation respectively.

However, some studies have suggested this may overestimate the normal range.<sup>99</sup>

- Cobb angles are also used in the AP dimension to assess coronal balance (► Fig. 10.4). Normally, there should be  $0^\circ$  of angulation in any segment. If there is angulation, Cobb angles are used from the top of the rostral vertebra involved in scoliosis, to the bottom of the most caudal vertebra involved.<sup>102</sup>
- The apical vertebra is defined as the one with has the greatest rotation or furthest deviation from the midline.<sup>104</sup>
- The neutral vertebra is the first vertebra on an AP view where both pedicles are equally visualized, and shows no rotation.
- The stable vertebra is the first one to be bisected by the central sacral vertical line. Identification of these landmarks is critical to operative planning.<sup>103</sup>

The spinopelvic parameters are useful prognostic indicators for adult spinal deformity and include:

- Pelvic incidence (PI): Is the angle between a line drawn perpendicular to



**Fig. 10.4** Cobb angle measurement. (Reproduced from An H, Singh K, *Synopsis of Spine Surgery*, 3rd edition, ©2016, Thieme Publishers, New York.)

the sacral plate (S1 endplate) at its midpoint and the line connecting this point to the femoral head axis.

- Pelvic tilt (PT): Is the angle between the line connecting the midpoint of the superior sacral plate to the axis of the femoral head and a vertical reference line.
- Sacral slope (SS): Is the angle between a horizontal line and the sacral plate (► Fig. 10.5).<sup>104</sup>
- The PI-LL: Is the offset between pelvic incidence and lumbar lordosis.
- The sagittal vertical axis (SVA): Represents the linear offset of the C7 vertebra against the posterosuperior corner of S1. It is utilized to assess global sagittal alignment(► Fig. 10.6).

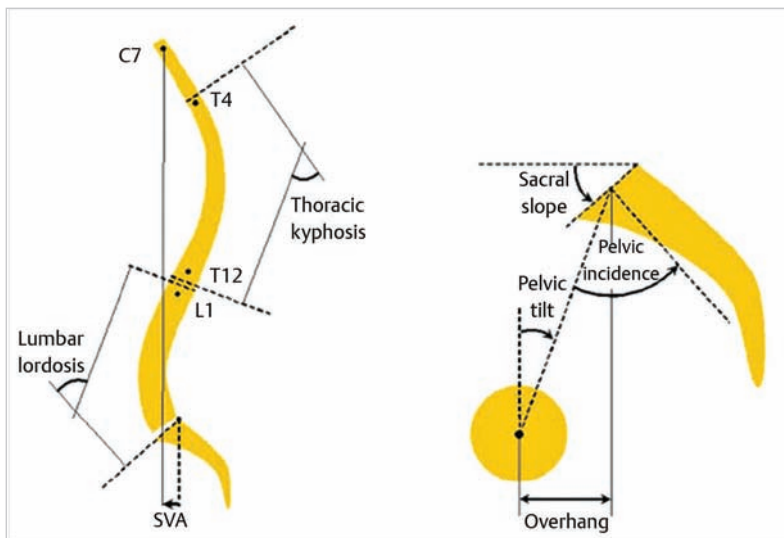
The SVA, PT, and PI-LL have been most strongly associated with outcomes.<sup>104</sup>

There are three broad categories of spinal deformities—kyphosis, lordosis, and scoliosis, as well as combinations of these.

### 10.8.1 Kyphosis

Kyphosis is the pathological accentuation of the normal apical-dorsal sagittal contour of the thoracic and/or sacral spine. It may be combined with coronal abnormalities, in which case it is termed kyphoscoliosis. While there is wide variation in asymptomatic individuals, a Cobb angle less than 40° in the thoracic spine is generally considered normal.<sup>101</sup> Kyphosis can lead to pain and cosmetic deformity with





**Fig. 10.5** Spinopelvic parameters in radiographic evaluation. (Reproduced from Newton P, O'Brien M, Shufflebarger H et al, *Idiopathic Scoliosis. The Harms Study Group Treatment Guide*, 1st edition, ©2010, Thieme Publishers, New York.)

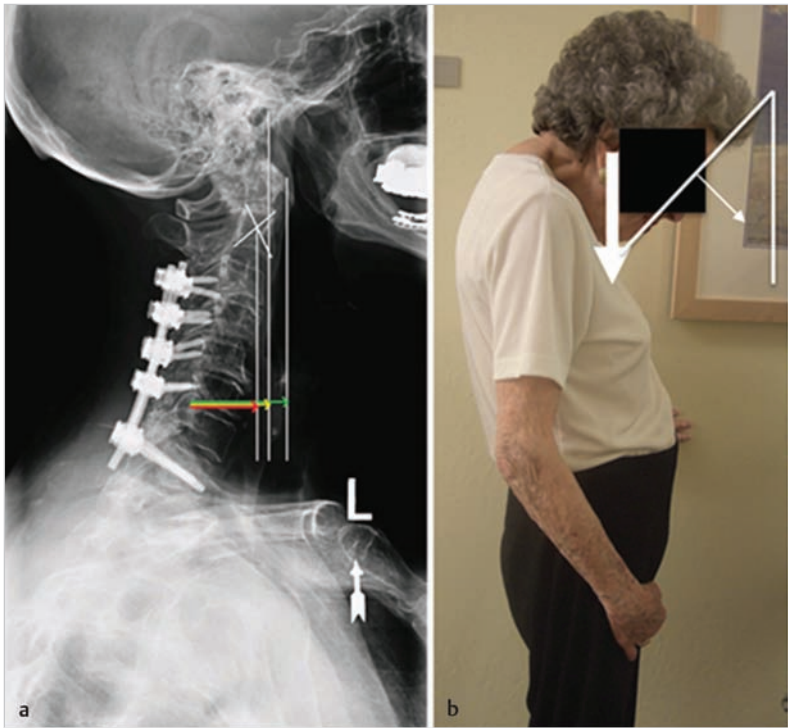
severe cases developing neurological deficits and cardiopulmonary problems. Pain and functional disability is more common in adult kyphosis.<sup>81</sup> Scheuermann disease is osteochondrosis of the spine in adolescents and is associated with pain and neurological symptoms in this group.<sup>105</sup> It is characterized by 5° of wedging, at each level, over three consecutive vertebrae.<sup>106</sup> Adult cases of kyphosis may arise following degenerative, inflammatory, traumatic, oncological, or infective disorders. Kyphosis follows a trimodal age distribution. Adolescents most commonly present with Scheuermann kyphosis, while patients in their 4<sup>th</sup>–6<sup>th</sup> decade present with associated ankylosing spondylitis (AS) or other inflammatory disorders, while elderly patients (> 60 years) present with degenerative changes.<sup>101</sup> Diagnosis in the thoracic spine is made using 36-inch standing lateral radiographs with the hips and knees

extended and with identification of a Cobb angle greater than 40°. Sagittal balance should be routinely assessed. An important consideration in management is assessing the flexibility of the spinal column. This is measured on a lateral radiograph of the patient lying supine over a bolster. Correction to 50° or less is considered flexible and can often be corrected with posterior-only fusion, while rigid deformities frequently require combined anterior and posterior procedures.<sup>107,108</sup>

### 10.8.2 Lordosis

The most common pathological lordosis is lumbar hyperlordosis, which is prevalent in dancers, but can also be due to obesity, hyperkyphosis, discitis, Ehlers-Danlos Syndrome, or benign juvenile lordosis. It is associated with axial back pain and is usually managed with conservative treatment.<sup>109</sup>





**Fig. 10.6** Cervical sagittal vertical axis (SVA) measurements **(a)** and chin-brow vertical angle (CBVA) **(b)**. **(a)** The green arrow represents the C1–C7 SVA (distance between a plumb line dropped from the anterior tubercle of C1 and the posterior superior corner of C7). The red arrow represents the C2–C7 SVA (distance between a plumb line dropped from the centroid of C2 and the posterior superior corner of C7). The yellow arrow represents the center of gravity to the C7 SVA (distance between a plumb line dropped from the anterior margin of the external auditory canal and the posterior superior corner of C7). **(b)** Representation of the CBVA measurement method portrayed on a clinical photograph of a patient standing with hips and knees extended while her neck is in a neutral or flexed position. The CBVA is defined as the angle subtended between a line drawn from the patient's chin to brow and a vertical line. (Reproduced from Vialle L, AOSpine Masters Series: Volume 3: Cervical Degenerative Conditions, 1st edition, ©2014, Thieme Publishers, New York.)

### 10.8.3 Scoliosis

Scoliosis and kyphoscoliosis can occur in adolescent (adolescent idiopathic scoliosis) and adult (adult degenerative scoliosis) populations.<sup>110,111</sup> A rare form of scoliosis is

juvenile idiopathic scoliosis, which happens to children under the age of 10 years, who are skeletally immature. Scoliosis is classically defined as a Cobb angle greater than  $10^\circ$  in the coronal plane, although any angulation in the coronal plane can be

considered pathological.<sup>112</sup> Scoliosis has two phases, curve initiation and progression.<sup>113</sup> Bone growth in the immature spine is inhibited by pressure on the growth plate. The normally kyphotic thoracic spine places a greater axial load on the ventral aspect of the vertebral bodies. If there is rotation at any point, there will be differential pressure on the growth plate and the subsequent development of scoliosis.<sup>114</sup> Reportedly, up to 95% of adolescent idiopathic scoliosis cases will progress and about 70% will require surgery.<sup>115</sup> Management of scoliosis may involve observation, use of an orthosis, or surgery. Adolescent idiopathic scoliosis is categorized by curve type according to the Lenke classification system with lumbar spine and sagittal thoracic modifiers.<sup>116</sup> Scoliosis with Cobb angles less than 20° are generally observed, those with 20–30° angles are treated with bracing and those with more than 30° angles may be surgically managed, taking into consideration bone maturity and the patient's clinical state.<sup>117,118,119</sup> Adult degenerative scoliosis progresses by approximately 3° per year.<sup>120</sup> Surgery is recommended for coronal angulation of more than 45°.<sup>121</sup>

## 10.9 Inflammatory Spondyloarthropathies

### 10.9.1 Ankylosing Spondylitis

AS is an inflammatory disease of the joints of the spine and/or pelvis, and has a strong genetic component. It commonly presents with back pain and stiffness of the spine, which characteristically improves with exercise.<sup>122</sup> Enthesitis and arthritis of other joints are common as are constitutional signs and fatigue.<sup>123</sup> Moreover, AS is associated with extra-articular symptoms, including uveitis and cardiovascular disease.<sup>124</sup> AS can be diagnosed with X-ray

imaging of the spine and pelvis, with squaring and loss of the normal concave contour of the vertebral bodies and development of syndesmophytes (which can eventually produce a “bamboo spine” appearance and fusion of the sacroiliac joints).<sup>125</sup> Inflammation at the points of joint insertion can cause sclerosis of the upper and lower limits of the vertebrae, characterized by the Romanus lesion. MRI and CT scans of the spine and pelvis may show early signs of sacroiliitis and enthesitis resulting in earlier diagnosis.<sup>126,127</sup> Medical treatment of AS consists of non-steroidal anti-inflammatory drugs, sulfasalazine, corticosteroids, and tumor necrosis factor- $\alpha$  inhibitors. Spinal surgical management can be considered in patients with complete fusion of a spine segment, but can be challenging, particularly in the context of traumatic injury, with associated anesthetic difficulties. These patients may benefit from osteotomy of the respective vertebral bodies.<sup>128,129</sup>

### 10.9.2 Rheumatoid Arthritis of the Cervical Spine

Rheumatoid arthritis commonly presents in the cervical spine.<sup>130</sup> The most common presenting pathologies are atlantoaxial subluxation, present in 49% of cases,<sup>131</sup> superior migration of the odontoid in 38%, and subaxial subluxation in 10–20% of patients.<sup>132</sup> About 25–80% of patients with rheumatoid arthritis will develop cervical spine involvement,<sup>133</sup> with only a minority developing neurological symptomatology. Common presentations include facial pain, ear pain, occipital neuralgia, myelopathy, and vertebral basilar insufficiency.

The clinical picture is classified according to the Ranawat classification<sup>134</sup> as:

- Class I: Pain with no neurologic deficit.
- Class II: Subjective weakness, hyperreflexia, dysesthesias.

- Class III with objective problems, where:
  - Class IIIa: Objective weakness, long tract signs, ambulatory.
  - Class IIIb: Objective weakness, long tract signs, nonambulatory.

Operative treatment depends on the clinical symptomatology and imaging findings. Symptomatic pathologies may require intervention, while there is controversy as to whether patients with minimal symptoms but radiographic instability require surgery.<sup>135</sup>

## 10.10 Spinal Infections

### 10.10.1 Epidural Spinal Abscess

Abscesses in the spinal epidural space have a reported incidence of 2.8 cases per 100,000 admissions and this figure is rising in the intravenous drug abusing population.<sup>136</sup>

The most common pathogen identified is *Staphylococcus aureus*.<sup>137</sup>

The abscess can lead to pain and neurological deficits through local mass effect and compression of the spinal cord/nerve roots as well as vascular compromise of the spinal cord leading to subsequent spinal cord ischemia. Symptomatology may evolve in four stages:<sup>138,139</sup>

1. Axial back pain at the affected spinal level.
2. Radicular pain at the affected nerve root.
3. Motor and sensory abnormalities, bladder and bowel dysfunction.
4. Paralysis.

The classic triad of spinal epidural abscess includes fever, back pain, and neurological deficit.<sup>137</sup> Suspicion for epidural abscess

should prompt immediate spinal MRI (ideally with contrast) to identify the lesion. Both medical and surgical management can be considered for these patients, as there is controversy regarding the optimal management strategy.<sup>140,141</sup> As a general rule, if neurological status is impaired or if the spine is unstable, then surgery is indicated. For patients with pain only and no neurological or stability issues, then empiric antibiotic therapy with antistaphylococcal coverage may be administered as part of a conservative treatment regimen, which can be tailored as cultures identify specific organisms. Stable patients without neurological deficits may undergo CT-assisted abscess aspiration, but any deterioration in clinical status should prompt emergency spinal decompression to avoid permanent neurologic deficit.

### 10.10.2 Vertebral Body Osteomyelitis

Vertebral body osteomyelitis (VBO) is the most common form of infection of the vertebral column. Pyogenic vertebral osteomyelitis was found primarily in older individuals with comorbidities such as diabetes mellitus, alcoholism, renal or liver failure, cancer, or immunosuppression, and younger intravenous drug abusers.<sup>142</sup> Symptomatology may be nonspecific, with an absence of fever in 40% of cases.<sup>142</sup> The most common bacterial species isolated is *Staphylococcus aureus*, followed by *Escherichia coli*.<sup>142</sup> CT scanning is valuable to evaluate bony erosion,<sup>143</sup> while MRI can assist in earlier detection of osteomyelitis and abscesses. Uncomplicated VBO should be initially treated with intravenous antibiotics for 4–6 weeks, and this may be followed by oral antibiotics for a further 2–6 weeks.<sup>144</sup> Immobilization with bedrest and/or use of an external orthosis may be considered as well. Surgical management may be needed for biopsy, symptomatic spinal cord compression, or refractory severe pain.

Follow-up imaging has not been shown to correlate with better results, so patients should be followed clinically to ensure response to antibiotics.<sup>142</sup>

### 10.10.3 Pott's Disease

Tuberculosis of the spinal column, also known as Pott's disease, involves both osteomyelitis and arthritis. In adults, tuberculosis spreads from the anterior aspect of the vertebra. In children, osteomyelitis most commonly spreads hematogenously, primarily affecting the intervertebral discs. A predilection for destruction of the anterior parts of the vertebral bodies can lead to kyphosis in addition to abscess formation and direct compression of the spinal cord. Patients with suspected Pott's disease should be assessed with a tuberculin (purified protein derivative) test and percutaneous CT-guided biopsy for culture.<sup>146</sup> The gold standard for the evaluation of Pott's disease is MRI, which shows characteristic thin and smooth enhancement of the abscess wall and a well-defined paraspinal signal.<sup>146</sup> Antituberculous medications are indicated in these patients, and surgery can be indicated in patients with neurological deficits or instability.<sup>147</sup>

## 10.11 Cauda Equina Syndrome

In most adults, the spinal cord will taper and end caudally at approximately the L1 level, forming the cauda equina, a collection of nerve roots that looks like a "horse's tail". Although the cauda equina is part of the peripheral nervous system, its compression may cause irreversible neurologic deficits and is, therefore, an emergency.<sup>148</sup> The cauda equina nerve roots may be particularly vulnerable due to their thin myelin sheath.<sup>149</sup> Common causes of cauda equina syndrome are traumatic,<sup>150</sup> degenerative,<sup>151</sup>

and malignant.<sup>152</sup> Degenerative lumbar disc disease can lead to cauda equina syndrome, with 70% of patients having back pain prior to the onset of cauda equina symptoms.<sup>153</sup> Neoplasms are an uncommon causes of cauda equina syndrome. However, the most common neoplastic pathological diagnoses are myxopapillary ependymomas,<sup>154</sup> schwannomas,<sup>155</sup> and paragangliomas.<sup>156</sup> The symptoms in cauda equina syndrome are:

- LBP.
- Radiculopathy (more commonly unilateral).
- Saddle anesthesia.
- Bowel/bladder incontinence or retention.
- Bilateral lower extremity motor and sensory deficit.
- Absent lower extremity reflexes.

Suspicion for cauda equina syndrome should be raised in patients with acute LBP accompanied by urinary changes. The diagnostic study of choice is MRI of the lumbosacral spine.<sup>157</sup> Surgical decompression is undertaken as an emergency in the first 48 hours, and preferably within in the first 6 hours of the onset of cauda equina syndrome.<sup>158</sup> Laminectomy with neural decompression is essential and in cases where stability is compromised, a fusion may be added. In addition, tumor resection may be attempted in emergency cases where a neoplasm is the underlying pathology.

## 10.12 Other Spinal Syndromes

### 10.12.1 Failed Back Surgery Syndrome

Failed Back Surgery Syndrome (FBSS) is defined as persistent or recurrent back pain after one or more surgeries that failed to improve the clinical condition.<sup>159</sup> It may be caused by residual or recurrent disc

herniation, alteration of spinal biomechanics and mobility, scar tissue, or psychological disturbances. Management modalities for FBSS include:<sup>160</sup>

- Physical therapy.
- Chiropractic care.
- Nonsteroidal anti-inflammatory drugs.
- Transcutaneous electrical stimulation (TENS).
- Facet joint injections.
- Antidepressants.
- Spinal cord stimulation (SCS).
- Intrathecal drug pump (IDP).

As both SCS and IMP are implantable devices used as a last resort in FBSS, a trial is offered before permanent implantation with these procedures. SCS is preceded by percutaneous implantation of an electrode to assess diagnostic and therapeutic responses, while IDP trials consist of a single intrathecal injection of morphine. The decision of one modality over the other is based on patient and physician preferences.

### 10.12.2 Tethered Cord Syndrome

Tethered cord syndrome is associated with thickening of the filum terminale causing tethering of the conus medullaris to the dorsal aspect of the spinal canal. It is associated with myelomeningoceles, scoliosis, and VACTERL (vertebral defects, anal atresia, cardiac defects, tracheo-esophageal fistula, renal anomalies, and limb abnormalities) syndrome.<sup>161</sup> Symptoms include deformities in the lower extremities and the spine, and peripheral stigmata, such as lower back lesions (hairy patch, dimples etc.) may be present. Lower extremity motor or gait disturbances, bladder disorders, LBP, and scoliosis can also accompany tethered cord syndrome. The diagnosis can be made with MRI. However, often times, clinical judgement is needed to ultimately decide which patients would benefit from

surgical intervention.<sup>162</sup> Early operative treatment is necessary in symptomatic patients to prevent neurological deterioration and permanent damage.<sup>163</sup> Surgery most often involves untethering the cord from the vertebrae; occasionally, a spine-shortening vertebral osteotomy may be performed.<sup>164</sup>

#### Pearls



- A thorough history and physical examination can be used to discern between the different etiologies of LBP including fracture-dislocations, spinal neoplasms, and infections.
- The most common spinal tumors are vertebral body metastases and the SINS score is a validated tool that should be used to evaluate these lesions.
- Spinal deformity should be assessed on standing 36-inch AP and lateral long films by calculating the sagittal balance and Cobb angle.
- Acute low back pain accompanied by lower extremity weakness and bowel/bladder symptoms should raise suspicion for cauda equina syndrome, which is a surgical emergency.

## 10.13 Top Hits

### 10.13.1 Questions

1. The spinopelvic parameter defined as the angle between the perpendicular to the sacral plate at its midpoint and the line connecting this point to the femoral head axis, is:
  - a) Pelvic incidence
  - b) Pelvic tilt
  - c) Sacral slope
  - d) Sagittal vertical axis

2. The most commonly isolated bacterial species in patients with vertebral body osteomyelitis is:
  - a) *Escherichia coli*
  - b) *Staphylococcus aureus*
  - c) *Pseudomonas aeruginosa*
  - d) *Streptococcus equisimilis*
3. According to the classification system developed by Anson and Spetzler, "low flow" spinal vascular malformations are defined as:
  - a) Type 1 (dural AVFs)
  - b) Type 2 (glomus AVMs)
  - c) Type 3 (juvenile intramedullary and extramedullary AVMs)
  - d) Type 4 (pial AVFs)

## 10.13.2 Answers

1. **a.** The pelvic incidence is defined as the angle between the perpendicular to the sacral plate at its midpoint and the line connecting this point to the femoral head axis.
2. **b.** The most common bacterial species isolated in patients with vertebral osteomyelitis is *Staphylococcus aureus*.
3. **a.** Type 1 (dural AVFs) spinal vascular malformations are defined as "low flow" lesions. Types 2, 3, and 4 are "high flow" lesions.

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# 11 Pain

James Mooney, Charles Munyon

## 11.1 Pathway Anatomy

Nociception is the process by which information about actual or potential tissue damage is relayed to the brain.

### 11.1.1 Peripheral Nerves

Peripherally, nociception is mediated by specialized free nerve ending receptors known as nociceptors that are attached to thin myelinated (fast) A $\delta$  and unmyelinated (slow) C fibers. Specific nociceptors respond to noxious stimuli including thermal, mechanical, and chemical. Polymodal neurons respond to multiple types of stimuli.

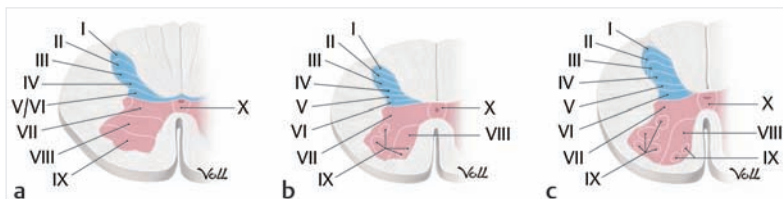
### 11.1.2 Spinal Cord

The gray matter of the spinal cord is divided into Rexed's laminae, which progress from posterior to anterior (► Fig. 11.1). Lamina I–III are known as the “substantia gelatinosa.” Laminae IV and V include the neurons that give rise to the spinothalamic tract. In the spinal cord, primary afferent nociceptors project

axons to the spinal cord through the dorso-lateral tract of Lissauer and terminate near second-order nerve cells in the substantia gelatinosa of the dorsal horn.<sup>1</sup> Second-order neurons give rise to axons that decussate in the ventral white commissure and ascend in one of two contralateral funiculi. Second-order wide dynamic range neurons have cell bodies in the dorsal horn of the spinal cord and respond to all somatosensory modalities in a broad range of intensity of stimulation. All second-order pain neurons ultimately ascend in the anterolateral quadrant of the spinal cord either in the direct lateral spinothalamic pathway or the indirect medial spinoreticulothalamic pathway (► Fig. 11.2).

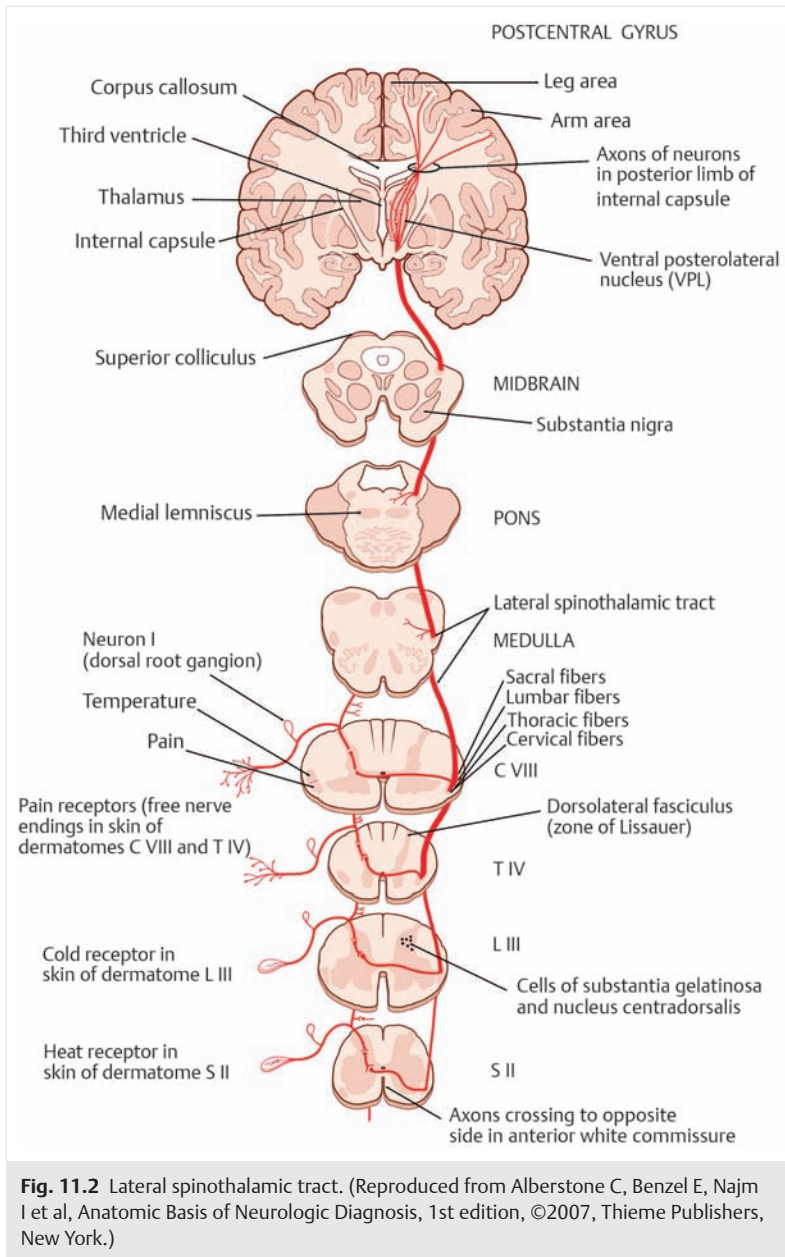
### 11.1.3 Thalamic and Cortical

Neurons in the ventrocaudal thalamus receive nociceptive inputs directly from projecting spinal neurons, and project directly to the somatosensory cortex. Neurons in the medial thalamus receive some indirect input from the spinal cord, but the major input is from the region of the



**Fig. 11.1** Synaptic layers in the gray matter. (a) Cervical cord. (b) Thoracic cord.

(c) Lumbar cord. Motor neurons are shown in red and sensory neurons in blue. The gray matter can also be divided into layers of axon termination, based on cytological criteria. This was first done by Swedish neuroanatomist Bror Rexed (1914–2002), who divided the gray matter into laminae I–X. This laminar architecture is especially well-defined in the posterior (dorsal) horn, where primary sensory axons make synapses in specific layers. (Reproduced from THIEME Atlas of Anatomy, Head and Neuroanatomy, ©2007, Thieme Publishers, New York. Illustration by Markus Voll.)



brainstem reticular formation to which the spinoreticular neurons project. The medial thalamus projects to widespread areas of the forebrain, including the anterior cingulate and somatosensory cortices.<sup>2</sup>

The lateral pathway is likely responsible primarily for localization and characterization of noxious stimuli while the medial spinoreticulothalamic pathway may modulate the affective and motivational aspects of pain.

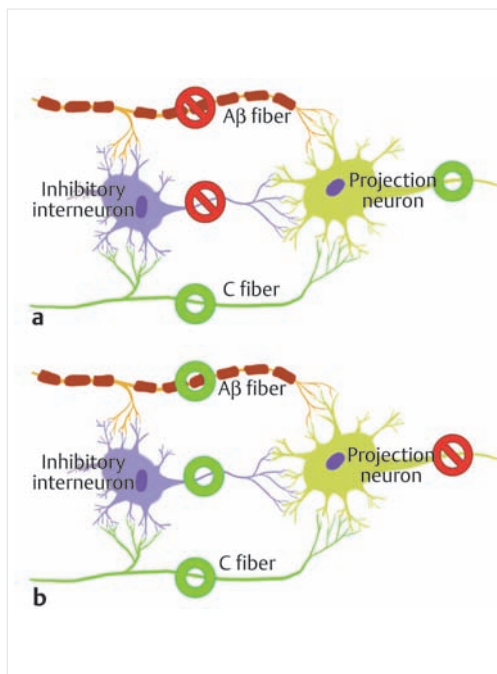
benign stimuli close the “gates” to painful stimuli, preventing pain from traveling to the brain. The theory requires that the passage of painful impulses via unmyelinated (C) and small myelinated ( $\delta$ ) fibers should be slowed or abolished by simultaneous input into the larger myelinated  $A\beta$  nerve fibers (responding to touch, pressure, and vibration).

Therefore, stimulation by non-noxious input is able to suppress pain.

### 11.1.4 Gate Control Theory

The gate control theory of pain, proposed in 1965 by Melzack and Wall,<sup>3</sup> asserts that

This theory reconciled earlier specificity and pattern theories of pain (► Fig. 11.3).



**Fig. 11.3** Gate control theory of pain. **(a)** The firing of the projection neuron determines pain. The inhibitory interneuron decreases the chances that the projection neuron will fire. Firing of C fibers inhibits the inhibitory interneuron (indirectly), increasing the chances that the projection neuron will fire. Inhibition is represented in blue, and excitation in yellow. A green circle signifies increased neuron activation, while a red crossed-out circle signifies weakened or reduced activation. **(b)** Firing of the  $A\beta$  fibers activates the inhibitory interneuron, reducing the chances that the projection neuron will fire, even in the presence of a firing nociceptive fiber. (Illustration by Zhu Xiao.)

## 11.2 Major Types of Pain

### 11.2.1 Nociceptive

This most common type of pain transmits information about injury or inflammation via small diameter afferent nerve fibers (δ or “pain” fibers).

It corresponds to an actual stimulus, and generally lessens with time and healing.

- **Somatic:** Well localized. Results from tissue injury, inflammation, or nerve/plexus compression. Responds to treatment of underlying pathology or inhibition of nociceptive transmission by analgesic or anesthetic medications.
- **Visceral:** Poorly localized. Arises due to direct stimulation of afferent nerves due to tissue injury, inflammation, or compression of the soft tissue or viscera. Lesser response to analgesic medications.

### 11.2.2 Neuropathic

Neuropathic pain is caused by a lesion of the peripheral and/or central nervous system, resulting in a sensation of pain that does not correspond to an actual stimulus.

Examples include painful diabetic neuropathy (PDN) and postherpetic neuralgia (PHN). It is typically burning, aching, continuous and frequently refractory to medical and surgical treatment. It is often chronic and can worsen with time.

- **Deafferentation:** Interruption of sensory conduction via damage to large diameter sensory nerve fibers (mediating touch and pressure sense) can alter upstream firing patterns, leading to pain in an area that is otherwise insensate. This pain is often described as crushing, tearing, or tingling.

- **“Sympathetically maintained”/Causalgia/Complex regional pain syndrome (CRPS):** All categorized by irregularities in autonomic nervous system function. See section 11.3.5 for further details.
- **Neuromas:** A neuroma is a disorganized growth of nerve cells at the site of a nerve injury (secondary to trauma or surgery). It can be a ball-shaped terminal stump in the case of nerve transection, or a neuroma “in continuity” in case of injury that has disrupted the axons but not the perineurium. It will typically cause pain or paresthesias when palpated or percussed.
- **Other:** Etiologies may also include alcoholic and chemotherapy induced polyneuropathies, entrapment neuropathies, HIV sensory neuropathy, neoplastic nerve compression, nutritional deficiency, postradiation, toxic exposure, post-traumatic, cervical spondylotic, multiple sclerosis/Parkinson disease, and post-stroke etiologies.

## Medical Treatment

In contrast to nociceptive pain that primarily involves non-narcotic and opioid analgesia, the initial treatment for neuropathic pain typically involves either anti-depressants (tricyclics, selective serotonin reuptake inhibitors/serotonin and norepinephrine reuptake inhibitors) or calcium channel ligands (gabapentin/pregabalin) with adjunctive topical therapy (lidocaine). Opioids should be considered as a second-line option.<sup>4</sup>

## 11.3 Craniofacial Pain Syndromes

### 11.3.1 Trigeminal Neuralgia

This is also known as *tic douloureux*. A pain disorder that affects the trigeminal nerve.

There are two main types:

- **Typical:** Results in episodes of severe, sudden, shock-like pain in one side of the face that lasts for seconds to a few minutes. Groups of episodes can occur over a few hours.
- **Atypical:** Results in a constant burning pain that is less severe. Episodes may be triggered by any sensory stimulus to the face.

More recently, attempts have been made to classify trigeminal neuralgia (TN) primarily based on patient history<sup>5</sup>:

- **Type 1:** Spontaneous onset with more than 50% predominant episodic pain.
- **Type 2:** Spontaneous onset with more than 50% constant pain.

## Pathophysiology

The most common causes are vascular compression of the trigeminal nerve at the root entry zone (80% by the superior cerebellar artery, ►Fig. 11.4),<sup>6,7,8</sup> a posterior fossa tumor with nerve compression, or a multiple sclerosis (MS) plaque within the brainstem. The common mechanism is demyelination leading to abnormal (ephaptic) transmission of benign sensory stimuli through the poorly myelinated A $\delta$  and C type pain fibers.

## Signs and Symptoms

The primary symptom is paroxysmal pain, generally lasting for a few seconds, that is isolated to the distribution of one or more branches of the trigeminal nerve unilaterally. This pain may be triggered by benign sensory stimuli to a specific area of the face, and is often shock-like or stabbing; no neurologic deficit is associated with this pain. When pain occurs as tic-like spasms in rapid succession, it is known as *status trigeminus*.

## Diagnosis

Diagnosis is made by clinical history, after ruling out other major causes of facial pain such as dental disease, disease of the orbit



**Fig. 11.4** MRI axial T1 image with contrast at the level of the mid pons showing an aberrant loop of the superior cerebellar artery (red arrow) impinging on the root of the trigeminal nerve. The patient presented with clinical symptoms of trigeminal neuralgia. (Reproduced from Gasco J, Nader R, *The Essential Neurosurgery Companion*, 1st edition, ©2012, Thieme Publishers, New York.)

or sinuses, temporal arteritis, tumor, and herpes zoster. The history must include the distribution and character of the pain as well as localizing the involved division(s) of the trigeminal nerve. The pain is characteristically paroxysmal, with pain free intervals; constant pain should prompt consideration of other diagnoses.

The neurologic examination should be normal unless the patient has undergone microvascular decompression or nerve ablation (see below), in which case there may be decreased sensation or even associated dysfunction of cranial nerves VII and VIII. Noniatrogenic neurologic deficit suggests a brain tumor or other lesion (neurosarcoidosis, demyelinating plaque, etc.). Tests of trigeminal nerve function include the corneal reflex, assessment of facial sensation to all modalities in all three divisions of the



trigeminal nerve, and assessment of bite strength (for *portio minor nervi trigemini*, the motor branch of the trigeminal nerve). To rule out orbital disease, one should assess extraocular movement function.

The International Classification of Headache Disorders, 3rd edition (ICHD-3) diagnostic criteria for classic TN are as follows<sup>9</sup>:

- At least three attacks of unilateral facial pain fulfilling criteria b and c.
- Occurring in one or more divisions of the trigeminal nerve, with no radiation beyond the trigeminal distribution.
- Pain has at least three of the following four characteristics:
  - Recurring in paroxysmal attacks lasting from a fraction of a second to two minutes.
  - Severe intensity.
  - Electric shock-like, shooting, stabbing, or sharp in quality.
  - At least three attacks precipitated by innocuous stimuli to the affected side of the face (some attacks may be, or appear to be, spontaneous).
- No clinically evident neurologic deficit.
- Not better accounted for by another ICHD-3 diagnosis.

## Treatment

### Medical Therapy

The first-line therapy for TN, carbamazepine, will give initial relief in 69% of patients. If patients fail to respond or become refractory to carbamazepine or oxcarbazepine, second-line agents include baclofen, tricyclic antidepressants, and gabapentinoids. Third-line agents such as phenytoin or benzodiazepines may be tried, but these have a low rate of clinical efficacy.

### Surgical Therapy

Surgical referral is recommended for patients that are refractory to or intolerant of medical management.

Ultimately, up to 75% of patients may eventually fail to benefit from medical therapy. Selection of the optimal treatment procedure depends on patient age, distribution of symptoms, prior treatment, and the side effect profile of the treatment modality.<sup>10</sup>

#### • Microvascular decompression (MVD):

A microsurgical exploration of the root entry zone is performed via retrosigmoid craniectomy. The vessel that is impinging on the nerve is dissected away and displaced using a nonabsorbable insulator to absorb the pulsations. Internal neurolysis or even intradural retrogasserian trigeminal nerve section may be performed during the MVD if no vascular compression is identified, although with modern imaging techniques, the vascular anatomy is usually delineated preoperatively.

#### • Ablative procedures:

- Percutaneous trigeminal rhizotomy: Interruption of pain transmission through selective destruction of the A $\delta$  and C nociceptive fibers while preserving the A $\alpha$  and A $\beta$  fibers which mediate touch and other sensory parameters. Methods include radiofrequency thermocoagulation, glycerol injection into Meckel's cave, and percutaneous microcompression via inflation of a Fogarty catheter balloon.
- Extradural subtemporal approach: Primarily of historical interest. The approach was used to expose the ganglion and then mildly traumatize it.
- Stereotactic radiosurgery (SRS): A small collimator size (4–5 mm) is used to place a 70–90 Gy lesioning dose on the portion of the trigeminal nerve as it enters the brainstem in the root entry zone. There is latency to pain relief, thus SRS is suboptimal for patients needing immediate relief.

## 11.3.2 Glossopharyngeal Neuralgia

### Pathophysiology

Glossopharyngeal neuralgia may be caused by irritation of the cranial nerve IX. As with TN, there are idiopathic and secondary forms of glossopharyngeal neuralgia. Demyelinating lesions, cerebellopontine angle tumor, peritonsillar abscess, carotid aneurysm, and Eagle syndrome (in which cranial nerve IX is compressed laterally against an ossified stylohyoid ligament) are examples of secondary glossopharyngeal neuralgia.



Vascular compression of cranial nerves IX and X can occur at the nerve root entry zone by the vertebral artery or posterior inferior cerebellar artery.

### Signs and Symptoms

Characterized by paroxysmal, severe, stabbing pain involving the ear, tonsillar fossa, base of the tongue, or beneath the angle of the jaw.

### Diagnosis

Evaluation includes a thorough history, with emphasis on triggering factors and the presence of nocturnal awakening. A careful intraoral and neck examination should be undertaken to help exclude local disease as a cause for the pain.



MRI/MRA is indicated in virtually all patients to rule out a mass lesion or vascular pathology<sup>11,12</sup>; plain skull films may reveal an ossified stylohyoid ligament (consistent with Eagle syndrome).

According to the ICHD-3, the diagnosis of glossopharyngeal neuralgia requires all of the following:

- At least three attacks of unilateral pain.
- Pain is located in the posterior part of the tongue, tonsillar fossa, pharynx, beneath the angle of the lower jaw and/or in the ear.
- Pain has at least three of the following four characteristics:
  - Recurring in paroxysmal attacks lasting from a few seconds to 2 minutes
  - Severe intensity
  - Shooting, stabbing, or sharp in quality
  - Precipitated by swallowing, coughing, talking, or yawning
- No clinically evident neurological deficit.
- Not better accounted for by another ICHD-3 diagnosis.

### Treatment

**Medical Therapy:** See medical treatment section for TN (section 11.3.1). Application of local anesthetics to the oropharynx may also prove diagnostic and therapeutic.

**Surgical Therapy:** For those who fail medical therapy, procedures include intracranial sectioning of cranial nerve IX plus the upper three to four rootlets of cranial nerve X at the jugular foramen, or vascular decompression.<sup>13,14,15,16</sup>

## 11.3.3 Other Craniofacial Neuralgias

Other craniofacial neuralgias include geniculate neuralgia (involves a somatic sensory branch of the facial nerve), occipital neuralgia, and supraorbital/supratrochlear neuralgia. All these conditions involve pain in the distribution of the involved nerve and may be treated with medications, nerve blocks, and decompressive surgery/ablative procedures.

### 11.3.4 Postherpetic Neuralgia

Following resolution of the rash caused by Varicella-zoster virus (VZV), a variable percentage of patients may continue to experience severe neuropathic pain. Major risk factors include older age, greater acute pain, and greater rash severity.<sup>17,18,19,20</sup> The risk is also likely increased with immunosuppression.<sup>21,22</sup> The pain usually resolves 2–4 weeks after the vesicular eruption has healed; when pain persists for more than 1 month, it is called PHN.

### Pathophysiology

Acute herpes zoster is caused by reactivation of latent VZV in the dorsal root ganglia of cranial or spinal nerves, often years after resolution of the original infection.

As cellular immunity wanes with age or immunocompromise, the virus is transported along peripheral nerves, producing an acute neuritis.<sup>20,23</sup>

### Signs and Symptoms

Pain associated with acute zoster infection and PHN can be burning, sharp, or stabbing in character and may be constant or intermittent.<sup>24,25</sup> More than 90% of patients with PHN also have allodynia (pain evoked by normally benign stimuli such as light touch). Patients with PHN often have deficits in thermal, tactile, pinprick, and/or vibration sensation within the affected dermatomes.<sup>26</sup> It usually presents soon after resolution of the rash, but has been reported to occur months to years after the initial event.<sup>27</sup>

### Diagnosis

The diagnosis of PHN is a clinical one, made when pain persists beyond 4 months in the same distribution as a preceding documented episode of acute herpes zoster. Additional supporting diagnostic factors include advanced age, severe prodromal pain and preceding rash with acute zoster, a dermatomal distribution, and the presence of allodynia.<sup>28</sup>

Rarely, nerve pain in acute zoster may emerge in the absence of a rash, as occurs in a condition called *zoster sine herpette* or in intercostal neuralgia. Pain in a trigeminal or radicular distribution combined with the detection of VZV by polymerase chain reaction (PCR) in the cerebrospinal fluid (CSF) supports the diagnosis of *zoster sine herpette*.<sup>29</sup>

On examination, the areas affected by PHN may be remarkable for scarring related to the vesicular eruption of the preceding acute herpes zoster infection, or by areas of excoriation caused by scratching. The affected skin may display decreased sensation to mechanical and thermal stimuli, hyperalgesia (increased sensitivity to painful stimuli), or allodynia.

### Treatment

**Herpes Zoster:** Pain associated with the acute attack of herpes zoster may be treated with epidural or paravertebral somatic block (intercostal) (See section on pain procedures).<sup>30</sup> Oral antiherpetic drugs include acyclovir (Zovirax), valacyclovir (Valtrex), and famciclovir (Famvir). These drugs reduce the incidence of PHN but may cause thrombotic thrombocytopenic purpura/hemolytic uremic syndrome when used in severely immunocompromised patients at high doses.

**PHN:** It is suggested to initiate therapy with lidocaine skin patches since this modality has the lowest potential for

serious side effects. Most drugs useful for TN are less effective for PHN. First-line drug treatments include tricyclic antidepressants, gabapentin, and pregabalin. These treatments along with opioids have proven more effective than placebo in systematic reviews.<sup>31,32,33,34</sup> Since the pain of PHN can be chronic, long-term therapy is often required, however, the long-term benefits of most therapies are uncertain, and side effects are common.<sup>35</sup>

- **Tricyclic antidepressants (TCA):** Amitriptyline, nortriptyline.
  - Recommended as initial treatment for those with moderate-to-severe PHN pain. Exceptions include patients with heart disease, epilepsy, or glaucoma.
  - Should be used cautiously in older patients especially those with cognitive impairment/dementia due to anticholinergic effects.
- **Antiepileptic drugs:** Gabapentin, oxcarbazepine, zonisamide.
  - Recommended for patients with moderate-to-severe PHN with contraindications to or intolerance of TCAs.
  - Side effects include dizziness, somnolence, ataxia, peripheral edema, confusion, and depression.
- **Topical treatment:** Capsaicin, lidocaine patch 5%.
  - Recommended for patients with mild-to-moderate localized pain from PHN who do not desire systemic therapy with TCAs.
- **Intrathecal steroids:**
  - An option for patients who continue to have intractable pain despite the above measures. These do not work for pain in the trigeminal nerve distribution.
- **Surgical treatment:**
  - No operation is uniformly successful in treating PHN. Procedures include nerve blocks, rhizotomy, cordotomy,

sympathectomy, neurectomies, acupuncture, dorsal root entry zone (DREZ) lesions, spinal cord stimulation (SCS), and motor cortex stimulation (for facial PHN). See procedures section.

### 11.3.5 CRPS/Causalgia

The term *causalgia* was introduced by Weir Mitchell in 1864 to describe a rare syndrome that followed a minority of partial peripheral nerve injuries in the American civil war. The syndrome is characterized by regional pain, limited range of motion, swelling, skin changes, vasomotor instability, and patchy bone demineralization, usually in the distal limb. It frequently begins following a fracture, soft tissue injury, or surgery. The syndrome has subsequently been reclassified as “complex regional pain syndrome” (CRPS).

Two subtypes of CRPS have been recognized<sup>36,37</sup>:

- **Type I** aka reflex sympathetic dystrophy or causalgia minor: Corresponds to patients with CRPS without evidence of peripheral nerve injury and represents about 90% of clinical presentations.
- **Type II** formerly termed causalgia: Refers to cases in which objective peripheral nerve deficits are present.

### Pathophysiology

The pathogenesis of CRPS is unknown. Early theories invoked ephaptic transmission between sympathetic and afferent pain fibers although this theory is rarely cited these days. Some studies have found that patients with CRPS have

significant increases in proinflammatory cytokines in affected tissue as well as in plasma and CSF.<sup>38,39,40,41</sup> The release of inflammatory mediators and pain-producing peptides by peripheral nerves has therefore been implicated as a possible mechanism.<sup>42,43,44</sup> Central sensitization, whereby increased activity in nociceptive afferents leads to increased synaptic transmission at somatosensory neurons in the dorsal horn of the spinal cord, is another possible explanation for pain and allodynia in CRPS.<sup>42</sup> Another more recent postulate involves excessive norepinephrine release at sympathetic terminals together with catecholamine hypersensitivity, which may explain autonomic manifestations of CRPS.<sup>45</sup>

## Signs and Symptoms

The primary clinical manifestations of CRPS are pain, sensory changes, motor impairments, autonomic symptoms, and trophic changes in the affected limb.<sup>46</sup> The onset generally occurs within 4–6 weeks of the inciting event.<sup>46,47</sup> The initial symptoms usually include pain, erythema, and swelling of the affected limb.<sup>43</sup> Pain is typically the most prominent and debilitating symptom and is described as a stinging, burning, or tearing sensation that is felt deep inside the limb in most cases. Sensory abnormalities include hyperalgesia, allodynia, or hypesthesia (diminished capacity for physical sensation) and usually occur in the distal limb.<sup>48</sup> Limb movement may be limited by edema, pain, or contractures. Trophic changes may include increased hair growth, increased or decreased nail growth, contraction and fibrosis of joints and fascia, and skin atrophy. These symptoms may spread over time to involve adjacent areas of the affected limb or other ipsilateral or contralateral limbs.<sup>49,50</sup>

## Diagnosis

The diagnosis of CRPS is based upon history and physical examination, using the following features<sup>48</sup>:

- Symptoms develop after limb trauma, usually within 4–6 weeks.
- Symptoms no longer fully explained by the initial trauma.
- Symptoms affect the distal limb, go beyond the region involved in the trauma, or extend beyond the territory innervated by a single nerve or nerve root.

In the absence of an agreed upon pathophysiology, no “gold-standard” diagnostic criteria have been developed. Tests that have been proposed include thermography, three-phase bone scan, osteoporosis on X-ray, response to sympathetic block and autonomic testing, but none of these has demonstrated adequate specificity.

## Treatment

A multidisciplinary approach is suggested for the management of CRPS, and treatment is more effective when started early in the course of the disease.<sup>51,52</sup> For patients with early CRPS, it is suggested to start with one or more of the following: nonsteroidal anti-inflammatory drugs (NSAIDs), an anticonvulsant (gabapentin or pregabalin), a TCA or other antidepressant drug effective for neuropathic pain (typically amitriptyline or nortriptyline), bisphosphonate treatment, or topical lidocaine/capsaicin cream. Medical therapy is usually ineffective. Other proposed treatments include:

- Sympathetic blocks (18–25% have satisfactory long-lasting relief).
- Intravenous regional sympathetic block: Particularly for upper extremity CRPS although not better than placebo in several trials.<sup>53,54</sup>
- Surgical sympathectomy: Some purport this relieves pain in greater than 90% of

patients. Other studies have shown this to be no more effective than placebo.<sup>55</sup>

- SCS: Some success reported.
- Dorsal root ganglion stimulation.

### 11.3.6 Peripheral Nerve

#### Pathophysiology

Peripheral nerve syndromes may be caused by compression of nerve segments such as in carpal tunnel syndrome but can also occur proximally at the root level such as when a herniated cervical disc compressed the spinal root. Pathology may be caused less commonly by transection, nerve ischemia, radiation, inflammation, degeneration, and metabolic problems.

#### Diagnosis and Treatment



Nerve conduction studies and electrodiagnostic studies such as electromyogram and are the most effective means of identifying and classifying peripheral nerve disorders.

MRI is also used to identify cervical spine disease, disc herniation, degeneration, and compression. Treatments include medication, splinting, steroid injections, and surgery for nerve decompression or transposition.

#### Syndromes

##### Carpal Tunnel

- Most common entrapment syndrome; involves median nerve in the wrist.
- Symptoms include hand tingling that is worse at night.
- Tinels (tapping of wrist) and Phalen's (flexion of wrist) tests are used to diagnose.

- Electrodiagnostic studies are the most sensitive for diagnosis.

##### Anterior Interosseous

- Rare, pure motor neuropathy with occasional reported dull forearm pain.
- Patient fails to make OK sign (flexion of thumb interphalangeal and index finger distal interphalangeal joint impaired).
- Can diagnose with pinch test (patient cannot pinch paper between thumb and index finger) as well as on ultrasound and MRI.

##### Posterior Interosseous

- Compression causes gradual onset of weakness of extension of the digits and wrist. Pain is not a primary feature and no sensory deficit.
- MRI can identify muscle signal changes indicating denervation.

##### Ulnar

- Can be compressed above elbow, at elbow, at cubital fossa, or Guyon's canal at the wrist.
- Most evident finding is first dorsal interosseous wasting. Other interossei wasting may occur.
- Results in claw deformity and decreased sensation over little finger and ulnar side of ring finger.
- Evaluate with electrodiagnostic studies and ultrasound.

## 11.4 Procedures for Pain

Medical therapy should be maximized before a patient becomes a candidate for a pain procedure. In general, nonablative procedures are exhausted before resorting to ablative procedures.

## 11.4.1 Electrical Stimulation

### Peripheral Nerve

Peripheral nerve stimulation (PNS) is a technique in which electrodes are placed along the course of peripheral nerves to control pain. PNS utilizes the previously mentioned gate control theory to suppress pain by stimulating the non-noxious sensory pathway (large myelinated A $\beta$  nerve fibers). A temporary trial electrode is left in place for a week or so to determine if PNS is helpful followed by implantation of a permanent electrode if the trial is successful.

### Dorsal Root Ganglion

The dorsal root ganglion contains the cell bodies of first-order afferent neurons. It occupies a predictable location in the neural foramen, and an epidurally inserted wire can be inserted under fluoroscopic guidance in order to provide relief within the dermatome innervated by that level. Adjacent dermatomes can also be stimulated via the *rami communicantes* (nerve fibers which run between nearby spinal levels).

### Spinal Cord Stimulation

SCS involves the insertion of electrodes into the posterior epidural space in order to interrupt pain transmission (► Fig. 11.5). The exact mechanism of action of SCS is undetermined, but likely involves both anterograde and retrograde modulation of sensory pathways, particularly the activity of wide dynamic range neurons in the dorsal horn of the spinal cord.

The most common indication for SCS is postlaminectomy pain syndrome or failed back syndrome; a condition characterized by persistent pain following back surgeries. SCS is also effective in CRPS type 1,<sup>56</sup>

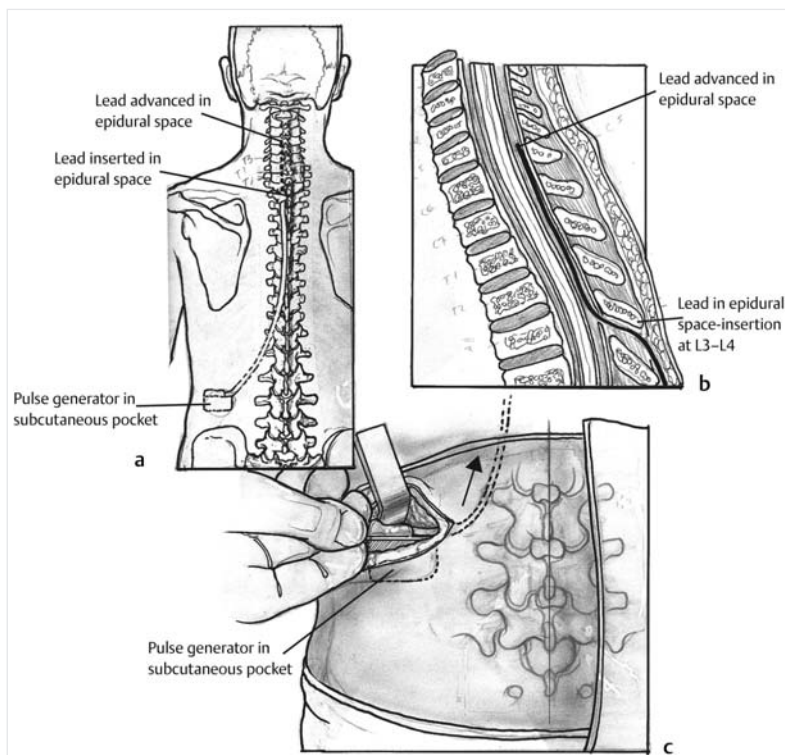
as well as post-thoracotomy pain, multiple sclerosis, diabetic neuropathy, refractory angina pectoris, painful limb ischemia from inoperable peripheral vascular disease, and sometimes PHN.

Following electrode placement, an external generator trial over several days determines if SCS is effective, in which case an implantable pulse generator is placed subcutaneously and connected to the electrodes. Complications of SCS include infection (3.5% incidence with plate electrodes), electrode migration, lead breakage, CSF leak, radicular pain, interference with cardiac pacemakers, and weakness. The success rate in pain control is approximately equal to 50% improvement in 50% of patients in experienced hands at specialized centers where multidisciplinary approach is available.<sup>57</sup>

### Deep Brain Stimulation

Deep brain stimulation (DBS) may be used to treat a variety of conditions including movement disorders, epilepsy, and pain syndromes. Deafferentation pain syndromes such as anesthesia dolorosa (pain felt in an area that is completely numb to the touch), pain from spinal cord injury, or thalamic pain syndromes may benefit from stimulation of sensory thalamus (ventral posteromedial or ventral posterolateral). DBS for chronic neuropathic pain produces a 40–50% reduction in pain in about 25–60% of patients.<sup>58</sup> Anecdotal reports of DBS and motor cortex stimulation have also been described for the treatment of intractable severe persistent pain states.<sup>56</sup>

Nociceptive pain syndromes are more likely to benefit from stimulation of periventricular gray matter or periaqueductal gray matter. The Food and Drug Administration (FDA) has failed to approve these devices for pain due to response rate of only about 20%.<sup>59</sup>



**Fig. 11.5** Schematic illustrating (a) spinal cord stimulator placement, (b) catheter tip location in epidural space, and (c) pulse generator in subcutaneous pocket. (Reproduced from Connolly E, McKhann II G, Huang J et al, *Fundamentals of Operative Techniques in Neurosurgery*, 2nd edition, ©2010, Thieme Publishers, New York.)

## Transcranial Magnetic

In transcranial magnetic stimulation (TMS), electromagnetic coils held against the scalp influence underlying cortical firing. Studies have shown that repetitive TMS of the motor cortical area corresponding to the painful area may have some efficacy to induce long-lasting pain relief that could have therapeutic potential.<sup>60</sup>

## 11.4.2 Drug Delivery

### Intraspinal Narcotics

Spinal narcotics can be administered intrathecally or epidurally for pain relief. In intrathecal drug delivery, the subarachnoid space is usually accessed from the lumbar region and medications are infused through a drug delivery system comprised of a pump and catheter. Prior to



implantation of an infusion pump, patients undergo an initial trial where medication is delivered through the catheter for a variable period of time depending on how long it takes to achieve an optimal dosage level. The pump is then implanted under the skin, usually in the abdomen, in a “pocket” between skin and muscle tissue.

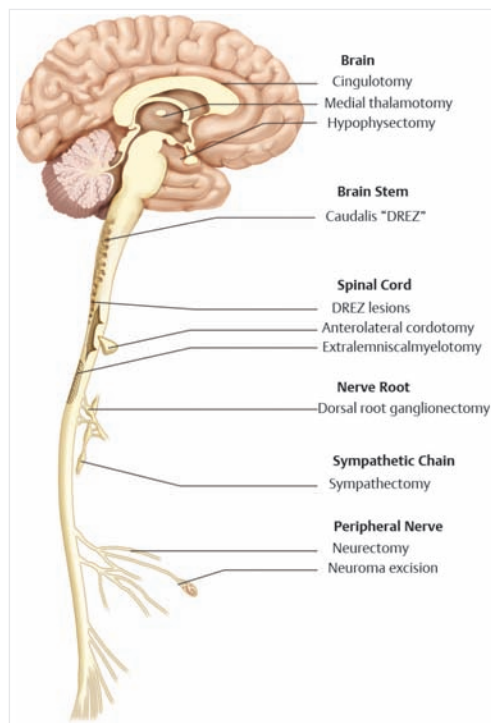
Advantages over systemic narcotics include less medication requirement, less sedation and/or confusion, less constipation, and possibly less nausea and vomiting. Increasing doses are required with time due to the development of tolerance and/or progression of disease.<sup>61</sup> Complications include meningitis and respiratory failure (rare). CSF fistula and spinal headache may also occur and dislodgement/disconnection of the catheter tip may occur but can

usually be surgically corrected. Long-term use of intrathecal or epidural opioids may cause formation of catheter-associated granulomas, inflammatory masses at the tip of intrathecal catheters that can possibly lead to neurological deficit and/or catheter revision. Cancer pain is significantly improved in up to 90% and success rates for neuropathic pain range from 25 to 50%.

Currently, the only medications approved by the FDA for intrathecal administration are morphine, ziconotide, and baclofen.

### 11.4.3 Spinal Ablative Procedures

► Fig. 11.6 demonstrates the central and peripheral nervous systems with the



**Fig. 11.6** Illustration of the central and peripheral nervous systems with potential lesion procedures segregated at each level of pain processing. DREZ, dorsal root entry zone. (Reproduced from Harbaugh R, Shaffrey C, Couldwell W et al, Neurosurgery Knowledge Update: A Comprehensive Review, 1st edition, ©2015, Thieme Publishers, New York.)

various lesional procedures that will be discussed below.

## Dorsal Root Entry Zone

DREZ lesions appear most effective in treating deafferentation pain from nerve root avulsion, spinal cord injuries, PHN, and postamputation phantom limb pain. During the procedure, the DREZ is identified under microscope and lesions are created ipsilateral to the avulsed nerve roots by radiofrequency current or selective incisions.

## Sympathectomy

Surgical sympathectomy is indicated for a variety of conditions including essential hyperhidrosis, primary Raynaud disease, shoulder-hand syndrome, and intractable angina. The procedure may also be used to treat the symptoms of causalgia major. Lumbar sympathectomy is indicated for causalgia major of the lower extremity and preoperative lumbar sympathetic blocks may be utilized to evaluate the patient for response. Removal of the L2 and L3 sympathetic ganglion is usually adequate to remove sympathetic tone from the lower extremities.

## Cordotomy

Cordotomy involves interruption of the lateral spinothalamic tract fibers in the spinal cord. This is the procedure of choice for *unilateral* pain below the C5 dermatome level in a terminally ill patient and may be performed open or percutaneously at the C1–C2 interspace. If any contralateral pain exists, it tends to be magnified following the procedure.



Bilateral cervical cordotomies carry the risk of a loss of automaticity of breathing (Ondine's curse).

A second procedure should be staged after normal respiratory function and CO<sub>2</sub> responsiveness are verified following the first procedure if bilateral cordotomies are desired.

With percutaneous cordotomy, radiofrequency current is used to lesion the lateral spinothalamic tract. In experienced hands, 94% will achieve significant pain relief at the time of discharge although this number drops to 60% at 1 year and 40% at 2 years. Complications include ataxia, bladder dysfunction, ipsilateral paresis, dysesthesia, sleep induced apnea, and death from respiratory failure.

## Commissural Myelotomy

This procedure interrupts pain fibers crossing in the anterior commissure on their way to the lateral spinothalamic tract. Indications include bilateral or midline pain, primarily below the thoracic levels. About 60% of patients have complete pain relief, 28% have partial, and 8% have none. Complications include lower extremity weakness (8%), dysesthesias, bladder dysfunction, sexual dysfunction, and injury to the anterior spinal artery (rare).

## 11.4.4 Intracranial Ablative Procedures

### Stereotactic Mesencephalotomy

This is used for unilateral head, neck, face, and/or upper extremity pain. MRI guidance is used to create a lesion 5 mm lateral to the Sylvian aqueduct at the level of the inferior colliculus. The main complication is diplopia due to interference with vertical eye movement (often transient).

## Cingulotomy

Cingulotomy theoretically reduces the unpleasant effect of pain without eliminating the pain. The procedure involves a bilateral lesion of the cingulate gyrus using MRI guidance. Potential side effects include nausea, vomiting, headaches, seizures, and flattened affect (10–30%).

### 11.4.5 Cancer Pain

Cancer pain can be extremely difficult to treat. Particularly if located peripherally, malignant tumors may cause pain. Cancer pain within the CNS, particularly the brain and spinal cord, may present only with the symptomatology of headache, and may be treated with other means.

Patients are generally referred to a neurosurgeon when their cancer pain is refractory to opioid medication. These patients may undergo a trial of either an intravenous narcotic pain medication regimen or a morphine pump infusion (see above).

Aggressive and invasive surgical techniques are also an option but are decreasingly utilized with the advent of the intrathecal morphine pump. These procedures include DREZ lesioning, cordotomy (open or percutaneous), and commissural myelotomy (for bilateral pain). DBS in the periaqueductal or periventricular gray matter may also be considered.

Recent randomized controlled trials of intrathecal drug delivery systems versus comprehensive medical management have shown that intrathecal drug delivery improves clinical success in pain control, relieves drug toxicities, reduces pain, improves patient survival, and decreases medical utilization over the first year post-implant in patients with refractory cancer pain.<sup>62,63</sup>

## Pearls



- Arriving at the correct diagnosis is absolutely critical in the treatment of pain. A multidisciplinary approach can help ensure that nothing is being overlooked, and a formal psychological evaluation may be indicated to determine whether maladaptive coping strategies or concomitant mood disorder may be playing a role in perpetuating the pain.
- Surgical therapies should not be considered “last resort.” In appropriately selected patients, they may result in faster resolution of pain and more durable relief with fewer side effects than medical therapies. The key is appropriate patient selection.
- Neuromodulatory therapies (such as stimulation or intrathecal drug delivery) should generally be preferred over neuroablative procedures when possible, due to their reversible and titratable nature. The exception is in cancer pain, where percutaneous cordotomy can result in essentially instantaneous relief.

## 11.5 Top Hits

### 11.5.1 Questions

1. Choose the answer that best describes the pathway for the sensation of pain in the nervous system.
  - a) Peripheral receptors, first-order neuron, dorsolateral tract of Lissauer, substantia gelatinosa, second-order neuron, ventral white commissure, spinothalamic tract.
  - b) First-order neuron, peripheral receptors, substantia gelatinosa, dorsolateral tract of Lissauer, second-order neuron, ventral white commissure, spinothalamic tract.

- c) Dorsolateral tract of Lissauer, peripheral receptors, first-order neuron, substantia gelatinosa, second-order neuron, spinothalamic tract, ventral white commissure.
    - d) Peripheral receptors, first-order neuron, ventral white commissure, dorsolateral tract of Lissauer, substantia gelatinosa, second-order neuron, spinothalamic tract.
  2. Surgical sympathectomy can be used to treat all of the following conditions except:
    - a) Essential hyperhidrosis
    - b) Primary Raynaud disease
    - c) TN
    - d) Shoulder-hand syndrome
  3. Pair each statement with the appropriate category of pain.
    - 1—Deafferentation pain,
    - 2—CRPS type I,
    - 3—Nociceptive pain,
    - 4—CRPS type II,
    - 5—Neuropathic pain/PHN.
    - a) A 24-year-old soccer player twists his ankle during a game and reports throbbing pain (6/10) and swelling immediately afterwards.
    - b) A Vietnam War veteran who had his right leg amputated above the knee after a traumatic injury reports burning and tingling in the area below his right knee.
    - c) A 40-year-old female complains of burning pain, muscle spasms, decreased mobility, and decreased hair growth, nail cracking, skin color changes, and increased sweating in her right arm and hand. She had sprained this arm 1 month ago and recently had a splint removed.
    - d) A 60-year-old male reports an intermittent burning and stabbing pain on the right side of his chest.
- On examination, there are areas that demonstrate increased pain to light touch as well as areas with anesthesia. He reports a vesicular eruption from several weeks prior that has since resolved.
4. A 45-year-old female comes to the physician's office complaining of a sudden sharp pain on the right side of her face that occurs when brushing her teeth. The pain will also come and go multiple times throughout the day without provocation. On examination, the patient's symptoms are reproduced with light touch to the right cheek. What is the best initial treatment for this patient?
    - a) Microvascular decompression
    - b) Carbamazepine
    - c) Phenytoin
    - d) SRS
  5. SCS can be used to treat pain caused by all of the following conditions except:
    - a) Postlaminectomy pain syndrome
    - b) Multiple sclerosis
    - c) Diabetic neuropathy
    - d) Prostate cancer metastasis
  6. Choose the most correct statement regarding CRPS:
    - a) CRPS type I corresponds to cases in which peripheral nerve injury is present.
    - b) Symptoms of CRPS include pain, swelling, decreased range of motion, skin changes, and bone demineralization.
    - c) The pathophysiology of CRPS involves reactivation of a virus that persists for years in the dorsal root ganglia of cranial or spinal nerves.
    - d) CRPS must include at least three attacks of unilateral pain that last from a fraction of a second to 2 minutes.

7. Peripheral nerve stimulation is a technique that utilizes the theory of gate control to suppress pain by stimulating:
  - a) A $\delta$  fibers
  - b) C fibers
  - c) A $\beta$  fibers
  - d) A $\alpha$  fibers
8. Match the complications with the associated treatment modality:
  - 1—Stereotactic mesencephalotomy,
  - 2—Cordotomy,
  - 3—Intraspinal narcotics,
  - 4—Cingulotomy.
  - a) Loss of automaticity of breathing (bilateral treatment)
  - b) Meningitis, spinal headaches, respiratory failure
  - c) Diplopia
  - d) Nausea, vomiting, seizures, flattened affect
9. A 64-year-old male with a history of heart disease presents to the office with severe intermittent burning and stabbing pain on the left side of his chest for 4 days. The pain is nonradiating but exacerbated by light touch. He reports having had a vesicular eruption in the same area that resolved one week ago. What is the most appropriate next step in treatment for this patient?
  - a) Sublingual nitroglycerin
  - b) Amitriptyline
  - c) Gabapentin
  - d) Topical lidocaine
10. A 65-year-old male with a history of diabetes and hypertension presents to the office with chronic persistent back pain that he describes as dull and aching and also involving his upper legs. He describes some occasional sharp, pricking and stabbing pain in his lower extremities. He has a history of three back surgeries for radiculopathy

due to recurrent disc herniation at L4–L5. Which of the following treatments is most indicated to relieve this patient's chronic back pain?

- a) Intrathecal baclofen
- b) SCS
- c) Peripheral nerve stimulation
- d) Dorsal root entry zone lesion

## 11.5.2 Answers

1. **a.** Pain transmission begins with peripheral receptors that transmit impulses via a first order primary afferent neuron that then projects to the spinal cord through the dorsolateral tract of Lissauer and terminates near second-order nerve cells in the substantia gelatinosa of the dorsal horn. Second-order neurons then give rise to axons that decussate in the ventral white commissure and ascend in either the lateral spinothalamic or indirect medial spinothalamic pathway. **(b)** and **(c)**, Peripheral receptors are the first transducers of pain in the pathway. **(d)**, Axons must ascend in the dorsolateral tract of Lissauer and synapse with a second order neuron near the substantia gelatinosa before crossing the midline in the ventral white commissure.
2. **c.** Surgical sympathectomy has been used to treat essential hyperhidrosis **(a)**, primary Raynaud disease **(b)**, shoulder-hand syndrome **(d)** as well as CRPS, social phobias, anxiety, and other conditions. Sympathectomy is not a treatment for TN **(c)** as the pathophysiology of TN generally involves compression or demyelination of the trigeminal nerve. Surgical treatment for TN involves microvascular decompression, rhizotomy, traumatization of the trigeminal ganglion, or SRS while carbamazepine is first-line for medical management.

3. **KEY: a-3, b-1, c-2, d-5.** Case (a) is an example of **nociceptive pain** since the pain came on suddenly as the result of an ankle sprain causing tissue injury and local inflammation. This pain should respond well to analgesic/ anesthetic medications. Case (b) is an example of **deafferentation pain** since this patient had an above knee amputation resulting in interruption of sensory conduction via damage to large diameter sensory nerve fibers. This interruption is responsible for the burning and tingling the patient feels below the level of amputation. Case (c) demonstrates **CRPS** since the patient reports symptoms of burning pain, spasms, and vasomotor changes (increased sweating/decreased hair growth). This is **type I CRPS** since this patient has no evidence of peripheral nerve injury (no deficits). Type I CRPS represents 90% of all CRPS cases. Case (d) is an example of **PHN** and the patient demonstrates typical symptoms of intermittent burning/stabbing pain in a unilateral dermatomal distribution following the resolution of a vesicular rash several weeks prior.
4. **b.** This patient demonstrates typical symptoms of TN with paroxysmal shooting pain in the distribution of a branch of the trigeminal nerve. (a) Initial management of this patient should be medical and surgical treatments should be pursued if the patient is refractory to medical management. (c) Phenytoin is a third-line drug for the treatment of TN. It has a low rate of clinical efficacy and should only be used if a patient is refractory to other drugs such as TCAs, baclofen, and gabapentinoids. (d) SRS is a treatment option for TN, however, there is a latency to pain relief and the technique is suboptimal for patients needing immediate relief. Medical therapy should also be attempted before SRS treatment.
5. **d.** The most common indication for SCS is postlaminectomy syndrome (a). SCS has also proven effective in the treatment of multiple sclerosis (b) and diabetic neuropathy (c). SCS involves the insertion of electrodes into the posterior epidural space to interrupt pain transmission via an undetermined mechanism. SCS has not traditionally been used to treat cancer pain which is more amenable to treatment with intravenous or intrathecal opioids, or more invasive procedures (cordotomy, DREZ, commissural myelotomy) in refractory patients.
6. **b. (a)** CRPS type I corresponds to cases in which signs of peripheral nerve injury are present. (c) This describes the pathophysiology of PHN. CRPS frequently begins following a fracture, soft-tissue injury, or surgery, and involves regional pain, swelling, skin changes, and bone demineralization usually in the distal limb. (d) This describes a criterion for the diagnosis of TN, not CRPS.
7. **c.** Peripheral nerve stimulation utilizes the Melzack and Wall gate control theory to slow the passage of painful impulses via unmyelinated (C) and small myelinated ( $\delta$ ) fibers via stimulation of larger myelinated A $\beta$  fibers that respond to touch, pressure, and vibration. (a) A $\delta$  fibers are small myelinated fibers involved in the passage of painful impulses and temperature sensation. They do not inhibit the passage of painful impulses when stimulated. (b) C fibers are unmyelinated fibers with a slow conduction velocity that are responsible for pain, temperature, and itch sensations. Thus, stimulation of these fibers via peripheral nervous system does not limit pain. (d) A $\alpha$  fibers are

the primary receptors of the muscle spindle and Golgi tendon organ and are not involved in the pain transmission pathway.

8. **KEY: a-2, b-3, c-1, d-4. (a)** Loss of automaticity of breathing (Ondine's curse) is a complication of bilateral cervical cordotomy. If a bilateral procedure is to be done, the second procedure should be staged after normal respiratory function and CO<sub>2</sub> responsiveness are verified following the first procedure. **(b)** These are all symptoms caused by violation of the dura matter surrounding the spinal cord that occurs with intraspinal narcotic administration. This can lead to low pressure headaches due to CSF leak, meningitis due to infection of the subarachnoid space, and respiratory failure due to the respiratory depression caused by narcotic medications. **(c)** Diplopia is a complication of stereotactic mesencephalotomy due to interference with vertical eye movement (often transient). **(d)** These symptoms can result from cingulotomy due to the intracranial nature of the procedure leading to symptoms of increased intracranial pressure (nausea, vomiting) and seizures due to the violation of brain matter and frontal lobe (flattened affect).
9. **c.** The key to this question is the fact that the patient reports a vesicular eruption in a dermatomal distribution that resolved 1 week ago. The intermittent burning/stabbing pain exacerbated by light touch (allodynia) is characteristic of PHN. The first-line medical treatment for this condition is gabapentin. **(a)** This would be appropriate if the patient were suffering from symptoms of coronary ischemia. However, this patient's symptoms are intermittent and nonradiating and are exacerbated by light touch, which is more characteristic of PHN. **(b)** Amitriptyline is generally considered the

initial treatment for those with moderate-to-severe PHN pain, however, this patient has a history of heart disease which is a contraindication to the use of the drug. **(d)** Topical lidocaine is recommended for patients with mild-to-moderate localized pain due to PHN who do not desire systemic therapy with TCAs. This patient reports severe pain for a number of days and is more likely to respond to TCA therapy.

10. **b.** This question stem describes a patient with failed back syndrome (chronic pain following multiple back surgeries). Failed back syndrome (aka postlaminectomy pain syndrome) is the most common indication for SCS. **(a)** Intrathecal baclofen is generally used to relieve spasticity caused by spinal cord injury or spinal cord disease. This patient does not demonstrate any symptoms of spasticity. **(c)** While peripheral nerve stimulation could potentially be used to treat certain types of back pain, SCS has proven to be the most effective. This patient has also had recurrent disc herniations at the same level and his chronic pain is likely due to a central process involving the spinal cord that is more amenable to SCS. **(d)** DREZ lesions are most effective in treating deafferentation pain from nerve root avulsion, spinal cord injuries, PHN, and postamputation phantom limb pain. It is not the most effective in treating failed back syndrome.

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# 12 Cerebrovascular

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## 12.1 Stroke

### 12.1.1 Definitions

Ischemic stroke is a result of vascular occlusion which decreases blood flow to brain tissue below the limit at which it can be supported. This results in permanent neurological dysfunction of the tissue affected by original insult. Transient ischemic attack (TIA) occurs when neurological dysfunction caused by ischemia is temporary, resulting in return to normal function within 24 hours. Hemorrhagic stroke is a variant in which blood flow is obstructed due to pressure effect after local bleeding into brain parenchyma or into the subarachnoid space.

### 12.1.2 Epidemiology

Stroke is a devastating disease causing almost 1 in 20 deaths in the United States (US).<sup>1</sup> It is the 3rd leading cause of death worldwide and the 5th cause of mortality<sup>2</sup> in the US. It affects almost 800,000 Americans each year. Eighty-five percent of all strokes are ischemic, with the rest being hemorrhagic.<sup>1</sup> The cost to the society has been estimated from \$33 to 70 billion.<sup>1,2</sup> In fact, stroke is the number one cause of chronic disability in affecting potential employment.<sup>1</sup> Black Americans are twice as likely to suffer from stroke as white Americans.<sup>1</sup> The most common modifiable risk factors include hypertension, tobacco smoking, hyperlipidemia, and heavy alcohol abuse.

### 12.1.3 Risk and Prognosis

#### Transient Ischemic Attack

Rate of ischemic stroke after a TIA can be estimated with the **ABCD**<sup>2</sup> score.<sup>3</sup>

The following point values are assigned:

- **Age** (1 point if  $\geq 60$  years old).
- **Blood pressure (BP)** (1 point if systolic blood pressure [SBP]  $\geq 140$  or diastolic blood pressure [DBP]  $\geq 90$  mm Hg).
- **Clinical features** (2 points for focal weakness, 1 point for speech impairment only).
- **Duration of symptoms** (2 points if  $\geq 1$  hour, 1 point if  $\leq 59$  minutes).
- **Diabetes** (1 point if present).

Risk of cerebrovascular accident at two days post TIA can then be calculated by summing the point at 0–3 = 1%, 4–5 = 4.1%, and 6–7 points = 8.1% risk.

## Return to Function

The degree of impairment with regards to activities of daily living (ADL) after stroke can be calculated using the modified Rankin Scale (mRS) (► Table 12.1).<sup>4</sup>

**Table 12.1** Rankin scale

| Scale | Disability                                                                  |
|-------|-----------------------------------------------------------------------------|
| 0     | No symptoms and no disability                                               |
| 1     | Symptoms but no disability                                                  |
| 2     | Minimal, able to carry out most activities                                  |
| 3     | Moderate, requires help but can ambulate without assistance                 |
| 4     | Moderately severe, requires assistance with ambulation and bodily functions |
| 5     | Severe, under constant nursing care and supervision                         |
| 6     | Dead                                                                        |

## ASPECTS

The Alberta Stroke Program Early CT Score (ASPECTS) can be a valuable tool in predicting middle cerebral artery (MCA) stroke based on CT scan.<sup>5</sup> Normal CT scan is assigned a score of 10, with values greater than or equal to 8 predicting favorable outcome in patients receiving tissue plasminogen activator (tPA) therapy. The score is calculated by subtracting 1 point for each of the following structures involved:

- Caudate nucleus
- Internal capsule
- Putamen
- Insula
- Frontal operculum (M1)
- Anterior temporal lobe (M2)
- Posterior temporal lobe (M3)
- Cortex anterosuperior to M1 (M4)
- Cortex laterosuperior to M2 (M5)
- Cortex posterosuperior to M3 (M6)

## Intracerebral Hemorrhage Score

The Intracerebral Hemorrhage (ICH) Score can be used to estimate mortality in a patient with spontaneous ICH (► Table 12.2).<sup>6</sup>

**Table 12.2** Intracerebral hemorrhage score

| Clinical aspect             | Scoring     |              |              |
|-----------------------------|-------------|--------------|--------------|
|                             | 3–4<br>(+2) | 5–12<br>(+1) | 13–15<br>(0) |
| Glasgow Coma Scale          |             |              |              |
| Age ≥ 80 years              | Yes (+1)    |              | No (0)       |
| Volume ≥ 30 mL              | Yes (+1)    |              | No (0)       |
| Intraventricular hemorrhage | Yes (+1)    |              | No (0)       |
| Infratentorial origin       | Yes (+1)    |              | No (0)       |

Total corresponding to the following mortality: 1: 13%, 2: 26%, 3: 72%, 4: 97%, 5+: 100%.

## 12.1.4 Stroke Evolution

Stroke represents an intricate cross-talk of molecular pathways across neurons and other cells such as astrocytes, microglia, and in later stages, inflammatory cells recruited from the bloodstream. In short, stroke is a result of:

- Intracellular metabolic demand
- Ionic dysregulation
- Cytotoxic edema
- Increased demand due to glutamate excitotoxicity
- Oxygen radicals
- Inflammatory response
- Necrosis and apoptosis
- Reperfusion injury

## Biochemical and Hemodynamic Requirements

High metabolic demands of brain tissue result in 25% of total bodily energy consumption for an organ that only comprises an average of 2% of total body weight.<sup>7</sup> Cerebral blood flow (CBF) is paramount in sustaining this collection of 100 billion neurons. Normal brain at rest requires 45–60 mL of blood flow per 100 g of tissue per minute with gray matter being more metabolically demanding than white matter.<sup>7</sup> CBF can be calculated by dividing cerebral perfusion pressure (CPP) by cerebral vascular resistance (CVR). CBF can also be obtained by subtracting the intracranial pressure (ICP) from mean arterial pressure (MAP) and dividing the result by CVR. Neuronal dysfunction becomes apparent at CBF values of 16–18 mL/g/min. Values below 10 mL/g/min result in cell membrane dysfunction and loss of ion gradients. Within 60–120 seconds of vascular occlusion, local oxygen levels fall by 80%.<sup>8</sup>

## Events at the Cellular Level

Once blood flow is interrupted to brain tissue, neuronal death begins to occur

within 2–3 minutes.<sup>8</sup> In contrast to other cell types, neurons exhibit poor energy stores. With the onset of stroke, almost 2 million neurons die each minute. Apoptosis, necrosis, and aponecrosis occur at the same time.

## 12.1.5 Initial Management

Current stroke management focuses on identifying the type of stroke, restoring blood flow to salvageable tissue, and preventing future strokes.

## Ischemic Stroke Subtypes

Ischemic stroke causes can be broadly classified as:

- due to large artery atherosclerosis
- cardioembolic
- due to artery-to-artery embolism
- small vessel disease
- hypercoagulable state
- cryptogenic

Surgical management of carotid artery atherosclerosis is described in detail in further sections.

## Diagnostic Approach

### CT Modalities

Initial CT scans can be free of abnormalities within the first 24 hours.<sup>7</sup>

Early findings of ischemic stroke can include the hyperdense MCA sign and loss of gray-white matter differentiation.

After this time, ischemic strokes appear as a local hypodensity with easily identifiable borders by 7–14 days. Breakdown of local parenchyma leads to appearance similar to density of CSF by

3 weeks. Although mass effect typically peaks by day 4, some mass effect can be present up to almost a month. CT angiography is not as useful in demonstrating stroke but is rather used for pinpointing the occluded vessel. CT perfusion is a modality that uses the difference between CBF and CBV (known as CBF/CBV mismatch) to identify tissue at risk that can still be saved.

### MRI Modalities

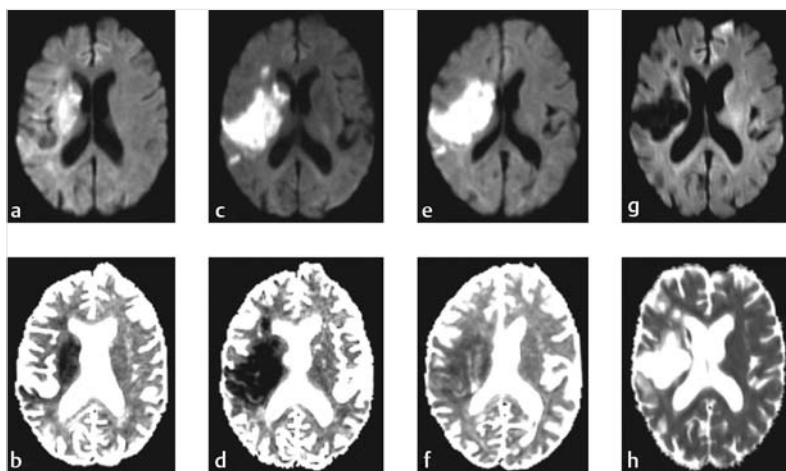
Unlike CT scans, MRI is much more sensitive at detecting stroke within the initial 24 hours.<sup>7</sup> Diffusion weighted imaging (DWI) sequence hyperintensity is the most common and useful sequence when correlated with apparent diffusion coefficient (ADC) hypodense regions at identifying areas of stroke. Alternatively, hyperintensity on exponential ADC sequence can be used to correlate DWI areas of interest. DWI is based on the principle that an area of stroke will have decreased rate of blood flow resulting in a static zone giving a hyperintense signal (► Fig. 12.1).

## Significance of Perfusion

At the heart of stroke treatment lies the concept of penumbra, or the tissue that can suffer complete infarction. Penumbra is a zone around the infarcted tissue that can still be salvaged if proper blood flow is restored.

## Diamox Challenge

Acetazolamide (Diamox) 1 g [given intravenous (IV)] challenge is commonly used in a nonacute setting to measure response of cerebral vasculature under heightened demand. Three zones can be identified after achieving vasodilator response.



**Fig. 12.1** Stroke evolution on diffusion weighted imaging. Evolution of right middle cerebral artery stroke from 6 hours to 3 months post event. Top row, DWI images. Bottom row, apparent diffusion coefficient images. At 6 hours (**a, b**), there is DWI hyperintensity that corresponds to hypointense signal on ADC. After 24 hours (**c, d**), the infarct size is at the highest level of signal. By day 5 (**e, f**), the ADC is at baseline. By 3 months (**g, h**), the infarct area becomes hypointense on DWI with inverse relationship on ADC. (Reproduced from Tsiouris A, Sanelli P, Comunale J, Case-Based Brain Imaging, 2nd edition, ©2013, Thieme Publishers, New York.)

Type I: Normal perfusion and blood flow with 60% increase after Diamox challenge.

Type II: Decreased CBF with less than 10% increase after challenge.

Type III: Decreased CBF with steal phenomenon resulting in decreased local perfusion.

## 12.1.6 Ischemic Stroke Therapeutic Management

### Acute Treatment

Initial definitive management aims at recanalization of the occluded vessel thus providing the required oxygen and nutrients to tissue at risk.

- **IV tPA:** Patients who receive therapy are 30% more likely to have no disability at 3 months.

Eligibility: Age more than 18 years, within 4.5 hours of last seen well (European Cooperative Acute Stroke Study III [ECASS III]), wake up stroke. If IV tPA cannot be given, aspirin 300 mg PR or 325 mg PO can be given.

- Contraindications: ICH, subarachnoid hemorrhage (SAH), aneurysm or arteriovenous malformation (AVM), active bleeding, anticoagulants or heparin within 48 hours, platelet count less than 100,000, head trauma or cranial surgery within 3 months,

SBP more than 185 mmHg, DBP more than 110 mmHg, caution if major surgery within 14 days.

- Outcomes: Almost 33% patients benefit, 7.9% rate of ICH (vs. 3.5% in controls), but no increased risk of death.
- **Mechanical thrombectomy:** By stent retriever, suction aspiration, or other devices.
  - Eligibility: within 8 hours of symptom onset.
  - Outcomes: 48–82% recanalization with 3–7% risk of adverse events, about 1/4th of patients improve to mRS less than 2 at 3 months. The Highly Effective Reperfusion Evaluated in Multiple Endovascular Stroke Trials (HERMES) showed earlier treatment with endovascular and medical therapy resulted in lower disability compared to medical therapy alone.<sup>9</sup> However, the treatment window from onset of symptoms was found to be 7.3 hours. After that time period, there was no benefit from combination therapy.

## Subacute Treatment

Subacute treatment focuses on optimization of hemodynamic parameters, electrolytes, and management of potential complications until the patient can be safely started on anticoagulation for secondary stroke prevention.

- **Permissive hypertension:**
  - Hypertension in acute ischemic stroke or TIA should not be aggressively treated unless SBP > 220 mmHg. Typical SBP floor for patients with no prior history of hypertension should be set at 160 mmHg and in those with such history at 180 mmHg.
    - If tPA was given, SBP captured < 185/110 mmHg.

- If mechanical thrombectomy, BP cap < 140 mmHg at our institution (guidelines unclear).
- Indications to treat include malignant hypertension (DBP > 140 mmHg), acute renal failure, aortic dissection, acute left ventricular failure.

### • Other management parameters:

- Eunatremia, serum glucose 140–180 mg/dL.
- Immediate deep vein thrombosis prophylaxis unless tPA given, if so, defer until 24 h.
- Patient should be evaluated by speech therapy for dysphagia.
- **Complications:** Malignant edema
  - Treat with hypertonic saline 23.4% 30 mL bolus q4 hours.
  - Mannitol at 0.5–1.25 g/kg, need to monitor serum osmolarity.
  - May need decompressive hemicraniectomy.

## Secondary Prevention

Once the acute risks have passed, patients should be anticoagulated to prevent secondary strokes. In addition, a full stroke workup to determine the cause and minimize risk factors should be obtained including:

- Glycosylated hemoglobin, lipid panel, transthoracic echocardiogram.
- Holter monitor if cardioembolic cause suspected.
- Dual therapy with aspirin 81 mg and clopidogrel 75 mg daily if intracranial atherosclerosis is present and thought to be the cause of stroke (Clopidogrel in High-Risk Patients with Acute Nondisabling Cerebrovascular Events [CHANCE] trial).<sup>10,11</sup>
- Lipid-lowering therapy with statins such as atorvastatin 40 mg if low density lipoprotein (LDL) > 70 or 80 mg if LDL > 100.<sup>12</sup>

- Anticoagulation with warfarin or new oral anticoagulants if atrial fibrillation present.

### 12.1.7 Intraparenchymal Hemorrhage Management

Hemorrhagic stroke is the cause of 15% of all strokes with vast etiology including hypertension, amyloid angiopathy, coagulopathy, vascular malformations, and hemorrhagic conversion of ischemic stroke.



Volume of hemorrhage can be calculated by using the approximation  $ABC/2$ . Where A, B, and C are measurements in each axis.

### Acute Treatment

Initial management is focused on preventing expansion of the hematoma with reversal of any underlying causes of coagulopathy if present.

Blood pressure management: SBP less than 180 mmHg; no clear benefit with SBP less than 140 mmHg as shown by the Antihypertensive Treatment of Acute Cerebral Hemorrhage II (ATACH-2).<sup>13</sup> Clevidipine or nicardipine drips are recommended. The primary difference is that clevidipine can be titrated quickly (within 90 s), whereas nicardipine can take up to 15 minutes.

- **Diagnostic imaging:** In the acute setting, CT head with interval scan at 6 hours is standard. Digital subtraction angiography (DSA) may be the next diagnostic modality of choice if aneurysmal rupture or AVM are suspected. MRI with and without contrast may be needed in the subacute setting if hemorrhage into tumor bed is suspected or if amyloid angiopathy is the culprit.
- **Surgical intervention:** The Surgical Trial in Lobar Intracerebral Hemor-

rhage (STITCH) I and II trials showed that there was no difference in patients receiving surgical versus conservative management in prophylactic supratentorial superficial hematoma evacuation. Those with deep-seated clots tend to do better with conservative management. External ventricular drain (EVD) placement and indications are discussed further in neurocritical care section. At the time of writing this text, the Minimally Invasive Surgery Plus Rt-PA for ICH Evacuation Phase III (MISTIE III) trial to evaluate role of minimally invasive clot evacuation is ongoing.

- **Coagulopathy:** Reversal of coagulopathy, either iatrogenic or acquired, is paramount in preventing hematoma expansion. However, in patients where the bleed appears stable or, in patients with significant comorbidities in which anticoagulation is preferred, a balance needs to be struck. Recent data from the Platelet transfusion versus standard care after acute stroke due to spontaneous cerebral hemorrhage associated with antiplatelet therapy (PATCH) trial suggests that patients randomized to receive platelet therapy in addition to standard of care in a setting of spontaneous ICH had almost 25% more adverse events.<sup>14</sup> More data is needed, however, this calls into question cavalier use of platelets in spontaneous ICH. Recommended reversal agents are outlined in ►Table 12.3.

### 12.1.8 Management of Carotid Atherosclerosis

Carotid atherosclerosis is a major cause of ischemic stroke. Intracranial carotid calcification is a significant predisposition in 75% of all strokes, with aortic arch calcification contributing to 45% of ischemic strokes as

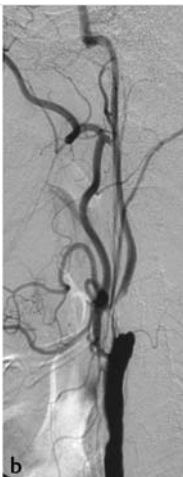
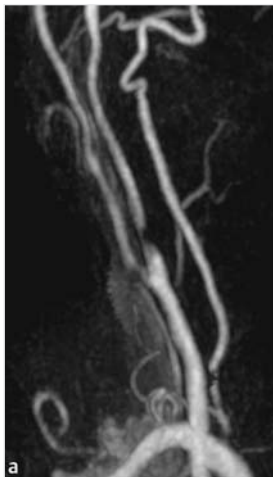
shown in the Rotterdam study.<sup>15</sup> For patients with extracranial carotid calcification, the risk for stroke was much lower at 25%. Management of symptomatic carotid artery stenosis has to be expedited to prevent future ischemic events (► Fig. 12.2). Pressure control decreases risk of stroke in patients with carotid artery stenosis, but aggressive

management is contraindicated. The Atrial Fibrillation Clopidogrel Trial with Irbesartan for Prevention of Vascular Events (ACTIVE) trial suggests that addition of clopidogrel to aspirin in patients with carotid artery stenosis and atrial fibrillation who are not suitable for vitamin K antagonists may actually be beneficial.<sup>16</sup> Surgical management of

**Table 12.3** Reversal agents

| Cause                        | Reversal agent                                              |
|------------------------------|-------------------------------------------------------------|
| Warfarin                     | Vitamin K 10 mg IV + Kcentra (or FFP at 10–15 mL/kg)        |
| Unfractionated heparin       | Protamine                                                   |
| Low molecular weight heparin | Protamine for enoxaparin, Kcentra or rVIIa for fondaparinux |
| Direct FXa inhibitors        | Kcentra                                                     |
| Direct FII inhibitors        | Kcentra, praxbind for dabigatran                            |
| IV tPA                       | Cryoprecipitate or tranexamic acid                          |
| Thrombocytopenia             | Transfuse platelets                                         |
| Liver disease with INR > 1.5 | Vitamin K 10 mg IV + PCC + FFP                              |
| Antiplatelet therapy         | Platelets or DDVAP at 0.4 µg/kg                             |

Abbreviations: DDVAP, desmopressin; FFP, fresh frozen plasma; INR, international normalized ratio; IV, intravenous; PCC, prothrombin complex concentrate; tPA, tissue plasminogen activator.



**Fig. 12.2** Internal carotid artery stenosis. Proximal internal carotid stenosis as seen on (a) Magnetic resonance and (b) Digital subtraction angiography. (Reproduced from Citow J, Macdonald R, Refai D, Comprehensive Neurosurgery Board Review, 2nd edition, ©2009, Thieme Publishers, New York.)



carotid artery stenosis represents the definitive management. Current invasive modalities include carotid artery endarterectomy, balloon angioplasty, and stenting. Regarding carotid endarterectomy, patients should be kept on aspirin for at least 2–5 days, prior to surgery and on the day of surgery.

Carotid artery endarterectomy has:

- Clear benefit in symptomatic patients with more than 70% stenosis.<sup>17</sup>
- Marginal benefit in symptomatic patients with 50–69% stenosis.
- Some benefit in asymptomatic patients with more than 60% stenosis.
- No to minimal role in lesions with less than 30% (North American Symptomatic Carotid Endarterectomy Trial [NASCENT]),<sup>17</sup> or less than 40% stenosis (European Carotid Surgery Trial [ECST]),<sup>18</sup> where intensive medical therapy is clearly preferred.

The procedure is generally contraindicated in patients with severe neurologic deficit, 100% occlusion, and other comorbidities that severely decrease the patient's expectancy independent of current carotid atherosclerotic disease. According to the Carotid Revascularization Endarterectomy vs. Stenting Trial (CREST), there is no difference in overall mortality and morbidity in those with symptomatic or asymptomatic carotid atherosclerosis undergoing stenting or carotid endarterectomy.<sup>19</sup> Most recent analysis of CREST data actually suggests that carotid endarterectomy is as safe as carotid artery stenting in terms of perioperative risk.<sup>20</sup> There is controversy and lack of data to show whether stenting is superior to carotid endarterectomy in patients with average risk.<sup>7</sup> CREST-2 and other trials are currently ongoing and aim to evaluate whether carotid endarterectomy or stenting plus modern medical therapy is superior to modern medical therapy alone in primary prevention of stroke in patients with high grade lesions.<sup>21</sup> However, results are not expected to be available until early 2020s.

Carotid angioplasty or stenting is indicated in the following populations<sup>7</sup>:

- Patients with significant cardiac comorbidities such as congestive heart failure (CHF) grade III or IV.
- History of myocardial infarction in the past month.
- Unstable angina.
- Complete occlusion of the contralateral carotid system.
- Severe scarring of the neck tissues due to surgery or radiation therapy.
- Damage or paralysis of contralateral laryngeal nerve.

## 12.1.9 Stroke Syndromes

### Internal Carotid Artery

Occlusion of the internal carotid artery (ICA) can result in strokes in up to 50% of patients depending on the collateral circulation. It results in contralateral hemiparesis, aphasia if the dominant lobe is involved, or hemineglect in non-dominant hemisphere. It can also cause various degrees of hemianopia.

### Anterior Cerebral Artery

Strokes in this artery distribution cause contralateral lower extremity weakness and loss of sensation. Occlusion of Huebner's artery will result in upper extremity and facial weakness without increased rigidity.

### Middle Cerebral Artery

Contralateral hemiplegia with hemianesthesia, and aphasia if dominant hemisphere involved. Upper division MCA strokes typically result in greater deficits of upper extremity and face than lower extremity. Lower division occlusion presents with Wernicke's aphasia and hemianopia. Occlusion of lenticulostriate arteries arising from MCA results in varying degrees of contralateral hemiparesis.



Gerstmann syndrome is a result of stroke in dominant hemisphere in angular and supramarginal gyrus. Patients present with agraphia, acalculia, finger agnosia, and left-right confusion.

- Foix-Chavany-Marie Syndrome is caused by bilateral anterior opercular strokes and presents with anarthria. It is also known as facio-labio-pharyngo-glosso-laryngo-brachial paralysis.

### Posterior Cerebral Artery

Visual deficits are most often seen, including quadrantanopia, hemianopia, cortical blindness, or Gerstmann syndrome.

- Weber's syndrome is caused by occlusion of midbrain perforators and results in ipsilateral oculomotor nerve palsy, palpebral palsy, mydriasis, diplopia, and contralateral hemiparesis.
- Benedict's syndrome is a result of occlusion of paramedian perforators and is characterized by symptoms similar to Weber's with addition of cerebellar ataxia.

### Superior Cerebellar Artery

Primarily results in ipsilateral ataxia, dysmetria, and dysarthria. If occluded, proximally can result in contralateral sensory deficits.

### Anterior Inferior Cerebellar Artery

Results in lateral pontine syndrome characterized by ipsilateral facial paralysis, loss of taste, deafness or tinnitus, extremity ataxia, and contralateral sensory loss.

### Posterior Inferior Cerebellar Artery

Also known as lateral medullary syndrome, it is distinguished by absence of pyramidal tract findings.

- Wallenberg's syndrome results in hemianesthesia, specifically, ipsilateral facial sensory loss but contralateral body sensory loss, diplopia, Horner's syndrome, pharyngeal and laryngeal paralysis, dysphagia, hoarseness, and ipsilateral ataxia.
- Dejerine's syndrome results in thalamic hypergesic hemiparesis.

### Basilar Artery

Can result in mesencephalothalamic syndrome, locked-in syndrome, Parinaud's syndrome, or Weber's syndrome.

### Vertebral Artery

Depending on proximal-distal location of vertebral occlusion patients present with diplopia, vertigo, ataxia, and facial weakness.

### Vertebrobasilar Insufficiency

Diagnosis requires two or more of the following: diplopia, drop attack, dysarthria, visual defect, or dizziness.

### Thalamic Strokes

The thalamus primarily receives blood supply from the posterior cerebral artery and posterior communicating artery. Occlusion at distinct divisions of the posterior cerebral artery (PCA) can result in vastly different symptom presentation.

- Anterior thalamus is supplied by the tuberothalamic and polar arteries from the posterior communicating artery (Pcomm). Ischemia results in neglect, aphasia, and amnesia.
- Paramedian thalamus receives its blood supply from the thalamosubthalamic branches of P1. Strokes result in loss of consciousness.

- Inferolateral thalamus strokes cause pure hemisensory loss due to occlusion of P2 thalamogeniculate vessels.
- Posterior thalamus ischemia is a result of P2 posterior choroidal vessel occlusion and causes poor memory and visual field cut.

Artery of Percheron is a rare variant in which a single artery arises from PCA to supply both thalami and the midbrain. Thrombosis can result in catastrophic bilateral stroke affecting consciousness and alertness.

imaging findings (► Table 12.5).<sup>23</sup> It should only be used in aneurysmal subarachnoid hemorrhage (► Fig. 12.3).

## Modified Fisher Scale

It is based on newer data and relies on simple grading scheme (► Table 12.6).<sup>24</sup>

World Federation of Neurosurgical Societies (WFNS) Scale.

The WFNS scale is used to provide a quick reference for the level of consciousness and neurological deficit in patients with aneurysmal SAH (► Table 12.7).<sup>25</sup>

## 12.2 Subarachnoid Hemorrhage

### 12.2.1 Epidemiology

SAH represents a subset of ICH. Traumatic SAH is the most common cause of SAH. Cerebral aneurysm rupture is responsible for up to 80% of all spontaneous causes of SAH, with AVMs being responsible for another 5%. Other causes include arterial dissection, rupture of small arteries, hemorrhage into tumor bed, coagulation disorders, and others. The cause is unknown in one-fifth of all cases.

### 12.2.2 Risk and Prognosis

#### Hunt-Hess Grading Scale

It is used to classify aneurysmal subarachnoid hemorrhage and predict mortality (► Table 12.4).<sup>22</sup> Indirectly, the Hunt-Hess scale may be thought of as an indicator of hydrocephalus given that an EVD will often be placed with a grade 3 or higher.

#### Fisher Scale

Predicts the risk of vasospasm following aneurysmal bleed or rupture based on CT

### 12.2.3 Initial Management

During the acute period, neurological examination and head CT should be performed in any patient with suspected SAH. If head CT does not show overt findings of SAH, but it is still suspected, then diagnostic lumbar puncture should be performed to assess for number of red blood cells and xanthochromia. CT angiography (CTA) or DSA is the next step to assess for aneurysm if the presenting symptoms and tempo of clinical worsening allow.

- Blood pressure management: SBP should be kept less than 140 mmHg for unsecured aneurysms. Clevidipine or nicardipine drips are recommended.
- Other parameters: Maintain euvolemia with normal saline + 20 mEq KCl/L at 2 mL/kg/h. Maintain normal ICP values if able. Arterial and central venous line access needs to be established.
- Airway management: Comatose patients or those with concern for airway patency should be intubated.
- Diagnostic imaging: Initially CT and CTA, with DSA being the definitive imaging of choice.

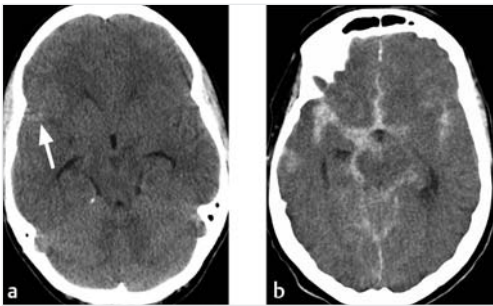
**Table 12.4** Hunt-Hess scale

| Grade* | Clinical presentation                                                                                                            | Mortality |
|--------|----------------------------------------------------------------------------------------------------------------------------------|-----------|
| 1      | Alert and oriented, mild headache, minimal if any neck rigidity                                                                  | 30%       |
| 2      | Alert and oriented, moderate-to-severe headache, nuchal rigidity present, cranial palsy but no other focal neurological deficits | 40%       |
| 3      | Confusion or lethargy, mild focal neurological deficit present                                                                   | 50%       |
| 4      | Stuporous, severe focal neurological deficit                                                                                     | 80%       |
| 5      | Comatose with posturing on neurological examination                                                                              | 90%       |

\* Note that one grade may be added for significant systemic disease such as atherosclerosis, chronic obstructive pulmonary disease, diabetes, hypertension, cardiomyopathy, or vasospasm.

**Table 12.5** Fisher scale

| Grade | Clinical presentation                                                                         | Risk   |
|-------|-----------------------------------------------------------------------------------------------|--------|
| I     | No radiographic evidence of SAH                                                               | 0–21%  |
| II    | Diffuse vertical layering of blood less than 1 mm in thickness                                | 0–25%  |
| III   | Vertical layering more than 1 mm in thickness or a discrete local clot                        | 23–96% |
| IV    | Intracerebral hemorrhage or ventricular hemorrhage with diffuse or no subarachnoid hemorrhage | 0–35%  |



**Fig. 12.3** Subarachnoid hemorrhage. CT imaging showing (a) Fisher grade 2 and (b) Fisher grade 3 subarachnoid hemorrhage. (Reproduced from Spetzler R, Kalani M, Nakaji P, Neurovascular Surgery, 2nd edition, ©2015, Thieme Publishers, New York.)

- **Surgical intervention:** EVD placement for initial stabilization if hydrocephalus is present or if significant intraventricular blood is present with concern for obstructive and/or communicating

hydrocephalus. Additional indications are discussed further in neurocritical care section. Definitive surgical treatment of the underlying lesion (aneurysm, AVM, etc.) is dictated by patient presentation.

**Table 12.6** Modified Fisher scale

| Grade | Presentation                                                | IVH | Risk   |
|-------|-------------------------------------------------------------|-----|--------|
| 0     | No radiographic evidence of SAH                             | 0   | 0%     |
| I     | Focal or diffuse thin SAH with thickness less than 1 mm     | –   | 6–24%  |
| II    | Focal or diffuse thin SAH with thickness less than 1 mm     | +   | 15–33% |
| III   | Focal or diffuse thick SAH with thickness greater than 1 mm | –   | 33–35% |
| IV    | Focal or diffuse thick SAH with thickness greater than 1 mm | +   | 34–40% |

Abbreviations: IVH, intraventricular hemorrhage; SAH, subarachnoid hemorrhage.

**Table 12.7** World Federation of Neurosurgeons (WFNS) scale

| Grade | GCS score | Focal Deficit |
|-------|-----------|---------------|
| 0     |           |               |
| 1     | 15        | –             |
| 2     | 13–14     | –             |
| 3     | 13–14     | +             |
| 4     | 7–12      | +/-           |
| 5     | 3–6       | +/-           |

Abbreviation: GCS, Glasgow Coma Scale.

Radiographically, it becomes apparent in 30–70% of all patients who undergo repeat CTA or DSA.<sup>26</sup> Only about 25% of all patients with SAH demonstrate clinical vasospasm. Clinical findings of vasospasm are not present in all cases of radiographic vasospasm. Transcranial dopplers (TCDs) or CTA can be used to detect vasospasm, but DSA is the gold standard as it also allows definitive management. TCDs are semiquantitative in their evaluation and rely on the Lindegaard ratio with values less than 3 being normal, 3–6 indicating mild vasospasm, and more than 6 showing moderate-to-severe vasospasm.

### 12.2.4 Vasospasm Prevention

Cerebral vasospasm, a narrowing of cerebral arteries, is a complication of SAH and is particularly dangerous in the subacute period.

Cerebral vasospasm typically peaks around day 7 post SAH, and usually manifests 3–14 days after hemorrhage. However, it can present as late as 21 days after the inciting event.

Other types of intracranial hemorrhage, trauma, surgery, and CSF diversion can all cause vasospasm to occur. It usually presents with confusion, altered sensorium, decreased consciousness, or focal deficits.

The Lindegaard ratio is simply the ratio of flow in the ipsilateral MCA to ICA. Values are highly operator dependent.

Prophylactic management of vasospasm is limited and typically relies on hydration, euolemia, and avoidance of anemia. Prophylactically, triple H therapy is not indicated.<sup>27</sup> Once vasospasm becomes a clinical possibility, immediate imaging of the brain with CT scan should be performed to rule out new-onset edema, expanding infarction, new hemorrhage, or hydrocephalus. Treatment options for confirmed vasospasm are discussed in more detail below.<sup>7</sup>

- **Pharmacological therapy:** Nimodipine, and other calcium channel blockers dilate arteries, but in clinical practice, they have not been shown to prevent radiologic vasospasm.<sup>28</sup> Effects of nimodipine are mediated through neuroprotection via its effects on blood rheology, anti-platelet effects, and dilation of collateral arteries rather than vasodilation. Statins have been shown to reduce vasospasm and mortality. Mannitol could be useful by improving blood rheology and microvascular perfusion. Of note, hypertonic saline may be preferable to mannitol for elevated ICP during the vasospasm window to allow for volume expansion.
- **Hyperdynamic therapy:** Places importance on CPP to maintain blood flow and prevent clinical vasospasm. It is named after its three major components:
  - Hypertension (SBP < 220 mmHg in clipped aneurysms).
  - Hemodilution with hematocrit 25–33%.
  - Hypervolemia (CVP elevation to 8–12 cmH<sub>2</sub>O).
 The hypertension component can be induced with dopamine at 2.5–20 µg/kg/min, levophed 1–64 µg/min, phenylephrine 5–64 µg/min, or dobutamine up to 20 µg/kg/min. Hypervolemia can be induced with normal saline or plasmalyte at 150–250 mL/h or DDAVP (desmopressin).
- **Endovascular therapy:** Represents direct treatment for vasospasm but may have to be done multiple times for repeat vasospasm. Angioplasty is usually more effective than intra-arterial drug therapy with verapamil or nicardipine.

thought to occur due to weakness in the vessel wall.

## 12.3.2 Epidemiology

Cerebral aneurysms occur in about 5% of the population<sup>29</sup> and their rupture can result in devastating SAH. Ruptured cerebral aneurysm account for 5–15% of all stroke cases.<sup>30,31</sup> About 45% of ruptured patients never reach the hospital in time to receive proper treatment.<sup>29,31</sup> A third of the survivors reaching the hospital will develop moderate-to-severe lifetime disabilities. Modifiable risk factors for cerebral aneurysms include hypertension and smoking.<sup>32</sup> Women make up two-thirds of all cerebral aneurysm cases with postmenopausal status being another risk factor.<sup>40,29</sup> Female sex is associated with increased risk of SAH and higher mortality.<sup>33</sup> Pediatric cases are rare.

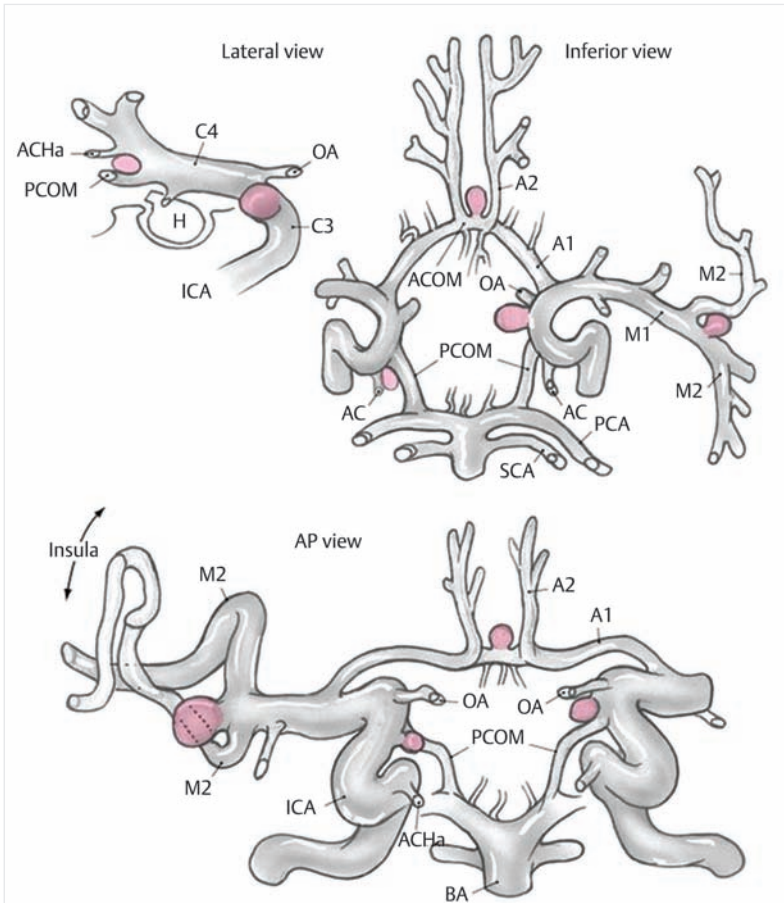
Almost 95% of all cerebral aneurysms are sporadically acquired defects.<sup>34,35</sup> Less than 5% are thought to be congenital or due to genetic diseases. Saccular aneurysms, named after their balloon-like shape, make up 90% of all aneurysms with fusiform and blister aneurysms making up the remaining 10%.<sup>29,31,34</sup> Fusiform aneurysms are more common in the vertebral system.<sup>7</sup>

Location within the circle of Willis appears to have an intricate relationship with aneurysm formation (► Fig. 12.4). Most of the cerebral aneurysms occur at bifurcations and are found in the carotid system (85–95%) rather than the posterior or vertebrobasilar system (5–15%). Aneurysms in the anterior communicating artery (ACoA) are the most common representing 30% of all cases. Pcomm and MCA are the second and third most common locations accounting for 25% and 20% of all cases, respectively. The basilar artery represents only 5–10% of all cases. Frequently, upon rupture or “sentinel-bleed”, the patients present

## 12.3 Aneurysms

### 12.3.1 Definitions

Cerebral aneurysms are local dilations of intracranial blood vessels and are



**Fig. 12.4** Cerebral aneurysm location. Drawing of most common locations of cerebral aneurysms within circle of Willis. (Reproduced from Nader R, Gragnaniello C, Berta S et al, *Neurosurgery Tricks of the Trade Cranial*, 1st edition, ©2013, Thieme Publishers, New York.)

with headaches, seizures, or stroke-like symptoms. Only 10% of all aneurysms are thought to result in rupture. However, ruptured cerebral aneurysms are responsible for 80% of all SAH cases.

Great progress has been made in understanding this potentially catastrophic disease but limited knowledge has been the constraining factor in development of new treatments.

### 12.3.3 Aneurysm Formation

Most cerebral aneurysms are thought to be sporadic rather than genetic. The current, most widely accepted hypothesis is that the initiating stressor damages the internal elastic lamina within the vessel wall. Aneurysm formation is thought to be a complex interplay between local hemodynamics and chronic inflammation which adversely affects vascular wall biomechanics. Animal studies suggest that high shear stress and shear stress gradients cause damage to the endothelium and internal elastic lamina (IEL) resulting in initial wall weakness.<sup>36,37,38</sup> Aneurysm growth is set into motion via apoptosis of endothelial cells,<sup>37</sup> increased secretion of local degradative enzymes such as the matrix metalloproteinases,<sup>39</sup> and activity of innate immune cells, primarily macrophages.<sup>40,41,42</sup> Smoking has been associated with increasing the risk of aneurysm growth by a factor of four.<sup>43</sup> Hypertension is highly associated with aneurysm formation and rupture.<sup>31,34</sup>

### 12.3.4 Other Aneurysms

Genetic causes represent less than 5% of all cases of cerebral aneurysms and include diseases such as a autosomal dominant polycystic kidney disease (ADPKD), Moyamoya disease, or connective tissue disorders. Other etiologies include embolic, infectious, and traumatic.

Up to 30% of patients with ADPKD have aneurysms. MRA scans are recommended every 2–3 years in symptomatic patients. About 10–30% of patients with ADPKD have cerebral aneurysms.

Aneurysms are also commonly seen in about 7% of all AVM cases. In Ehlers-Danlos syndromes, a mutated gene COL3A1 results in deficient collagen metabolism.<sup>45</sup> These patients are more likely to form aneurysm within the whole cardiovascular system and

about 2.1% of all patients suffer from major cerebrovascular hemorrhagic events.<sup>46</sup>

Mutation in fibrillin-1 gene known as FBN-1 (0.01% of the population) results in Marfan syndrome.<sup>47</sup> Fibrillin is responsible for a sheath around elastin proteins, which together form the elastin layer in the IEL. FBN-1 loss of functions leads to defective transforming growth factor- $\beta$  (TGF- $\beta$ ) signaling.<sup>48</sup> Patients with Marfan syndrome commonly experience cardiovascular complications, which are the cause of 58% of all deaths in this patient population.<sup>47,49</sup>

Other important conditions that have incidence of cerebral aneurysms include Osler-Weber-Rendu syndrome<sup>50</sup> and fibromuscular dysplasia. In fact, patients with fibromuscular dysplasia has a 7% aneurysm prevalence in renally predominant disease, and 21% in disease with aortocranial features.

Mycotic aneurysms are rare and represent only 1–2% of all cerebral aneurysms.<sup>51</sup> Initial treatment focuses on identifying the pathogen involved and administering proper antibiotic therapy. Most of the aneurysms thrombose on their own with this initial management. Repeat DSA is necessary to evaluate the lesion. If the aneurysm is found to be enlarging, endovascular coiling is the next step. There are no official guidelines as this type of aneurysms is so rare precluding proper clinical trials.

### 12.3.5 Initial Management

Initial management is dictated by patient presentation and aneurysm status. First-line medical therapy is to institute antihypertensive therapy with SBP cap at 140 mmHg to prevent rupture or rebleeding. If an aneurysm is unruptured, more care can be taken in preoperative planning and, depending on aneurysm location and size, watchful waiting can be an option. Cumulative 5-year rupture rate risk can



be estimated using location and size as published by Wiebers et al (► Table 12.8). It should be noted that the International Study of Unruptured Intracranial Aneurysms (ISUIA) results have been controversial as clinically, small aneurysms represent the majority of ruptured aneurysms that are seen.

Intraoperative rupture during clipping is a significant concern with 20–40% risk rate.<sup>7</sup> This translates to increased mortality and morbidity rate of 35%. Recanalization rates for coiled aneurysms are cited to be 17%. In contrast, recurrence for clipped aneurysms is very low with only 1.5% risk at 4 years. After coiling, it is recommended that repeat CTA or MRA with contrast be performed at 6 months, 1.5 years, 3 years, and then every 5–10 years. Clipped aneurysms should be re-evaluated with CTA 1 year after surgery, at 5 years, and then every 10 years.<sup>7</sup> Total costs for diagnosis and treatment of post-aneurysm rupture are about \$25,000 per patient.<sup>52</sup> Cerebral aneurysm rupture is a significant risk although it is estimated that 65% of aneurysms do not rupture.<sup>31</sup> SAH exposes patients to additional risk for vasospasm, and thus secondary stroke.<sup>29,30,31,53</sup>

### 12.3.6 Treatment Options

Cerebral aneurysms have fascinated surgical specialists since their early

discovery. First attempts at treatment were reported in 19th century and focused on ligating the carotid arteries as popularized by John Hunter with the goal of redirecting flow. Although frequently successful at causing intraluminal thrombosis of the aneurysm, many patients developed debilitating infarcts leading to hemiplegia. In 1931, Normann Dott reported using muscle wrapping of the affected artery to prevent rupture. In the 1960s, aneurysm clipping saw several improvements. Modern procedures rely on three major techniques including clipping, coiling, and use of stents/pipeline devices to effectively isolate the aneurysm sac and prevent rupture.<sup>29,31</sup>

### Aneurysm Clipping

Walter Dandy was the first one to use clips to treat aneurysms.<sup>54</sup> Modern clipping relies on MRI-safe titanium clips of variable sizes, shapes, and material.<sup>55</sup> Clipping is more advantageous for treatment of fusiform aneurysms, or aneurysms with a wide neck, than coiling. It is also indicated for MCA aneurysms, giant aneurysms, and recanalized aneurysms after coiling. Due to need for craniotomy, younger patients are a better group for this procedure. Surgical techniques have expanded to include clipping with an endoscopic endonasal approach.<sup>56</sup>

**Table 12.8** International study of unruptured intracranial aneurysms (ISUIA) cumulative aneurysm rupture risk

| Location          | < 7 mm   | 7–12 mm | 13–24 mm | > 25 mm |
|-------------------|----------|---------|----------|---------|
| Cavernous carotid | 0%       | 0%      | 3%       | 6.4%    |
| ACA/MCA/ICA       | 0–1.5%   | 2.6%    | 14.5%    | 40%     |
| PCA/Pcomm         | 2.5–3.4% | 14.5%   | 18.4%    | 50%     |

Abbreviations: ACA, anterior cerebral artery; ICA, internal carotid artery; MCA, middle cerebral artery; PCA, posterior cerebral artery; Pcomm, posterior communicating artery.

However, as in the case of coiling, clipping also carries with it the risk of causing aneurysm rupture during procedure in a phenomenon known as “scissoring”, which can occur due to failure of the device or lack of its proper application.<sup>57</sup> Aneurysm clipping has been described as the surgical gold standard, although coiling is now generally preferred to clipping due to its minimally invasive approach. Proper selection of patient population is key.<sup>53,58</sup> Minimally invasive craniotomies offer a challenge to endovascular approaches, but their efficacy and safety profile are not fully known due to low number of cases.<sup>59</sup>

## Additional Open Approaches

Additional methods of isolating the aneurysm and preventing future rupture have been described but have not gained as much traction as aneurysm clipping. Those include muscle wrapping, cotton wrapping, Teflon wrapping, or use of fibrin glue. Trapping of the aneurysm through creation of vascular bypass such as external carotid-internal carotid (EC-IC) or other artery-to-artery systems have been reported on extensively, but are usually associated with significant risk of stroke, either ischemic due to occlusion, or hemorrhagic.<sup>58</sup>

Complex aneurysm cases may require intracranial-extracranial or intracranial-intracranial bypass procedures.<sup>59,60,61,62</sup> Modern approaches attempt to rely on intracranial-intracranial bypass in order to protect the bypass within the confines of the cranium.<sup>59,60</sup> The major drawback is that as other techniques such as endovascular coiling have gained prominence, the demand on the experience and skill of the surgeon performing the procedure have increased.<sup>59,60</sup>

## Endovascular Coiling

Aneurysm coiling was first introduced by Guido Guglielmi in 1991. It relies on

electrolytically detachable platinum coils. These Guglielmi Detachable Coils (GDCs) are inserted into the aneurysm dome with a catheter via an endovascular approach with the goal of causing intra-aneurysmal thrombosis and tissue ingrowth.<sup>63</sup> More intricate coil systems have been introduced that contain collagen coatings<sup>64</sup> or biodegradable polymers.<sup>65</sup> Experience with hydrogel-coated coils indicates that the recurrence rate is two-thirds of bare-platinum rate.<sup>66</sup> Preclinical studies have also explored gene-delivering coils,<sup>67</sup> and chemokine releasing coatings capable of local immunomodulation.<sup>68</sup>

Coiling has seen more frequent use in the last decade; it is minimally invasive and leads to better perioperative outcomes.<sup>29,58</sup> However, recent studies have shown that in the case of very small (< 3 mm) aneurysms<sup>69</sup> clipping might be superior. Other supporting devices have greatly expanded the patient population that can be treated with coiling. Stent-coiling, a method utilizing a stent and a coil, to treat aneurysms with difficult shapes or wide necks, has seen more frequent use with comparable outcomes.<sup>70</sup> Other occlusive devices have been introduced such as the Onyx liquid embolic system, which have been used with great success to treat wide-necked, giant aneurysms, and complications of endovascular approach such as accidental puncture through vessel wall.

## Clipping versus Coiling

The International Subarachnoid Aneurysm Trial (ISAT) showed that mortality or dependency was significantly higher in the patients who underwent aneurysmal clipping than coiling.<sup>71</sup> Rebleeding was higher in the endovascular than in neurosurgical group. Moreover, patients in the endovascular group had lower rates of disability than patients who underwent neurosurgical clipping at 10-year follow-up. Results from the Barrow Ruptured Aneurysm Trial

(BRAT) suggest that clipping and coiling are comparable for anterior circulation aneurysms.<sup>72</sup> However, coiling was superior for posterior circulation aneurysms despite increased need for retreatment due to suboptimal aneurysm obliteration. Older studies suggest that one-fourth of coiled aneurysms will have a stable neck remnant, with almost a third of patients experiencing aneurysm neck enlargement.<sup>7</sup> In more recent studies, 40% of patients were found to have long-term changes in aneurysm obliteration pattern and 8% had to undergo recoiling or reclipping due to extensive recanalization.<sup>73</sup> Most studies cite recanalization rate at 4–5 years postprocedure at 17–32%.<sup>74</sup> This is in contrast to previously cited recanalization risk of 1.8%.<sup>7</sup> Surgical aneurysm clipping is more expensive than coiling in terms of length of hospital stay and patient costs.<sup>75</sup> Although costs are comparable between coiling and clipping for unruptured aneurysms, the cost of materials in coiling is balanced by longer hospital stays in clipping.<sup>75,76</sup> On average, clipping can be almost as expensive, if not less, than coiling at the same institution.<sup>58,76</sup> Both approaches are associated with important risk factors such as intraoperative rupture, thromboembolism, and thrombosis of the parent vessel.<sup>29,31,53,69</sup> Cerebral aneurysm recurrence is rare and represents about 2% of patient population.<sup>77</sup>

## Pipelines and Flow Diverters

Pipeline embolization devices (PEDs), or flow diverters, represent a new type of a device that is distinct from stents with their higher mesh ratio and typically longer dimensions. They have successfully been used to treat fusiform, wide-necked, or large and giant aneurysms.<sup>78,79</sup> Fusiform aneurysms have historically presented a challenge to both clipping and coiling, but flow diversion with pipeline

devices have proved to be especially useful in these cases.<sup>80</sup> These new devices allow for diversion and maintenance of flow in the parent artery, while isolating out the lesion area and inducing prothrombotic low-flow conditions.<sup>79</sup> PED efficacy has been well-demonstrated in unruptured aneurysms at 6 months postprocedure.<sup>59,78,79</sup> Re-endothelialization across the device and the neck of the aneurysm allows for proper artery structure resulting in an aneurysm that is shut off from circulation.<sup>59,78,79</sup> PEDs are a reasonable alternative to stent-coiling.<sup>81</sup> Their use in ruptured aneurysms, is generally contraindicated because of the need for antiplatelet and/or anticoagulation therapy to prevent parent or distal artery thrombosis after procedure.<sup>59,78,79</sup>

## Medical Therapy

As of the time of writing this text, no proven pharmacotherapy exists that would allow for treatment of cerebral aneurysms and lesion regression. In the 2012 Guidelines for the Management of Aneurysmal Subarachnoid Hemorrhage, it was shown that BP control is beneficial in hypertensive patients in order to prevent aneurysmal rupture.<sup>44</sup> Nevertheless, no studies have been done that would attempt to elucidate which anti-hypertensives would be superior in this patient population. Based on the inflammatory hypothesis of cerebral aneurysm formation, there has been much interest in using nonsteroidal anti-inflammatory agents and molecular therapy to slow down or prevent aneurysmal growth and rupture.<sup>82</sup> In the ISUIA trial, patients on aspirin were less likely to suffer from intracranial aneurysm rupture than those in control group.<sup>82</sup> One of the most significant issues with finding a proper medical therapy for cerebral aneurysms lies in the fact that most of these lesions are found

upon rupture at which point vascular wall biomechanics may have already reached a point of no return. Future therapies will heavily depend on our ability to detect cerebral aneurysms before they rupture.

## 12.4 Vascular Malformations

Vascular malformations represent a number of diverse vascular lesions without malignant potential. They include AVMs, cavernous malformations, direct fistulas, venous angiomas, and capillary telangiectasias.

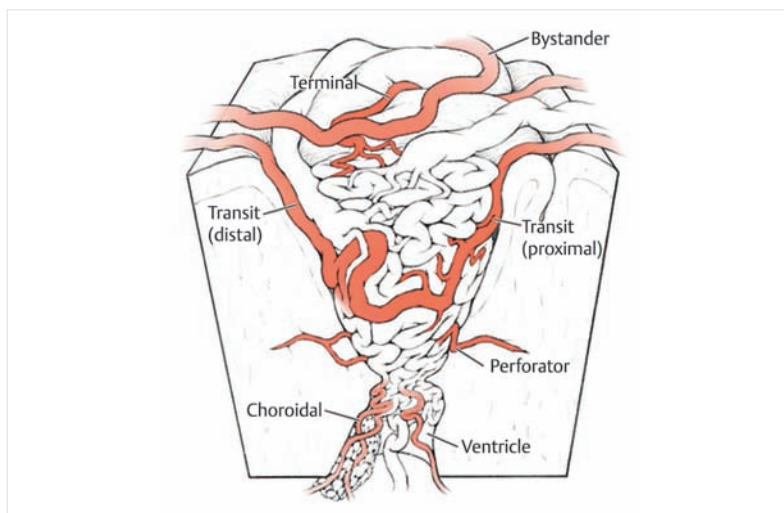
### 12.4.1 Arteriovenous Malformations

#### Definition

AVMs are most simply described as a collection of arteries and veins with dysplastic elements and no clear capillaries. No brain tissue is found within this vascular tangle. Arterial vessels found within this lesion can have distinct functions (► Fig. 12.5).

#### Epidemiology

AVMs are uncommon lesions with prevalence at 0.14% in the general population.



**Fig. 12.5** Arteries within arteriovenous malformations (AVMs). The terminal artery feeds the nidus without normal supply and is defined by high flow. Arteries that supply the AVM and normal brain parenchyma are known as transit arteries. The perforating artery is a small artery penetrates the white matter and ends in the lesion. Arteries that are located along the ventricle and feed the ependymal AVM surface are known as choroidal feeding arteries. Normal arteries feeding local brain tissue that are close to the nidus without actually supplying the AVM are known as bystander arteries. (Reproduced from Lawton M, *Seven AVMs, Tenets and Techniques for Resection*, 1st edition, ©2014, Thieme Publishers, New York.)

They are more commonly seen in certain congenital conditions such as Osler-Weber-Rendu patients.

AVMs are congenital lesions that typically enlarge with age as they mature from low-flow to high-flow lesions. The most common presentation is hemorrhage (50–60%), seizures, or mass effect resulting in cranial nerve defects. Younger age at presentation is more commonly associated with seizures. Also 1 in 14 patients with AVM will also have an associated aneurysm. Additional presentations include ischemia, hydrocephalus, and others.

Hemorrhage most often occurs at 15–20 years of age and can be a devastating event with 10% mortality and up to 50% morbidity.



The risk of major hemorrhage with an AVM is thought to be approximately 2–4% per year.

Risk of rebleeding has been cited at 6–18% depending on the study.

## AVM Molecular Pathways

AVMs are considered congenital lesions and are thought to develop due to dysregulation of endothelial cell proliferation. After age of 18 years, the lesions are thought to stabilize.

## Estimating Risk

The Spetzler-Martin grade is a convenient way to classify AVMs based on lesion size, location, and venous drainage (►Table 12.9). Eloquence describes whether the lesion is located next to an area of the brain responsible for functions such as sensory, motor, and internal capsule, language, vision, hypothalamus and thalamus, brainstem, deep cerebellar nuclei, and cerebellar peduncles. Venous

**Table 12.9** Spetzler-Martin grade

| Lesion characteristic  | Points |
|------------------------|--------|
| <b>Size</b>            |        |
| < 3 cm                 | 1      |
| 3–6 cm                 | 2      |
| > 6 cm                 | 3      |
| <b>Eloquence</b>       |        |
| Yes                    | 0      |
| No                     | 1      |
| <b>Venous drainage</b> |        |
| Superficial            | 0      |
| Deep                   | 1      |

**Table 12.10** Annual hemorrhage risk in arteriovenous malformations postoperatively

| Grade | Hemorrhage Risk | Major or Minor Deficit |
|-------|-----------------|------------------------|
| 1     | 3.5%            | 0%                     |
| 2     |                 | 5%                     |
| 3     |                 | 16%                    |
| 4     | 2.5%            | 27%                    |
| 5     |                 | 31%                    |

drainage is considered deep if any occurs through deep veins such as internal cerebral, basal vein of Rosenthal, etc.

The points are summed providing a grade. Spetzler-Martin grade can be used to estimate annual hemorrhage risk as well as the risk of neurological deficit postoperatively (►Table 12.10).

## Initial Management

Initial management focuses on establishing the relation of the lesion to local brain parenchyma and vascular territory. CT

imaging can be used to show the nidus of the lesion as well as provide information about recent hemorrhage. MRI imaging can provide information about feeding arteries and drainage. The gradient echo sequence can provide information about previous hemorrhages. Angiography can also be used for delineating the vascular supply, venous drainage, and presence of associated aneurysms.

## Treatment

Definitive treatment options for AVM include surgery, radiosurgery, and endovascular techniques. Surgical resection has historically remained the primary treatment modality with the benefit of instantaneously eliminating risk of hemorrhage. However, difficult to reach lesion may not be amenable to surgery and perioperative risk may be high. Stereotactic radiosurgery (SRS) has become a more frequently used modality, especially for small and deep lesions. The major drawback is that the lesion may take up to 3 years to involute and that the risk of bleeding persists during that period. Endovascular techniques rely on embolization with Onyx, ethanol, polyvinyl particles, acrylate adhesives, or other compounds. The benefit is that it still represents a minimally invasive approach and can be used in combination with SRS. The problem is that this approach may require multiple procedures and off target effects of embolization can result in complications. About a tenth of the patients will suffer from a mild deficit, another tenth from a transient deficit, with up to 2% risk of death.

### 12.4.2 Cavernomas

#### Definition

Cavernous malformations, also known as cavernomas, cavernous angiomas, or cavernous hemangiomas, are lesions

composed of clusters of abnormal and thin-walled blood vessels with high propensity to bleed and expand the lesion.

## Epidemiology

Cavernomas are uncommon lesions occurring in 0.5–1% of the population. However, they account up to 15% of all vascular malformations. About 1 in 5 of cases are familial in nature with 30% of patients affected by these lesions experiencing a hemorrhage by their 30s. Some studies report that up to a half of these lesions may be familial.<sup>83</sup>

## Cavernoma Formation

Cavernous malformations are thought to form due to proliferation of endothelial cells and support cells known as pericytes. They have been associated with hormonal changes and are commonly seen in pregnant women. Radiation can also induce lesion formation. Some of the most commonly associated gene mutations or deletions have been found to involve *CCM1* (*KRIT1*), *CCM2* (malcavernin), and *CCM3*. *CCM1* and 2 are transcription factors and scaffolding proteins, respectively, that are involved development of arterial blood vessels. *CCM1* mutations are more often seen in Hispanics. However, no clear function of these proteins has been identified and much research remains to be done.

## Estimating Risk

The average annual risk of bleeding is 1.2%.<sup>7</sup> Rehemorrhage risk for hemorrhagic cavernous malformations has been cited as high as 22.9%.<sup>84</sup> Up to 60% of patients initially present with seizures. Bleeding risk has not been associated with lesion size. Pregnancy have not been known to increase rebleeding risk.

## Initial Management

CT scans are not typically used for detection of cavernous malformations. These lesions are angiographically occult and DSA is of limited value. Asymptomatic lesions can be followed with outpatient MRI scans every 2 years. Surgery is typically considered for patients in whom neurological deficits are considerable or seizures cannot be controlled with medication.

Cavernous malformations are best detected with MRI with or without contrast. Gradient echo sequences are especially sensitive for detecting these lesions with a “popcorn-like” appearance.

## Treatment

Surgery is considered the gold standard for treatment of cavernous malformations. The primary goal of surgery is complete lesion resection and in patients with seizures, special care should be taken in removing portions of the brain parenchyma stained with blood breakdown products. Other options include watchful waiting and SRS. In case of brainstem cavernomas, surgery should be considered in lesions with more than two prior hemorrhages.<sup>84</sup>

Results with SRS have been controversial.<sup>7</sup> It is thought that SRS induces significant morbidity. However, more recent histopathological studies have shown that vascular sclerosis of these lesions with SRS may be incomplete and that increased bleeding may be due to neovascularization.<sup>85</sup> More data on the role of SRS in treatment of cavernomas is needed.

### 12.4.3 Moyamoya Disease

#### Definition

Moyamoya disease represents a stenooclusive disease in which small arteries,

typically around basal ganglia, become progressively constricted, resulting in formation of local collateral vessels. These smaller collaterals are frequently fragile and prone to rupture resulting in hemorrhage.

The name of the disease means “puff of smoke” in Japanese and refers to the appearance of the lesion on angiography.

## Epidemiology

Disease prevalence in the US is approximately up to 0.17 per 100,000 patients/years. Its prevalence is higher in the Japanese at 0.35/100,000 patients/years than other populations. Up to 10% of cases are familial. Women are twice as likely to be affected as men. There appear to be two forms, with a peak in disease prevalence in childhood and midadulthood. In children, 81% of all cases are ischemic and result in 6% of all childhood strokes. In adults, 60% of cases are hemorrhagic.

## Molecular Pathways

Much of the molecular pathways in the formation of this disease are not known. Multiple gene loci have been implicated including *RNF213*.<sup>86</sup> It is thought that inflammation plays a major role with initial spontaneous occlusion of one or both of the ICAs and formation of collaterals. Over time, the collaterals begin to involve other vessels of the circle of Willis including anterior cerebral arteries (ACAs) and MCAs. In the final stages, collaterals from the external carotid artery develop as well. Several other diseases have been associated with Moyamoya-like syndrome including Graves disease, Down syndrome, Marfan syndrome, systemic lupus erythematosus (SLE), and head-trauma to name a few.<sup>7</sup>

## Initial Management

Due to presentation similar to ischemic or hemorrhagic stroke, the workup usually follows stroke pathway with CT and MRI/MRA. Cerebral angiography can be useful in further workup and revascularization. CBF studies are not essential but may show utilization of posterior circulation over anterior aspect.

## Treatment

Currently, no studies have shown that any medical therapy might be useful in treatment of this disease. In fact, medical therapies with antiplatelet agents, steroids, or antihypertensives have not been proven to be beneficial. Surgical treatment goals include revascularization, restoration of blood flow to affected portions of the brain, and decreasing hemodynamics stress on friable Moyamoya collateral vessels. Direct revascularization is preferred with the superficial temporal artery (STA)-MCA bypass. However, indirect revascularization methods including temporalis muscle layering, STA layering over dural defect (encephaloduroarteriosynangiosis, or EDAS), and omental grafting can also be employed. In case of poor flow in the ACA territory, a piece of galea can be layered over the interhemispheric fissure to create additional collaterals. Special care needs to be paid to blood pressure control as hypertension can cause bleeding postbypass while hypotension can result in thrombosis of the graft.<sup>7</sup>

### 12.4.4 Other Malformations

#### Venous Angiomas

Venous angiomas, also known as developmental venous anomalies, are low-flow malformations of the venous drainage with involved brain parenchyma. On their own, they are typically not symptomatic

but can be associated with cavernous malformation. They are not familial and do not usually require treatment.



If there is an associated cavernous malformation, the venous angioma should not be resected to prevent ischemic infarcts due to lack of venous drainage.

Of note, angiograms can sometimes be identified by starburst or caput medusae pattern.<sup>13</sup>

## Vein of Galen Malformation

These lesions involve the vein of Galen that has increased in size, either congenitally or due to increased high flow from deeper associated malformations.



They are often discovered shortly after birth in the first few weeks with associated heart failure or cranial bruit.

They have very poor prognosis with high mortality if untreated. Vein of Galen malformations are classified based on the fistula and whether it is

- Internal.
- Being fed by thalamoperforators.
- Mixed.
- Receives blood from AVM.

Treatment involves surgical intervention including feeding vessel embolization.<sup>7</sup>

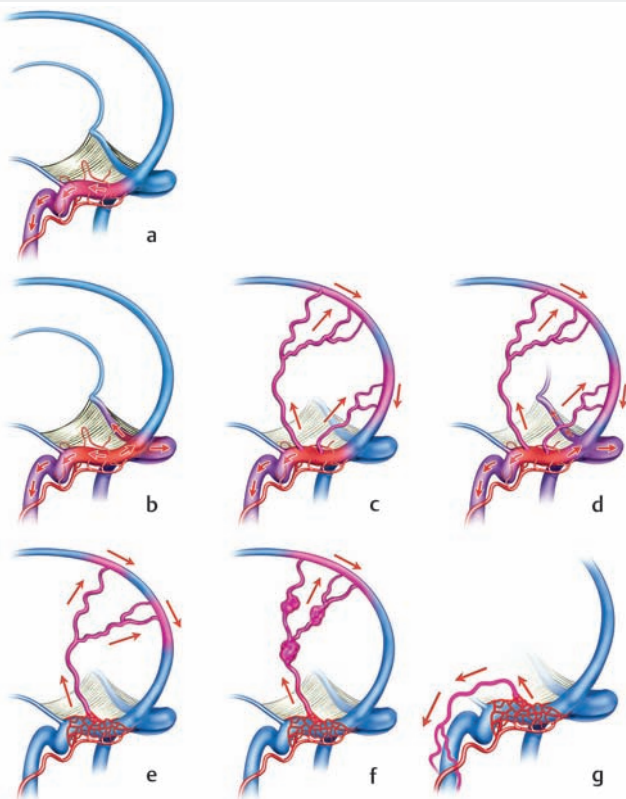
## Dural Arteriovenous Malformations

Dural AVMs are direct arteriovenous fistulas that are contained within the dura mater. They are typically found next to dural sinuses with the transverse sinus being the most common site. Other locations include the tentorium, cavernous



sinus, or off the vertebral artery. They are a fairly small subtype of AVMs and almost two-thirds occur in women. The most common symptoms at presentation include pulsatile tinnitus, cranial bruit,

and headaches. These lesions are most conveniently classified using angiographic imaging (► Fig. 12.6). Definitive treatment can include endovascular embolization and/or surgery. Endovascular treatment



**Fig. 12.6** Classification of dural arteriovenous malformations (AVMFs). Cognard classification system is very convenient in classifying dural AVMs. Venous drainage is the most important factor within the system. **(a)** CG1, antegrade sinus flow; **(b)** CG2a, retrograde flow into sinus; **(c)** CG2b, retrograde reflux into cortical veins only; **(d)** CG2a+b, retrograde flow into the sinus and cortical veins; **(e)** CG3, outflow into cortical veins only; **(f)** CG4, drainage into cortical veins only but with venous ectasia; and **(g)** CG5, outflow into perimedullary spinal veins. (Reproduced from Bendok B, Naidech A, Walker M et al, Hemorrhagic and Ischemic Stroke: Medical, Imaging, Surgical and Interventional Approaches, 1st edition, ©2011, Thieme Publishers, New York.)

can utilize coils, Onyx, or ethanol-based compounds with the goal of complete obliteration of arteriovenous shunting on angiogram. Special caution needs to be exercised with surgical intervention due to possibility for large volume blood loss. SRS can also be used with good success rate resulting in complete lesion obliteration in almost 60% of the cases.<sup>7</sup>

### Pearls



- Normal brain at rest requires 45–60 mL of blood flow per 100 g tissue/min.
- Carotid endarterectomy has definite benefit in symptomatic patients with more than 70% stenosis and marginal benefit in those with 50–69% stenosis.
- Trauma is the most common cause of SAH, while aneurysmal rupture accounts for 80% of spontaneous SAH.
- 95% of cerebral aneurysms are sporadic rather than due to other causes.
- Anterior circulation is the most common location for aneurysm with ACoA representing 30% of all cases.
- The most common presentation for AVMs is hemorrhage.
- Cavernous malformations are best detected on MRI.

## 12.5 Top Hits

### 12.5.1 Questions

1. Which of the following is NOT one of the modifiable risk factors for stroke prevention?
  - a) Hypertension
  - b) Alcohol consumption
  - c) Lipid levels
  - d) Cigarette smoking
  - e) None of the above
2. Which of the following therapies could be used in a setting of stroke that occurred 7 hours ago due to a thromboembolus?
  - a) IV tPA
  - b) Mechanical thrombectomy
  - c) Intra-arterial tPA
  - d) IV alteplase
3. Within what time period can IV tPA be utilized to treat vaso-occlusive ischemic stroke?
  - a) 3 hours
  - b) 3.5 hours
  - c) 4 hours
  - d) 4.5 hours
  - e) 5 hours
4. Occlusion of which artery would result in bilateral thalamic and brainstem stroke?
  - a) Posterior choroidal artery
  - b) Labyrinthine artery
  - c) Artery of Percheron
  - d) Artery of Heubner
5. What does the Fisher scale predict?
  - a) Risk of mortality after aneurysmal SAH
  - b) Risk of mortality and morbidity after aneurysmal SAH
  - c) Risk of vasospasm in aneurysmal SAH
  - d) Risk of vasospasm in any SAH
6. Which of the following is a major preoperative consideration with aneurysmal clipping?
  - a) Clipping is not a reasonable alternative to coiling for fusiform aneurysms
  - b) Mortality and morbidity can be decreased when clipping is combined with minimally invasive craniotomy approach
  - c) Intraoperative rupture presents a considerable risk
  - d) Need for future MRI scans may require coiling rather than clipping

7. Which of the following is true about pipelines or flow diverters?
    - a) They cannot be used to treat wide-based neck aneurysms
    - b) Their use in treatment of ruptured aneurysms is contraindicated
    - c) They are not an alternative to stent-coiling
    - d) Their efficacy has not been well-described
  8. In what way is endovascular coiling superior to clipping in treatment of cerebral aneurysms?
    - a) It is less expensive than coiling
    - b) There is lower chance of rebleeding
    - c) Coiling results in lower mortality or dependence than clipping
    - d) It is more durable than clipping
  9. What is the most common location for dural AVM fistulas?
    - a) Transverse sinus
    - b) Tentorium
    - c) Sigmoid sinus
    - d) Vertebral artery
  10. What is the value of angiography in evaluating cavernous malformations?
    - a) It is the gold standard in detecting these vascular lesions
    - b) It can detect most lesions
    - c) It is useful in delineating some lesions
    - d) It cannot be used to detect these lesions
3. **d.** IV tPA has been shown to have clear benefit if given within 4.5 hours of the onset of stroke symptoms.
  4. **c.** Artery of Percheron is a variant in which a single artery arises from PCA to supply both thalami and the midbrain.
  5. **c.** The Fisher scale is used to predict vasospasm risk in aneurysmal SAH based on CT imaging.
  6. **c.** Clipping carries a 20–40% risk of intraoperative rupture. Fusiform aneurysms are better treated with clipping than coiling alone, although combined technique of stent-coiling has proven to be an alternative in treatment of certain aneurysms. Minimally invasive craniotomy aneurysmal clipping has not been proven to have higher efficacy or lower mortality than the typical approaches. Modern clipping techniques utilize MRI-safe titanium clips.
  7. **b.** Pipelines and flow diverters can be used to treat some aneurysms in lieu of stent-coiling.<sup>81</sup> Because of the need for antiplatelet and anticoagulation therapy, their use in ruptured aneurysms has generally been limited.<sup>59,78,79</sup>
  8. **c.** Based on data from the ISAT trial, mortality or dependency was lower for coiling than clipping. Rebleeding risk is actually higher in coiling than clipping. Costs appear to be comparable between coiling and clipping, however, the cost of materials in coiling is balanced by longer hospital stays in clipping. Clipping represents a more durable option for treatment. Surgical aneurysm clipping is more expensive than coiling in terms of length of hospital stay and patient costs.

## 12.5.2 Answers

1. **e.** All of the listed items are modifiable risk factors for stroke. In addition, antiplatelet therapy has been shown to reduce risk of future events in certain types of strokes.
2. **b.** According to the HERMES study, treatment with endovascular and medical therapy results in lower disability if treatment is initiated with 7.3 hours of onset of symptoms.<sup>17</sup> At most institutions, patients can be eligible within 8 hours of symptom onset.
3. **d.** IV tPA has been shown to have clear benefit if given within 4.5 hours of the onset of stroke symptoms.
4. **c.** Artery of Percheron is a variant in which a single artery arises from PCA to supply both thalami and the midbrain.
5. **c.** The Fisher scale is used to predict vasospasm risk in aneurysmal SAH based on CT imaging.
6. **c.** Clipping carries a 20–40% risk of intraoperative rupture. Fusiform aneurysms are better treated with clipping than coiling alone, although combined technique of stent-coiling has proven to be an alternative in treatment of certain aneurysms. Minimally invasive craniotomy aneurysmal clipping has not been proven to have higher efficacy or lower mortality than the typical approaches. Modern clipping techniques utilize MRI-safe titanium clips.
7. **b.** Pipelines and flow diverters can be used to treat some aneurysms in lieu of stent-coiling.<sup>81</sup> Because of the need for antiplatelet and anticoagulation therapy, their use in ruptured aneurysms has generally been limited.<sup>59,78,79</sup>
8. **c.** Based on data from the ISAT trial, mortality or dependency was lower for coiling than clipping. Rebleeding risk is actually higher in coiling than clipping. Costs appear to be comparable between coiling and clipping, however, the cost of materials in coiling is balanced by longer hospital stays in clipping. Clipping represents a more durable option for treatment. Surgical aneurysm clipping is more expensive than coiling in terms of length of hospital stay and patient costs.
9. **a.** Transverse sinus is the most common location of dural arteriovenous fistulas.
10. **d.** Cavernous malformations cannot be detected with cerebral angiography as they are low-flow lesions. They are best evaluated with MRI.

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## 13 Neurosurgical Oncology

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### 13.1 Lymphomas and Hematopoietic Tumors

Primary central nervous system lymphoma (PCL) represents extranodal non-Hodgkin lymphoma that involves the brain, meninges, eyes, and spinal cord. It is a rare entity with approximately four cases per million people per year in the general population. Incidence is 3,600 times higher among patients with AIDS with a lifetime risk of 20% and may be present in up to 10% of patients with AIDS at autopsy.<sup>1,2</sup> Presentation is variable given the large potential area of involvement and may include focal neurologic deficits (70%), neuropsychiatric issues (43%), raised intracranial pressure (ICP) (33%), seizures (14%), ocular involvement (4%).<sup>3</sup> Meningeal disease is seen in approximately 40% of patients resulting in cranial neuropathies and headache.<sup>4</sup> Ocular involvement is seen in 15 to 25% of patients classically involving the posterior segment of the globe resulting in uveitis, retinal detachment, and retinal/vitreous hemorrhages.<sup>3</sup> Over 90% represent high grade, CD20-positive, diffuse large B-cell non-Hodgkin lymphomas. The remainder include Burkitt's, Burkitt's-like, lymphoblastic B-cell, and T-cell lymphomas.<sup>5</sup> The pathogenesis is incompletely understood as B cells do not typically reside within the central nervous system (CNS) and may involve latent Epstein-Barr virus (EBV) B-cell infection. Lesions are usually periventricular (60%) with variable density and intensity on computed tomography (CT) and T2-weighted magnetic resonance imaging (MRI), respectively. There is homogeneous enhancement including perivascular spaces.<sup>6</sup> Mass effect, vasogenic edema, calcification, hemorrhage, cysts, and ring enhancement are often present (► Fig. 13.1).

#### 13.1.1 Diagnosis

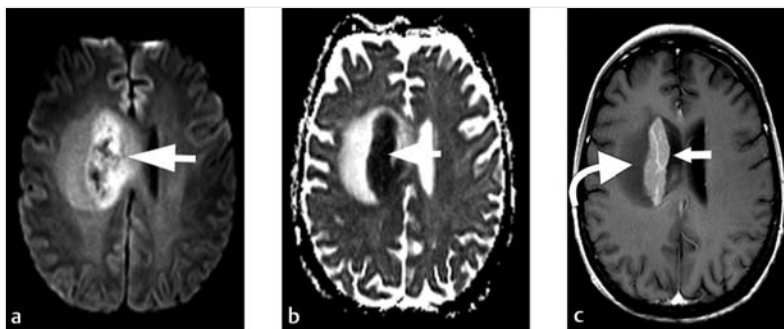
Stereotactic needle biopsy is highly specific and is the gold-standard diagnostic modality. If there are no contraindications to lumbar puncture (e.g., mass effect), cerebrospinal fluid (CSF) analysis should be analyzed by cytology, flow cytometry, and polymerase chain reaction (PCR) for immunoglobulin heavy-chain rearrangements. Malignant lymphocytes are present in up to 40% (higher sensitivity with leptomeningeal involvement). CSF typically shows elevated protein and lymphocytic pleocytosis. Glucose concentration may be decreased in cases of leptomeningeal involvement. Histologically, there are large immunoblastic and centroblastic cells with reactive perivascular T-cell infiltrates. Commonly expressed markers include MUM1, BCL6, and BCL2.

#### 13.1.2 Treatment

Surgery is limited to acute reduction of mass effect in the setting of an acute decline. Chemotherapy and radiation are the treatment modalities of choice.

#### 13.1.3 Outcome

Untreated PCL has a mean survival of 1.5 years postdiagnosis. However, mean survival after chemotherapy with or without radiation is usually 40 to 50 months, with a 30% 5-year survival rate among immunocompetent adults. Age greater than 60 years, Eastern Cooperative Oncology Group (ECOG) performance status score greater than 1, elevated serum lactate dehydrogenase (LDH), elevated CSF protein, and involvement of deep brain



**Fig. 13.1** Primary central nervous system lymphoma mimicking acute infarct. **(a)** Axial diffusion-weighted imaging and **(b)** apparent diffusion coefficient map in a patient with primary CNS lymphoma show a region of restricted diffusion in the right periventricular white matter due to hypercellularity of the tumor (*arrow*). **(c)** Contrast-enhanced T1-weighted image shows intense enhancement of the periventricular mass (*arrow*) with surrounding hypointense vasogenic edema (*curved arrow*). (Adapted from Leite C, Castillo M, Diffusion Weighted and Diffusion Tensor Imaging, A Clinical Guide, 1st edition, ©2015, Thieme Publishers, New York.)

regions are negative prognostic factors. Secondary lymphomas occur when systemic lymphomas metastasize to the CNS and is associated with testicular involvement. The cornerstone of management is treatment of the primary disease. Median survival is 2 to 4 months.

## 13.2 Mesenchymal Tumors

These tumors originate from connective tissue in and about the nervous system and have no neuroectodermal origins per se.

### 13.2.1 Chordomas

Chordomas (< 1% of intracranial tumors) are destructive, locally aggressive tumors with metastatic potential that arise from persistent rests of fetal notochord. Genetic abnormalities include 1p36 loss, RB mutations, telomerase activation, and

overexpression of platelet-derived growth factor receptor  $\beta$  (PDGFR- $\beta$ ).

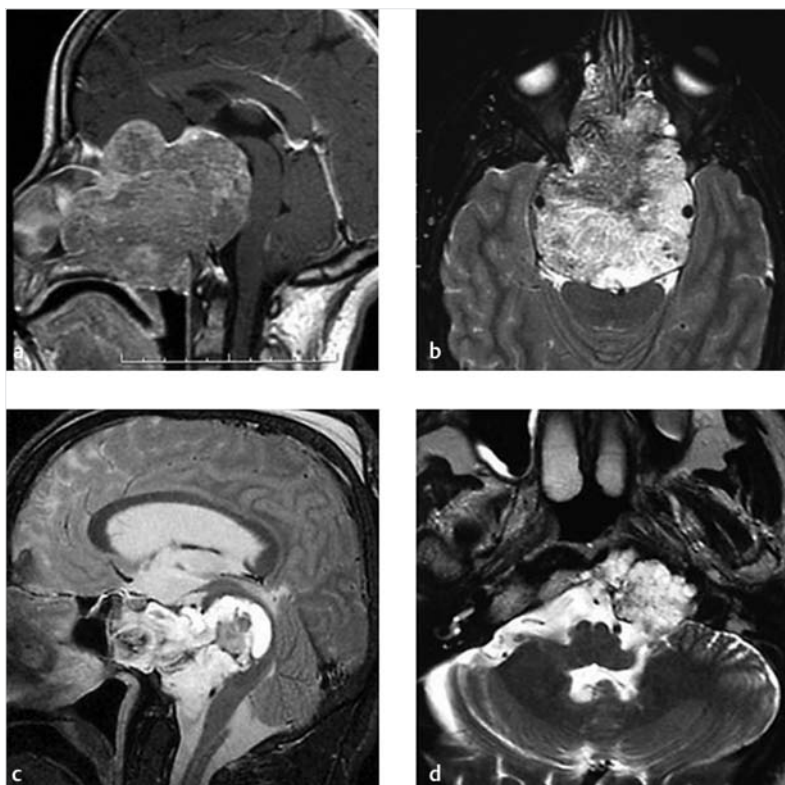
Chordomas are hyperintense on T2-weighted imaging (T2WI), isointense on T1WI. Septations, calcification, and a “honeycomb” pattern of enhancement are characteristic features (► Fig. 13.2).

Surgery followed by proton beam radiation is the standard therapy. Chordomas stain positive for brachyury, S-100, cytokeratin, and epithelial membrane antigen (EMA) and may demonstrate bubble-like physaliferous bodies. The 5- and 10-year survival rates of chordoma are approximately 51 and 35%, respectively.<sup>8</sup>

### 13.2.2 Chondrosarcomas

Chondrosarcomas (< 0.15% of all intracranial tumors) are indolent bone neoplasms thought to arise from persistent rests of fetal cartilage and are associated with Paget’s





**Fig. 13.2** Magnetic resonance imaging scans illustrating three examples of chordomas. **(a)** Sagittal T1-weighted MR image illustrating involvement of the whole clivus by a chordoma. **(b)** Corresponding axial T2-weighted MR image illustrating involvement of the whole clivus by a chordoma with lateral displacement of the internal carotid arteries. **(c)** Sagittal T2-weighted MR image showing a chordoma of the upper clivus with intradural extension. **(d)** Axial T2-weighted MR image demonstrating chordoma of the jugular foramen. (Adapted from Nader R, Gragnaniello C, Berta S et al, *Neurosurgery Tricks of the Trade, Cranial*, 1st edition, ©2013, Thieme Publishers, New York.)

disease, Ollier's disease, and Maffucci's syndrome. CT shows a well-defined lytic lesion with chondroid calcification. They are hyperintense on T2, hypointense on T1 with intense, often heterogeneous enhancement. Most involve the clivus (32%) and temporo-occipital junction (27%).

Unlike chordomas, chondrosarcomas typically occur off-midline due to their origin from sites of synchondrosis.

Management is like that of chordomas. Treated chondrosarcomas have a good prognosis with 5-year mortality rate of 11.4%.<sup>9</sup>

### 13.2.3 Meningeal Tumors

#### Meningiomas

These are the most common nonglial tumors which arise from arachnoid cap cells and account for 20 to 25% of all intracranial neoplasms. Most prevalent after age 50 with a F:M ratio of 2:1 and cranial:spine ratio of 10:1. Most (80%) are benign WHO grade I lesions that occur sporadically.



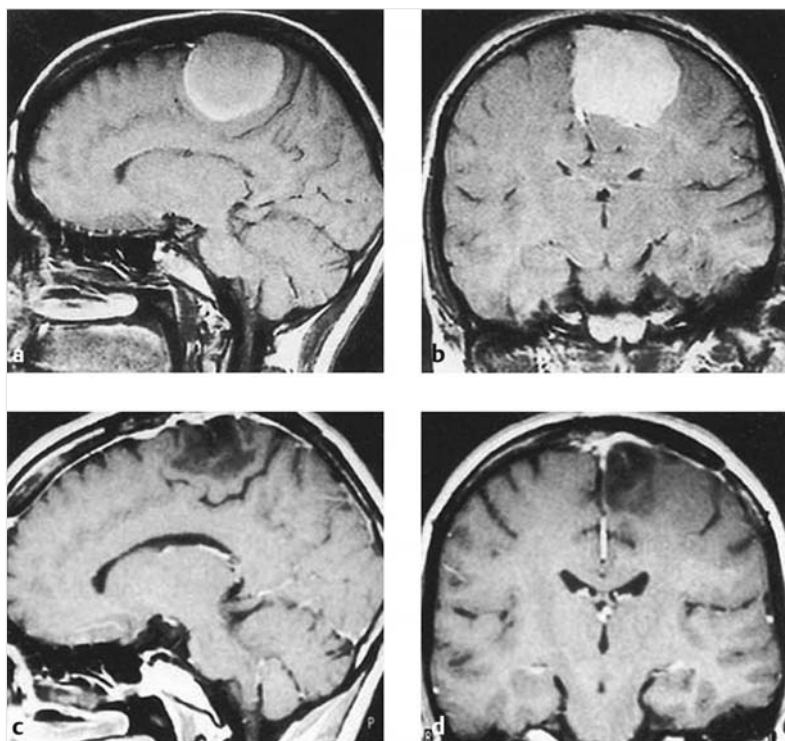
Multiple meningiomas occur in 1 to 9% of sporadic cases and as a feature of neurofibromatosis type 2 (NF2).

Risk factors include ionizing radiation, partial loss of chromosome 22 at the site involving the NF2 locus and protein 4.1B on 18p11.3. Progesterone receptors are present in half of meningiomas but this is of unknown significance. These may manifest as spherical, lobulated, or flat “en plaque” well-circumscribed dural lesions with clearly delineated tumor–brain interface. The majority appear hyperdense on CT with focal or diffuse calcification seen in 20 to 25%. Hyperostosis may be striking due to bony destruction. On MRI, they are T1 and T2 hypointense with homogeneous enhancement (► Fig. 13.3).

Surgery is the primary treatment modality. The Simpson Grading Scale<sup>10</sup> (► Table 13.1) is used to describe the extent of resection and together with histological grade provides the most important prognostic indicator. Fractionated external beam or stereotactic radiosurgery is reserved for surgically inaccessible lesions, recurrence, and higher-grade lesions.

#### Benign Mesenchymal Tumors

These are rare entities with variable clinical presentations, management, and prognosis. CNS **rhabdomyomas** are rare. **Angiolipomas** are associated with Proteus' syndrome. These are composed of mature adipose tissue and abundant vascular channels of variable caliber without cytologic atypia or structural vascular channel abnormalities. Surgical resection may be curative. **Chondromas** are benign cartilage-producing bony lesions that typically involve the long bones and appendicular skeleton. These present as sporadic lesions or as a component of Ollier's disease or Maffucci's syndrome. The lesions are difficult to distinguish from meningioma on neuroimaging and may have markedly delayed contrast enhancement. Surgical resection may be curative. Primary CNS **leiomyomas** (e.g., uterine fibroids) have rarely been described with fewer than 25 cases in the literature. They are associated with EBV infection in immunosuppressed patients. Lesions homogeneously enhance and look like meningiomas. Gross total resection (GTR) is curative. **Osteochondromas** are benign tumors characterized by focal ossification within hyaline cartilage. They are usually sporadic but have been reported in the context of Maffucci's syndrome, Noonan's syndrome, and Ollier's disease. There is avid contrast enhancement and are often confused with meningiomas.<sup>11</sup> **Benign fibrous histiocytoma** is a rare mesenchymal lesion of soft tissue and bone with occasional retroperitoneal organ involvement. Dura and parenchyma are rarely involved. GTR may be curative but may behave more aggressively in older adults in whom it may be associated with recurrence and mortality. Adjunctive therapy should be considered in older individuals. **Osteomas** are benign bone-forming tumors usually involving the axial skeleton. These occur in the extremities of children



**Fig. 13.3** A 25-year-old woman with a 6-week history of jacksonian seizures and with minor spastic weakness of the right leg. The MRI—(a) sagittal and (b) coronal (anteroposterior) revealed a left-sided parasagittal meningioma in the central area. At exploration, two small nodules of tumor were found within the superior sagittal sinus, which was occluded. These nodules were removed together with a section of the wall of the sinus, which was then grafted using periosteum. There was also marked tumor adherence to other structures within the tumor bed, but the leptomeningeal arteries could be dissected free. The postoperative course was good; her leg weakness resolved over the ensuing 6 weeks. Postoperative MRI: (c) sagittal, (d) coronal (anteroposterior). (Reproduced from Yasargil M, *Microneurosurgery*, Volume IV B, *Microneurosurgery of CNS Tumors*, 1st edition, Thieme; ©1995, Thieme Publishers, New York.)

and adolescents and involve the posterior arches of the vertebrae, sinuses, facial bones, skull, and mandible. These are present in up to 5% of autopsy cases. No associated chromosomal loss or translocation has been identified to date. Observation with

resection of symptomatic or enlarging lesions is recommended. En bloc surgical excision may be curative. **Solitary fibrous tumors** and **hemangiopericytomas** (SFTs/HPC) were previously classified separately and are now recognized as the histological

**Table 13.1** Simpson grading scale

| Grade | Definition                        | Recurrence |
|-------|-----------------------------------|------------|
| I     | GTR with removal of dura and bone | 9%         |
| II    | GTR with coagulation of dura      | 19%        |
| III   | GTR only                          | 29%        |
| IV    | STR                               | 44%        |
| V     | Decompression/biopsy              |            |

Abbreviations: GTR, gross total resection; STR, subtotal resection.

Note: Simpson divided meningioma resection into five grades based on the extent of resection and management of the dura and overlying bone.<sup>10</sup> Recent refinements have included proliferative index but has not resulted in a significant deviation from the originally proposed framework.

spectrum of a single tumor entity. Heterogeneous iso- to hyperdense lesions appear on noncontrast CT. Lesions are T1 isointense, T2 hypointense with intense but heterogeneous contrast enhancement. GTR may be curative; subtotal resection may lead to local recurrence, which is associated with reduced survival. Malignant tumors carry a high rate of recurrence (80%) and systemic metastasis (25%), but prognosis is good for lower grades with complete surgical resection. Extended follow-up is suggested in all cases as no case of CNS SFT/hemangiopericytoma can be considered definitively cured. **Lipomas** are benign lesions composed of mature adipose tissue representing 0.46 to 1% of intracranial tumors. Intracranial lesions often asymptomatic, while spinal lesions often present with cord compression and are associated with CNS dysgenesis. Lesions are midline in

80 to 90% and usually at the surface of the corpus callosum, dorsal midbrain, cerebellar vermis, and spinal cord. As it is thought to result from the abnormal persistence and maldifferentiation of the meninx primitiva, the term lipomatous hamartoma is used interchangeably. There is marked hypodensity on CT without contrast enhancement and capsular calcification in interhemispheric lesions. They are homogeneously hyperintense on T1WI, hypointense with fat suppression, and hypointense on T2WI without enhancement. Surgery is rarely indicated and often associated with high morbidity and mortality secondary to the highly vascular nature of lipomas and their adherence to surrounding tissue.

### Malignant Mesenchymal Tumors

These are rare, aggressive lesions representing less than 0.1% of intracranial tumors. Cell of origin may be pluripotent, primitive mesenchymal cells of the meninges, periadventitial spaces, tela choroidea or the stroma of the choroid plexus. Prior CNS radiation is a risk factor. EBV is associated with intracranial leiomyosarcoma in individuals with AIDS. These lesions show variable differentiation often resembling fibrous tissue (e.g., fibrosarcoma, malignant fibrous histiocytoma), muscle, cartilage, bone, or blood vessels, and are usually found in the temporal and parietal lobes. As there is a high incidence of leptomeningeal spread, imaging of the full neuraxis is essential. Systemic metastases (lungs, bone, liver) rarely occur. Radiographic appearance is often nonspecific with contrast enhancement on CT and MRI. Management strategies include maximal safe resection and radiotherapy. Chemotherapy is largely ineffective for CNS sarcomas. The 5-year survival rate was 52% overall but only 28% for patients with high-grade lesions versus 83% among patients with low-grade

lesions. Specific entities include **fibrosarcomas**, **rhabdomyosarcomas**, **leiomyosarcomas**, **Ewing's sarcoma** (primitive neuroectodermal tumor [PNET]), osteosarcoma, **Kaposi's sarcoma**, **liposarcoma**, **angiosarcoma**, and **malignant fibrous histiocytoma**.

### 13.2.4 Hemangioblastoma

These are vascular WHO grade I tumors of unknown histogenesis associated with the leptomeninges and associated with von Hippel-Lindau (VHL).

Inactivation of the VHL tumor suppressor gene and gain of function in HIF2A have been reported in sporadic forms. Genetic changes are isolated to the stromal elements of the tumor but not the vasculature. Surgery is the mainstay of treatment if symptomatic or demonstrating growth on serial imaging. Antiangiogenic agents have been used when other modalities are not feasible.<sup>12</sup>

### 13.2.5 Melanocytic Lesions

These include melanocytomas, malignant melanomas, and meningeal melanomatosis. They originate from leptomeningeal melanocytes and are typically found in the posterior fossa, perimedullary and high cervical cord, and less frequently, in the thoracic and lumbar spine. They are T1 hyperintense and T2 hypointense contrast-enhancing lesions. Melanocytomas may exhibit fine punctate areas of decreased signal intensity on T1WI and show no contrast enhancement. Meningeal melanomatosis may show diffuse leptomeningeal enhancement with nodular parenchymal enhancement. The imaging characteristics vary depending on melanocytic content and hemorrhage. Treatment entails surgical resection for focal lesions;

radiation and temozolomide have been trialed in diffuse leptomeningeal disease. Melanocytoma is considered a WHO grade I lesion with a slow-growing indolent course and surgery may be curative. Meningeal melanomatosis typically has a dismal outcome.<sup>13</sup>

## 13.3 Neuroepithelial Brain Tumors

Neuroepithelial cells give rise to all CNS neurons and glial cells and thus neoplasms from cells of neuroepithelial origin constitute a substantial proportion of primary brain neoplasms. All tumors of glial origin are considered gliomas. The 2016 WHO classification of CNS neoplasms incorporated cytogenetics for classification of tumors with a less prominent role for histology. Isocitrate dehydrogenase (IDH) mutation and 1p/19q codeletion play an essential role in the new classification schema with additional information provided by ATRX loss, TP53 and TERT mutations.

### 13.3.1 Astrocytomas

Astrocytomas are gliomas derived from astrocytes and range from WHO grade I to IV.

Glioblastoma multiforme (GBM) is a WHO grade IV lesion and is the most common primary malignant CNS tumor overall representing nearly 50% of primary CNS malignancies, while pilocytic astrocytomas (WHO grade I) are the most common type in the pediatric population.<sup>14</sup>

### Diffuse Infiltrating Glioma

These are WHO grade II gliomas with microscopic invasion of brain parenchyma

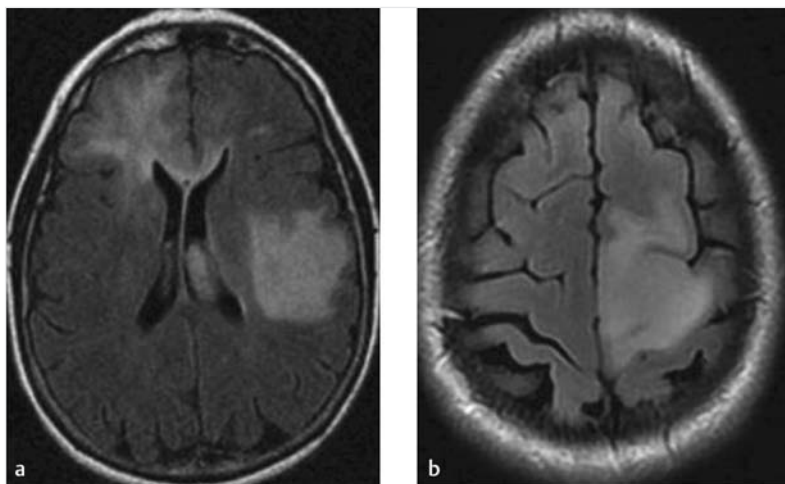
and thus lack sharp boundaries. Typical MRI features include a homogeneous mass with minimal mass effect and vasogenic edema without contrast enhancement. There is T2/fluid-attenuated inversion recovery (FLAIR) hyperintensity (► Fig. 13.4).

Lesions are hypodense on CT and sometimes calcification is present. Nearly 80% present with seizures although headaches, cognitive and behavioral changes, hemiparesis, hydrocephalus, and aphasia are other common presenting features. GTR can be difficult as a result of microscopic infiltration and some authors advocate resection of all T2 hyperintensity if this can be safely performed.

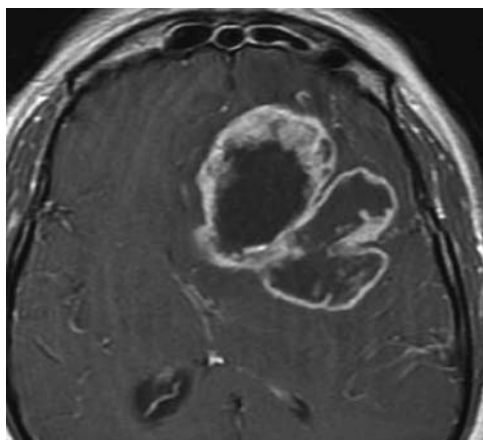
GBM shows contrast heterogeneous ring enhancement and frequently has a necrotic core (► Fig. 13.5).

## Pilocytic Astrocytoma

It usually affects children although can be seen in adults. They typically occur in the cerebellum, optic nerve, or brainstem. Adult pilocytic astrocytomas follow a more aggressive clinical course compared to the pediatric population. Constitutive RAS/RAF/MAPK activation is important in the pathogenesis of sporadic pilocytic astrocytomas. CT scan characteristically shows a cystic lesion with an enhancing mural nodule. MRI reveals a solid tumor (50%) with variable contrast enhancement or cystic lesions with contrast-enhancing mural nodules (21%), mixed cystic and solid areas (29%), and occasional intratumoral hemorrhage (► Fig. 13.6).



**Fig. 13.4 (a)** Axial fluid-attenuated inversion recovery image of diffuse tumor infiltration into the left posterior frontal lobe and the right frontal lobe with involvement of the corpus callosum. These findings indicate a diffuse glioma. **(b)** Axial FLAIR image demonstrating a glioma within the left motor cortex. Both images show tumors that cannot be removed without serious neurologic sequelae and are best managed with a biopsy. (Reproduced from Bernstein M, Berger M, *Neuro-Oncology: The Essentials*, 3rd Edition, ©2014, Thieme Publishers, New York.)



**Fig. 13.5** Glioblastoma multiforme. T1-weighted post-contrast image demonstrates a large, heterogeneously enhancing left frontal lobe mass that effaces the frontal horns of the lateral ventricles and causes significant leftward midline shift. Note that the enhancement is thick and irregular, with a central nonenhancing region that reflects necrotic tumor. (Reproduced from Tsiouris A, Sanelli P, Comunale J, Case-Based Brain Imaging, 2nd edition, ©2013, Thieme Publishers, New York.)



**Fig. 13.6** Juvenile pilocytic astrocytoma. **(a)** Postcontrast axial T1-weighted image of the posterior fossa shows a cystic lesion in the medial aspect of the right cerebellar hemisphere, resulting in effacement of the fourth ventricle. There is an enhancing mural nodule, as well as thin enhancement along an internal septation. **(b)** Axial T2W image shows a relatively hyperintense appearance of the nodule, corresponding to a high internal water content. **(c)** Axial apparent diffusion coefficient map shows a hyperintense signal (diffusion of  $1,750 \times 10^{-6} \text{ mm}^2/\text{s}$ ), indicating facilitated diffusion in this pilocytic astrocytoma (WHO grade I). (Reproduced from Choudhri A, Pediatric Neuroradiology: Clinical Practice Essentials, 1st edition, ©2016, Thieme Publishers, New York.)

For pilocytic astrocytomas, GTR may be curative, while subtotal resection of the nodule may provide excellent control.

Adjuvant radiotherapy and/or chemotherapy employed in lesions are not amenable to surgical resection (optic gliomas, brainstem lesions). Overall survival at 5 and 10 years is 87 and 77%, respectively.



## Chordoid Glioma of the Third Ventricle

These are rare, low-grade neoplasms arising from the roof of the third ventricle or anterior wall, female preponderance, and age of onset between 30 and 70 years. The ependymal cells (tanycytes) of the lamina terminalis are their postulated source of origin. It presents with obstructive hydrocephalus, endocrine imbalance, dysautonomia, and progressive weight gain with hyperphagic behavior attributed to pressure on the surrounding suprasellar structures and hypothalamus. MRI shows a T1 isointense, T2 iso- to hyperintense ovoid the third ventricular mass. Surgical resection is the treatment of choice although this can often prove difficult due to the deep-seated location. Chemo- and radiotherapy are not effective modalities. Outcome is often poor due to incomplete resection, associated morbidity, and high recurrence rates.

### 13.3.2 Pediatric Neuroepithelial Lesions

#### Pediatric Brainstem Glioma

These account for 25% of infratentorial CNS tumors in children with median age of 7 to 14 years. Prognosis is poor with 2-year mortality over 90%. The pons is usually the most commonly affected location followed by the medulla and midbrain. Four pathologic patterns are identified based on growth: diffuse (all are malignant), cervicomedullary (72% low-grade astrocytomas), focal (medulla with 66% low-grade astrocytomas), and dorsally exophytic (most favorable prognosis). MRI is the preferred diagnostic modality and often obviates the need for surgical biopsy, which is no longer recommended for diagnosis.

Partial resection is associated with improved survival in the first 9 months post-op for dorsally exophytic tumors.<sup>15</sup>

Diffuse intrinsic pontine glioma (DIPG) is the most common type and is associated with a grave prognosis (► Fig. 13.7).

Palliative radiotherapy remains the mainstay of treatment for pediatric brainstem lesions. Chemotherapy has not proven very beneficial.

A new entity called “diffuse midline glioma, H3K27 mutant” has been defined which includes tumors previously referred to as DIPG. It was included in the WHO 2016 classification of CNS tumors. The mutation is found in 71% of patients with DIPG. Radiotherapy is the standard treatment and leads to neurologic improvement and improved progression-free survival without improvement in overall survival. Median survival is less than 12 months.<sup>16,17</sup>

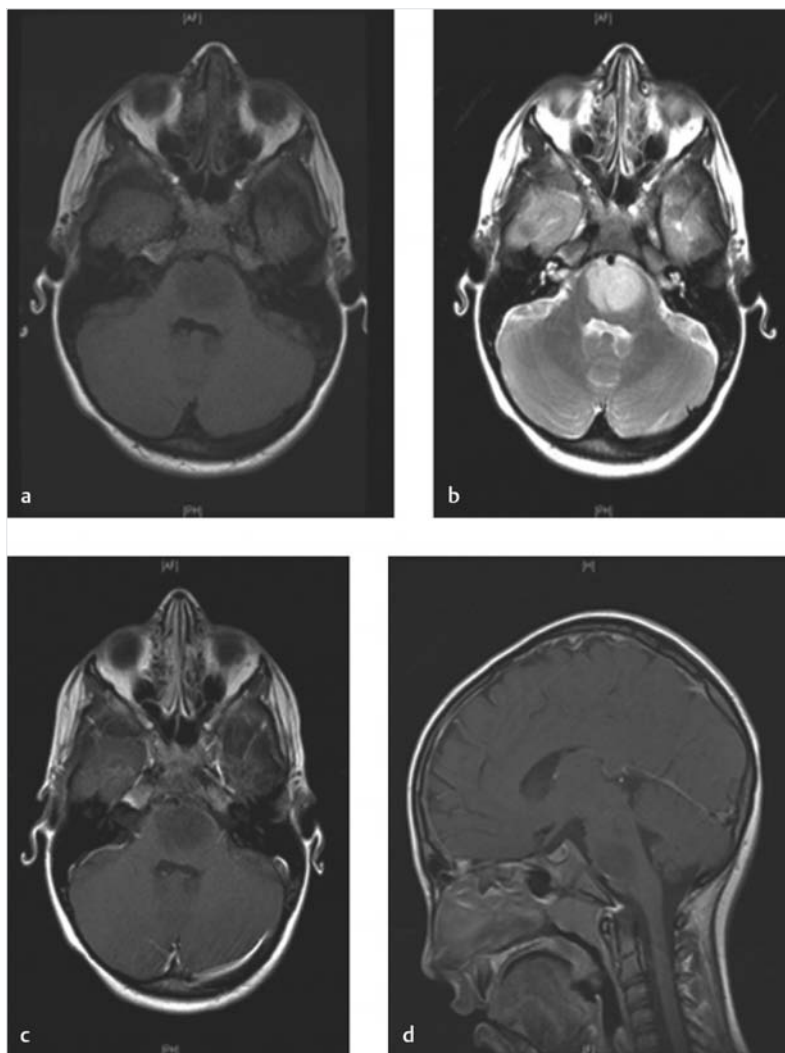
#### Tectal Glioma

These are typically low-grade gliomas arising from the tectal plate of the midbrain and account for 6% of surgically treated brain tumors in children. Median age of presentation is 6 to 10 years. Management is usually conservative with treatment of hydrocephalus. Stereotactic radiosurgery often offered for progressive lesions. Outcome is generally favorable with median interval of tumor progression of 7.8 years from the time of shunt insertion and 11.5 years from initial presentation in a single-institution series.<sup>18,19</sup>

#### Pilocytic Myxoid Astrocytoma

Pilomyxoid astrocytoma was introduced first in 1985 as “diencephalic pilocytic astrocytoma with clinical onset in infancy.” Median age of onset is 10 to 18 months. Histologically, the tumor appears similar





**Fig. 13.7** Diffuse intrinsic pontine glioma. **(a)** Axial T1-weighted magnetic resonance image of a child with DIPG demonstrating classic hypointensity and indistinct margin. **(b)** Axial T2-weighted MR image of the same patient demonstrating classic hyperintensity. **(c)** Axial T1-weighted MR image with gadolinium contrast demonstrating lack of enhancement. **(d)** Sagittal T1-weighted MR image with gadolinium contrast. (Reproduced from Albright A, Pollack I, Adelson P, *Principles and Practice of Pediatric Neurosurgery*, 3rd edition, ©2014, Thieme Publishers, New York.)

to pilocytic astrocytomas with the addition of a prominent myxoid matrix. Outcomes are poor compared to classical pilocytic astrocytoma with lower progression-free survival (38.7% at 1 year vs. 69.2% for classic pilocytic astrocytomas).<sup>20,21</sup>

### 13.3.3 Other Low-Grade Glial Tumors

#### Angiocentric Glioma

Angiocentric glioma is a tumor entity defined in 2005. Refractory epilepsy is the most common presenting feature. The mean age at presentation is 17 years. They are often located in the frontoparietal region, temporal lobe, and hippocampus. MRI reveals a T1 hypointense, T2 hyperintense, nonenhancing well-circumscribed mass with a stalk-like extension to the subjacent ventricle. GTR is potentially curative and there is no established role for chemoradiotherapy.



Histological analysis of an angiocentric glioma reveals bipolar cells with an angiocentric growth pattern and pseudorosettes reminiscent of ependymoma.

#### Astroblastoma

These are rare tumors that arise from astroblasts with a mean age of presentation between 10 and 30 years. Lesions are large, peripherally located, supratentorial, lobulated, solid, cystic masses with little vasogenic edema and tumor infiltration. Multiple cysts are commonly seen giving rise to a bubbly appearance. Lesions are isointense on T1 and T2 with calcifications in 85% of lesions on CT. Resection with adjuvant radiotherapy improves survival in patients with high-grade lesions.<sup>22</sup>

## 13.4 Ependymoma and Subependymoma

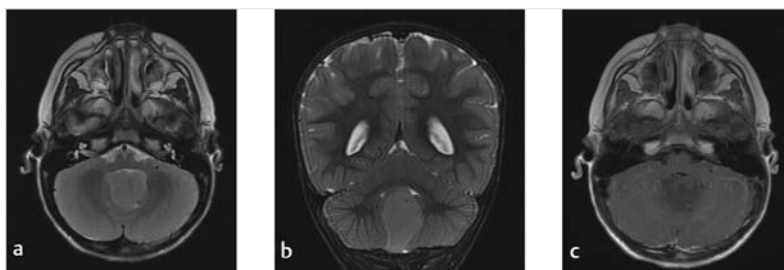
Ependymomas arise from ependymal cells lining the cerebral ventricles or central canal of the spinal cord. They are most common in children and young adults without gender predilection. They are T1 iso- and T2 iso- to hyperintense with heterogeneous contrast enhancement with frequent intratumoral hemorrhage, calcification, and cysts (► Fig. 13.8).

Supratentorial ependymoma has *RELA*- or *YAP1* fusion, which activate nuclear factor kappa B (NF- $\kappa$ B) pathway. Standard treatment is maximal safe resection followed by radiation therapy. The efficacy of chemotherapy remains controversial. Five-year survival is 70 to 90% and 60 to 65% for grades II and III tumors, respectively.

Subependymomas in contrast occur in older individuals and present as a sharply demarcated iso- or hypodense lesion on CT with occasional calcification. They are hypo- to isointense on T1 and hyperintense on T2-weighted MRI without contrast enhancement. These are considered benign lesions and management includes surgical resection without adjuvant therapy. Prognosis is good in the setting of a GTR.<sup>14</sup>

## 13.5 Pineal Region Tumors

The most frequent tumor in the pineal region is a **germ cell tumor** (35.3%), followed by pineal parenchymal tumor (PPT) (27.9%). PPTs consist of pineocytoma (WHO grade I), pineal parenchymal tumor of intermittent differentiation (PPTID) (WHO grade II/III), pineoblastoma (WHO grade IV), and papillary tumor of the pineal region (PTPR) (WHO grade II/III). **Pineocytoma** occurs in patients from 10 to 60 years, with a slight predominance in females. It presents with intracranial



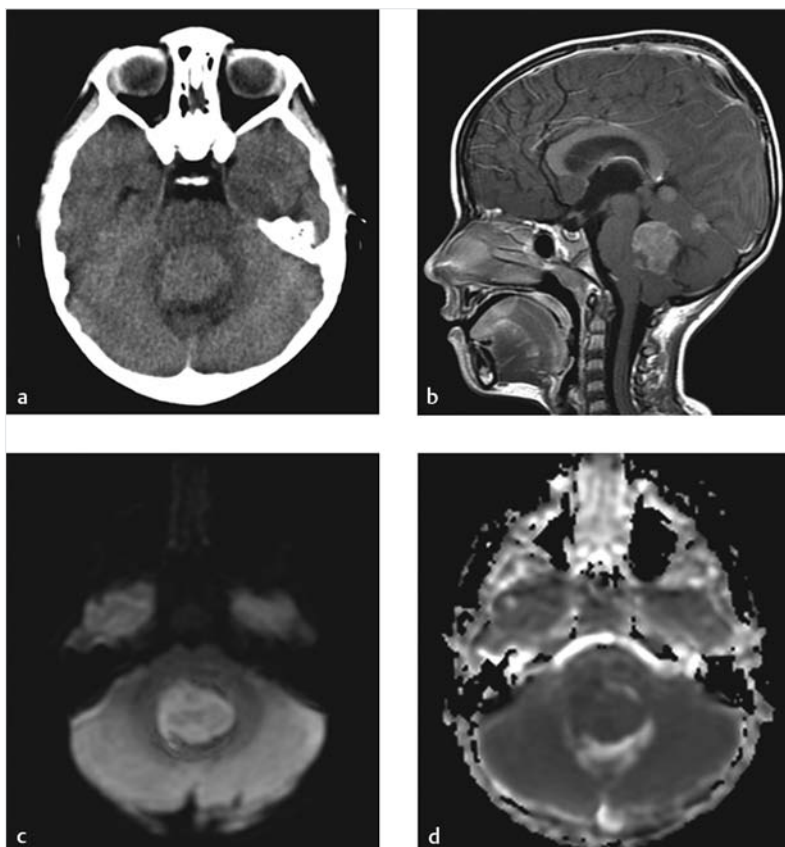
**Fig. 13.8** Ependymoma. **(a)** Axial T2W image shows a mass of intermediate intensity within the fourth ventricle. **(b)** Coronal short tau inversion recovery image shows that the mass extends caudally through the foramen of Magendie. **(c)** Axial T1 plus contrast image shows that the lesion does not demonstrate significant enhancement. This lesion was an ependymoma. (Reproduced from Choudhri A, Pediatric Neuroradiology: Clinical Practice Essentials, 1st edition, ©2016, Thieme Publishers, New York.)

hypertension due to obstructive hydrocephalus caused by compression of the mesencephalic aqueduct. It usually presents as globular, well-demarcated masses with occasional cysts. CT shows calcification usually in the periphery of the mass. Complete resection may lead to cure. If residual tumor is observed postoperatively, local radiation therapy is usually done. **Pineoblastomas** are WHO grade IV neoplasms, which arise from pineal parenchymal cells. They occur in children and young adults without gender predilection. The standard treatment is surgical resection followed by whole-brain radiation therapy and multiagent chemotherapy. In adult patients, GTR and radiation therapy with more than 40 Gy improves the prognosis. **Papillary tumors of the pineal region** are WHO grade II or III tumors thought to arise from ependymal cells at the subcommissural organ. They occur in all ages but most frequently in young adults without gender predilection. Treatment is resection, then radiation therapy with chemotherapy reserved for recurrence or CSF dissemination.<sup>30,31</sup>

## 13.6 Embryonal/PNETs

### 13.6.1 Medulloblastoma

Medulloblastomas comprise 15 to 20% of pediatric brain tumors. Approximately 75% occur in children younger than 15 years with a peak age of 7 years and a male:female ratio of 2:1. They are composed of small primitive neuroepithelial cells thought to arise from the external granular layer or subependymal matrix cells at superior and inferior velum. The cerebellar vermis and fourth ventricles are involved in 75% and the cerebellar hemispheres in 25%. These are WHO grade IV invasive tumors and 10 to 35% present with sub-arachnoid dissemination. The tumor appears as a well-circumscribed solid mass in the cerebellar vermis, hemisphere, or fourth ventricles. CT shows a high-density mass due to high cellularity. The lesions are hypo- to isointense on T1, iso- to hyperintense on T2, and enhance on gadolinium T1-weighted images. There is restricted diffusion on diffusion-weighted imaging (DWI) (► Fig. 13.9).



**Fig. 13.9** Medulloblastoma. **(a)** Axial CT image of the posterior fossa shows a mass within the fourth ventricle that is hyperdense relative to white matter and shows no macroscopic calcification. **(b)** Sagittal T1 plus contrast image shows the mass nearly filling the fourth ventricle. Two metastatic deposits are seen along the superior margin of the vermis. **(c)** Axial diffusion-weighted image shows a hyperintense signal for the lesion, and **(d)** an axial apparent diffusion coefficient map shows low values (diffusion of  $675 \times 10^{-6} \text{ mm}^2/\text{s}$ ), confirming the highly cellular nature of the tumor. (Reproduced from Choudhri A, Pediatric Neuroradiology: Clinical Practice Essentials, 1st edition, ©2016, Thieme Publishers, New York.)



Pathological examination of medulloblastomas may reveal both perivascular pseudorosettes and Homer Wright rosettes.

### 13.6.2 Molecular Biology

The most consistent chromosomal aberrations are loss of 17q (35–40%), 8p, 10q, 11q, 16q, and 17p. Amplification of MCN or MYCC is observed in 5% and  $\beta$ -catenin nuclear accumulation is seen in 25%; these are poor prognostic factors. Medulloblastomas are currently divided into four molecular subtypes:

1. Wnt-activated group (group 1): Wnt pathway activation leads to accumulation of  $\beta$ -catenin immunoreactivity in tumor cell nuclei and expression of downstream *Wnt* genes. Approximately 85% of Wnt-activated medulloblastoma has monosomy 6 and/or *CTNNB1* mutation and virtually all classic histology. This group has overall good prognosis with 5-year survival greater than 90%.
2. Sonic hedgehog (SHH)-activated group (group 2): *SHH* genes function in association with midline CNS structures and is produced by Purkinje's cells of the developing cerebellum. SHH-activated tumors also have germline or somatic *TP53* mutations. This subgroup shows desmoplastic/nodular histology.
3. Group 3: Classic and many of the large-cell/anaplastic medulloblastoma are included in this subgroup. This group is characterized by MYC amplification and has a 5-year survival rate of approximately 30%.
4. Group 4: This is the most frequently occurring subgroup representing more than 30% of cases. Frequent genetic

abnormalities include 17q loss (66%), near universal loss of X, as well as mutations in *KDM6A*, *SNCAIP*, *MYCN*, *OTX2*, *CDK6*, *TP53*, and *MLL2* genes.

### 13.6.3 Treatment

Maximal surgical resection, followed by adjuvant chemotherapy and radiation therapy with treatment of the entire neuraxis with a boost to the tumor bed is standard of care. There is no standard chemotherapy regimen but a combination of platinating and alkylating drugs is usually used. For patients younger than 3 years, radiation therapy is reserved for recurrence or a reduced radiation dose is used. Risk stratification is based on residual tumor volume and presence of CSF dissemination.<sup>32</sup>

### 13.6.4 Atypical Teratoid Rhabdoid Tumor

Highly malignant WHO grade IV tumor accounting for 1 to 2% of pediatric brain tumors with a slight male predilection. Over 90% occur in children younger than 5 years with an average age of 2 years. Tumors are typically supratentorial with frequent infratentorial localization in patients younger than 2 years. They are composed of rhabdoid cells with primitive neuroectodermal, epithelial, mesenchymal, neural, and glial cells. Inactivation of *INI1/hSNF5* is a characteristic feature. Atypical teratoid rhabdoid tumors (ATRTs) appear similar to medulloblastomas on imaging. They are hypo- to hyperintense on T1- and iso- to hyperintense on T2-weighted MRI with heterogeneous contrast enhancement. GTR improves median survival to 21.3 months. Combined chemo- and radiation therapy are usually administered postoperatively.<sup>33,34,35</sup>

## 13.7 Tumors of Cranial and Paraspinal Nerves

This category includes neuromas, schwannomas, neurofibromas, and malignant peripheral nerve sheath tumors. **Neuromas** are not true neoplasms but instead represent an inflammatory nidus with Schwann cells, fibroblasts in a bed of tangled axons. They are usually rubbery and painful. **Schwannomas** are benign neoplasms with eccentric growth encapsulated within an epineurium capsule. Intracranially they are most commonly associated with the vestibular nerve. They also occur at root entry zones of spinal sensory nerves. GTR is often curative. Intracranial cases may require adjunctive therapy with stereotactic radiosurgery. Unlike schwannomas, **neurofibromas** are unencapsulated and fusiform benign neoplasms. Complete removal requires nerve transection. There is no reliable diagnostic imaging modality to determine a priori whether a tumor is a schwannoma or neurofibroma. **Malignant peripheral nerve sheath tumors** are usually painful (unlike schwannomas and neurofibromas). They frequently result in motor deficits and 50% are seen in the setting of neurofibromatosis type 1 (NF1). Resection and radiation are required for adequate treatment.

### 13.7.1 Germ Cell Tumors

Germ cell tumors (GCTs) are a group of neoplasms derived from totipotent primordial germ cells fated to become genital organs. GCTs occur most frequently in adolescent males and are more common in East Asia. CNS involvement is thought to occur as a result of mismigration and accounts for 0.5% of primary and 3.9% of pediatric brain tumors. CNS GCTs typically involve the pineal gland (54%), neurohypophysis (20.4%), and basal ganglia. CNS GCTs can be divided into three main

categories: germinomas, nongerminomatous germ cell tumors (NGGCT), and mixed germ cell tumors. Germinomas account for 50 to 60%, mixed GCTs for 30% with the remainder as NGGCT.

### 13.7.2 Germinomas

These are highly cellular tumors with characteristic “two-cell pattern” and cobblestone arrangement of large tumor cells with interstitial inflammatory cells. They usually show well-demarcated, contrast-enhancing masses on MRI scans. CT is beneficial in detecting calcification, which may suggest a teratoma component. Germinomas are exquisitely radiation sensitive and preoperative imaging should be limited to prevent shrinkage of the tumor. Bifocal or synchronous tumors at neurohypophysis and pineal gland are pathognomonic. Syncytiotrophoblastic giant cells (STGC) are often present. They occasionally show weak positivity to human chorionic gonadotropin (hCG).

### 13.7.3 Nongerminomatous Germ Cell Tumors

#### Embryonal Carcinoma

Embryonal carcinomas are known as the pure tumor and are typically seen as a component of mixed GCTs. They consist of pluripotent cells with inability to become germ cells. These are highly malignant tumors with positivity for cytokeratin, CD30, LIN28A, Oct4, and placental alkaline phosphatase (PLAP).

#### Yolk Sac Tumor

Yolk sac tumors, also known as endodermal sinus tumors, are composed of epithelial tumors arranged in sheets, cords, papillary and ribbon-like vitelline patterns.

Schiller–Duval bodies have an appearance akin to glomeruli and are often present. The histology recapitulates the yolk sac, allantois, and extraembryonic mesenchyme. Tumor cells are typically positive for alpha fetoprotein (AFP), LIN28A, SALL4 and cytokeratin.

## Choriocarcinoma

It is composed of two distinct cell types reminiscent of syncytiotrophoblasts and cytotrophoblasts. Intratumoral hemorrhage is frequent and may be symptomatic. Tumor cells are positive to  $\beta$ -hCG, cytokeratin, and EMA.

## Teratoma

Mature teratoma consists of well-differentiated somatic tissue derived from two or three germ layers (ectoderm, mesoderm, and endoderm). Tissues like skin, respiratory epithelium, cartilage, bone, adipose tissue, and CNS are mixed in a disorderly fashion. Immature teratoma contains immature, embryonal, or fetal tissue. Malignant degeneration within teratomas can occur leading to squamous cell carcinomas, adenocarcinomas, and rhabdomyosarcomas.

## Mixed Germ Cell Tumor

Many GCTs have more than one histological component in their tissue, most frequently germinoma, followed by teratoma, yolk sac tumors, embryonal carcinoma, and choriocarcinoma.

### 13.7.4 Treatment

Hydrocephalus associated with aqueduct stenosis or occlusion caused by pineal region tumor should be addressed first. Acutely presenting hydrocephalus is treated by external ventricular drainage; otherwise, endoscopic third ventriculostomy and biopsy of the

tumor concurrently (if possible) are employed. The basic principle of treatment is decided based on the pathology, so most suspected cases of GCTs require surgery or biopsy. Germinomas are sensitive to radiation therapy. Mature teratoma can be cured with GTR while adjuvant therapy is not effective. Other NGGCT and mixed GCTs are treated with maximal surgical resection, followed by radiation and chemotherapy. Radiation therapy is given to whole ventricles and spine in addition to the local site. Any residual tumor after chemotherapy and radiotherapy is removed with “second-look” surgery.

### 13.7.5 Prognosis

Germinoma has a 5-year overall survival and progression-free survival of 99 and 95%, respectively, while the rates for mixed GCTs are 75 and 87%, respectively. The rates for NGGCTs are 65 and 71%, respectively.<sup>34,35,36</sup>

## 13.8 Sellar Tumors

Several neoplastic entities are seen in the region of the sella. The two main lesions seen in this location are pituitary tumors and craniopharyngiomas.

### 13.8.1 Pituitary Tumors

Pituitary tumors are usually slow-growing, benign tumors of the pituitary gland. They are classified as typical or atypical adenomas or carcinomas or as functional and nonfunctional tumors. They become clinically apparent either by mass effect on the surrounding structures (optic chiasm, hypothalamus, cavernous sinuses) or through hypothalamus-pituitary-adrenal (HPA) hormonal dysregulation. Mass effect is usually managed surgically and hormonal dysregulation is often managed medically. Additional tumors secrete adrenocorticotrophic hormone (ACTH),

growth hormone (GH), thyroid-stimulating hormone (TSH), and gonadotropins. Approximately 30% are nonfunctional.

**Pituitaryomas** are very rare, low-grade primary tumors of the posterior pituitary gland (neurohypophysis), with only a handful of case reports existing in the literature.



For prolactinomas, medical management is the first-line and often only therapy necessary. Among functional tumors, prolactinomas are most common.

## 13.8.2 Craniopharyngioma

Craniopharyngiomas are solid or mixed solidcystic tumors of the sellar/suprasellar region, often referred to as Rathke's pouch tumors or hypophyseal duct tumors. They are rare tumors, with an incidence of 0.5 to 2 cases per million people per year and account for approximately 1.2 to 4% of childhood intracranial tumors. Craniopharyngiomas exhibit a bimodal age distribution, presenting most commonly in children age 5 to 14 years, and in adults age 50 to 75 years without gender predilection.

The adamantinomatous subtype is more common in children, while papillary craniopharyngiomas are more common in adults. Clinical presentation in children typically includes signs of increased ICP, visual impairment, and endocrine deficits. Hormonal deficits are more pronounced in adult-onset disease and include deficits in GH secretion (75%), gonadotropins (40%), ACTH (35%), and TSH (25%). Children often present with reduced growth rate (as early as the first year of life), while significant weight gain due to hypothalamic dysfunction usually occurs later. Craniopharyngiomas are comprised of embryonic tissue and may originate from either of the ectodermal remnants of Rathke's pouch, or from embryonal epithelium of the anterior pituitary gland and

infundibulum. Most tumors contain solid components with fluid-filled cysts containing turbid, cholesterol-containing fluid.

**Adamantinomatous craniopharyngiomas** likely originate from remnants of the embryonic craniopharyngeal duct, which connects Rathke's pouch to the stomodeum during development. These tumors are characterized by dense islands of squamous epithelium arranged in cords, nodules, and irregular trabeculae, bordered by palisaded columnar epithelium. These regions are interspersed with loose aggregates of squamous cells known as stellate reticulum. "Wet keratin" nodules are present throughout (pale nuclei embedded within eosinophilic keratin aggregates). Granulomatous inflammation with giant cells may be present. Piloid gliosis with Rosenthal fibers can also be seen (of note, these are also present in pilocytic astrocytoma). Malignant transformation is rare. More than 70% of adamantinomatous craniopharyngiomas have a mutation of the  $\beta$ -catenin gene, most of which affect the degradation targeting box of the  $\beta$ -catenin, leading to accumulation of nuclear  $\beta$ -catenin protein.

**Papillary craniopharyngiomas** are thought to result from metaplasia of the adenohypophyseal cells in the pars tuberalis, a hypothesis that is supported by the presence of metaplastic nests within the gland. These tumors are characterized by a monomorphous mass of squamous epithelium without surface maturation, "picket fence-like" palisades, and wet keratin. In contrast to the adamantinomatous subtype, papillary tumors are not usually calcified, and rarely contain ciliated epithelium and goblet cells. Papillary craniopharyngiomas are associated with the V600E mutation in the BRAF oncogene.

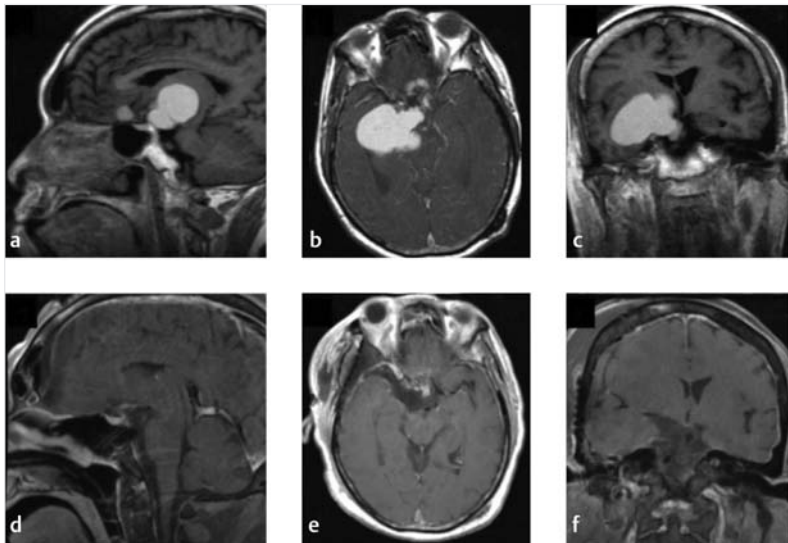
Craniopharyngiomas may arise at any point along the craniopharyngeal canal and commonly (95%) have a suprasellar component. Calcifications are most reliably seen on CT imaging; therefore, preoperative CT and MRI play an important role in diagnosis. Signal intensity on T2-weighted MRI is variable



and is dependent on the protein concentration within the cystic fluid. A combination of solid, cystic, and calcified components is usually seen on MRI (► Fig. 13.10).

If there is no involvement of hypothalamic or optic structures, preferred treatment is an attempt at complete surgical resection. For tumors involving these structures, controversy exists whether complete resection should be attempted versus incomplete resection followed by radiotherapy. Tumor control rates in published series are reported from 67 to 94%. Endocrine abnormalities are common following treatment. Panhypopituitarism occurs in the majority of cases, and

hypothalamic dysfunction can cause obesity, disorders of temperature regulation, diabetes insipidus, or sleep disorders. Visual deterioration, seizures, and cerebrovascular events are also potential treatment sequelae. Following radiation therapy, patients may develop vascular malformations including cavernomas and aneurysms. Radiation therapy may also cause secondary malignancies, most commonly meningiomas or malignant glial tumors. Posttreatment follow-up typically includes annual MRI, monitoring of endocrine function and hormone replacement therapy, and annual visual field testing.<sup>38,39</sup>



**Fig. 13.10 (a–c)** Preoperative magnetic resonance imaging of a large parasellar cystic craniopharyngioma extending into the sylvian fissure that was removed via a right modified orbitozygomatic approach. A near-total resection was performed with residual calcified tumor that was adherent to the right optic nerve and right posterior communicating artery perforators. **(d–f)** Postoperative MRI shows excellent decompression of the optic chiasm, temporal lobe, and brainstem. (Reproduced from Sekhar L, Fessler R, Atlas of Neurosurgical Techniques: Brain, Volume 2, 2nd edition, ©2015, Thieme Publishers, New York.)

## 13.9 Cysts and Tumor-Like Lesions

Cysts lined by cuboidal to columnar mucin-producing epithelium occur in several sites throughout the CNS. These are referred to Rathke's cleft cysts in the sella, colloid cysts in the third ventricle, and neurenteric (neuroepithelial, neuroglial, enterogenous, or bronchogenic) cysts when they occur in the anterior spinal region, or intracranially. These cysts are thought to be developmental, not neoplastic. Radiographic appearances are similar among these benign developmental cysts.



Symptomatic lesions (which may be associated with increasing size of greater than 1 cm as is the case for colloid cysts) requiring surgical drainage and excision are rare and the recurrence rate of these lesions is low.

Lesions include **Rathke's cleft cysts, colloid cysts, enterogenous cysts, neuroglial cysts, epidermoid, and dermoid cysts.**<sup>40</sup>

### Pearls

- In general, the goal of neurosurgical intervention is to maximize the extent of resection while minimizing complications.
- In the presurgical evaluation, attempt to make the best prediction about lesions that may be surgically curable and plan accordingly (for example Simpson grade I resection of a WHO grade I meningioma).
- Have a multidisciplinary approach to the treatment of patients with neuro-oncological diseases with early involvement of neuro-oncologists, medical oncologists, radiation oncologists, and other health professionals such as speech, physical, and occupational therapists as deemed appropriate.

## 13.10 Top Hits

### 13.10.1 Questions

1. All of the following are characteristic histopathologic features of ependymoma EXCEPT:
  - a) Pseudorosette.
  - b) Ependymal rosette.
  - c) Speckled nuclear chromatin.
  - d) Microcysts.
2. Which description is appropriate about ependymoma?
  - a) Standard treatment is biopsy, followed by radiation and chemotherapy.
  - b) Age less than 3 years is a poor prognosis factor.
  - c) The dominant occurrence location for pediatric cases is supratentorial and spinal cord.
  - d) Ependymoma has a high number of mutations.
3. Which description is appropriate about management of pineal region tumors?
  - a) Pineocytoma is treated by maximal surgical resection followed by radiation and chemotherapy.
  - b) Pineoblastoma is treated with biopsy followed by radiation and chemotherapy.
  - c) Age less than 5 years is a poor prognostic factor.
  - d) Papillary tumor of pineal region has a good progression-free survival of more than 50% in 5 years.
4. Which of the following tumors has a tendency for hemorrhagic conversion?
  - a) Choriocarcinoma.
  - b) Pineoblastoma.
  - c) Astrocytoma.
  - d) Pineocytoma.

5. All of the following statements regarding medulloblastoma are correct EXCEPT:
  - a) Gorlin's syndrome accompanies medulloblastoma.
  - b) SHH group has the worst prognosis in the fourth molecular classification.
  - c) Wnt group is characterized by *CTNNB1* mutation.
  - d) About 75% of medulloblastomas occur in children younger than 15 years.
6. Which of the following description is incorrect?
  - a) INI1 positivity is characteristic for atypical teratoid rhabdoid tumor.
  - b) CNS-PNET is not listed in WHO 2016 classification of central nervous system tumors.
  - c) Atypical teratoid rhabdoid tumor is characterized by PNET cell on histopathology.
  - d) Extent of surgical resection does not have a significant influence on prognosis for atypical teratoid rhabdoid tumor.
7. Which description is incorrect regarding the tumor markers for germ cell tumors?
  - a) PLAP is elevated in teratoma.
  - b) AFP is elevated in immature teratoma.
  - c) hCG is elevated in choriocarcinoma.
  - d) hCG is elevated in germinoma with syncytiotrophoblastic giant cells.
8. Which description is correct regarding treatment of germ cell tumors?
  - a) Maximal surgical resection is prognostic for germinoma.
  - b) Mature teratoma is sensitive to radiation therapy.
  - c) Second-look surgery is the next management step for residual tumor after adjuvant therapy for nongerminomatous germ cell tumor.
  - d) Radiation therapy is given to the tumor bed for germinoma.

### 13.10.2 Answers

1. **d.** Microcysts in the setting of nuclear clusters in a fibrillary background is a feature of subependymoma, not ependymoma. All other features are prominent in ependymomas.
2. **b.** Age less than 3 years is a poor prognostic factor for ependymomas. Treatment is attempted gross total resection, not biopsy. Most cases are infratentorial.
3. **c.** Age less than 5 years is a poor prognostic factor for pineal region tumors. Pineocytomas are WHO grade I lesions curable with GTR with residual disease managed with radiation without chemotherapy. Pineoblastomas are highly malignant WHO grade IV tumors managed with maximum safe resection, multiagent chemotherapy, and whole-brain radiation. Papillary tumors of the pineal region are WHO grade II or III lesions. Treatment is maximum safe resection followed by radiation with chemotherapy reserved for recurrence. Risk of recurrence is significant.
4. **a.** Hemorrhagic brain metastases can be memorized using the following mnemonic:
  - M—melanoma
  - R—renal cell carcinoma
  - C—choriocarcinoma
  - T—thyroid carcinoma
  - B—bronchogenic carcinoma
  - B—breast cancer

5. **b.** SHH group medulloblastomas carry an intermediate prognosis in between Wnt (best prognosis) and the groups 3 and 4 which carry dismal prognoses.
6. **d.** GTR followed by chemoradiation improves the prognosis for patients with ATRT to almost 2 years, a significant improvement when compared with subtotal resection alone.
7. **a.** Plasma alkaline phosphatase (PLAP) is a marker of embryonal carcinoma. The diagnosis of teratoma is based primarily on histopathology and there are no widely accepted diagnostic molecular markers.
8. **c.** The treatment paradigm for NG-GCTs is maximal surgical resection followed by chemoradiation. Any residual disease following maximal therapy is revisited with "second-look" surgery.

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# 14 Pediatric Neurosurgery

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## 14.1 Examination

### 14.1.1 Newborn and Infant

The newborn neurologic examination contains similar components to that of children and adults with additional maneuvers incorporated to assess nervous system development and maturation. The basic examination consists of the traditional areas of focus including assessment of consciousness, cranial nerve function, motor function, and sensory capacity. Primitive reflexes and evaluation of head circumference are additional components of the neurologic examination of infants.

Unique to newborns and neonates is the presence of primitive reflexes, a helpful tool used to assess the stage of development of the nervous system in infants and young children. These reflexes typically appear during gestation and persist for a finite amount of time postpartum. Persistence beyond expected age, absence, delay, or asymmetry of any of the primary primitive reflexes may indicate nervous system pathologies, developmental delay, or other anomalies (► Table 14.1).

The neurologic examination of the newborn and infant may be impacted by prematurity, so it is important to know the gestational or corrected age of the child at the time of examination. The gestational age may be calculated during prenatal appointments utilizing a standardized curve of intrauterine growth and development.<sup>1,2,3</sup>

### 14.1.2 Head Size and Shape Evaluation of Head Size

The most common cause for neurosurgical intervention in children from infancy

to young adulthood is hydrocephalus, a condition of increased cerebrospinal fluid (CSF) volume that may be detrimental to development.<sup>4</sup> Early intervention is key to prevention of further impairment of brain development, such that a critically important component of the infant examination requires assessment of the head circumference. This should include the evaluation of the shape and size of the head, and the skin covering the skull.



Fronto-occipital head circumference is the primary method used to assess head size and the volume of fluid inside the skull.

Excess CSF in an infant will produce enlargement of the head circumference to compensate for the elevation in intracranial pressure (ICP). The child may display fullness of the anterior fontanelle, splaying of the calvarial sutures, or bulging scalp veins from venous engorgement. These may be seen in conjunction or in the absence of other possible signs including sunsetting of the eyes, lethargy, vomiting, irritability, and other signs of elevated ICP.<sup>5</sup> Enlargement of an infant's head circumference could also be due to mass lesions such as tumors, arachnoid or other developmental cysts, or hemorrhage. It is important to consider trends in the head circumference and relativity to the height and weight percentiles to determine whether imaging is necessary to evaluate for pathologic causes of an enlarged head. Increases in head circumference of several percentiles, or elevation beyond the 99th percentile may prompt concern.

**Table 14.1** Primitive reflexes of the infant physical examination

| Reflex                          | Physician maneuver                                                                                                                                                                      | Observed response                                                                                                                                                                                                                                   | Age range                                       |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|
| Palmar grasp                    | Press a single finger into the center of the infant's palm                                                                                                                              | Infant's fingers flex to grasp the physician's finger                                                                                                                                                                                               | Birth to 3/4 months                             |
| Plantar grasp                   | Touch the sole of the infant's foot at the base of the toes                                                                                                                             | Toes plantar flex toward physician's finger                                                                                                                                                                                                         | Birth to 6/8 months                             |
| Plantar (Babinski) <sup>6</sup> | Firmly stroke the sole of the infant's foot in an arc from the lateral heel to the medial base of the great toe<br>Note: Lack of firmness in this maneuver may elicit the plantar grasp | Toes fan outward, the great toe extends in the upward direction, and the ankle, knee, and hip flex in a brisk and synchronized movement<br>Note: Flexor response (as expected in adults) is not an indication of pathology in neonates <sup>7</sup> | Birth to approximately 1 year <sup>8,9,10</sup> |
| Rooting                         | Use a finger to stroke the skin around the infant's mouth                                                                                                                               | The infant's mouth opens and he/she rotates the head in the direction of the sensation                                                                                                                                                              | Birth to 3/4 months                             |
| Startle (Moro)                  | Hold the infant supine with adequate neck support and abruptly lower the body ~2 ft                                                                                                     | Arms: abduct and extend<br>Legs: flex<br>Hands: open<br>The infant may also cry                                                                                                                                                                     | Birth to 4 months                               |
| Asymmetric tonic neck reflex    | Hold the infant supine and turn the neck to face one side placing the chin over the shoulder                                                                                            | The infant's ipsilateral (to the direction of gaze) limbs extend while the contralateral limbs flex                                                                                                                                                 | Birth to 2 months                               |
| Parachute                       | Hold the infant prone, being careful to adequately support the neck. Lower the infant's head toward a surface                                                                           | Arms and legs extend toward the imminent surface                                                                                                                                                                                                    | Appears by 8 months and persists                |

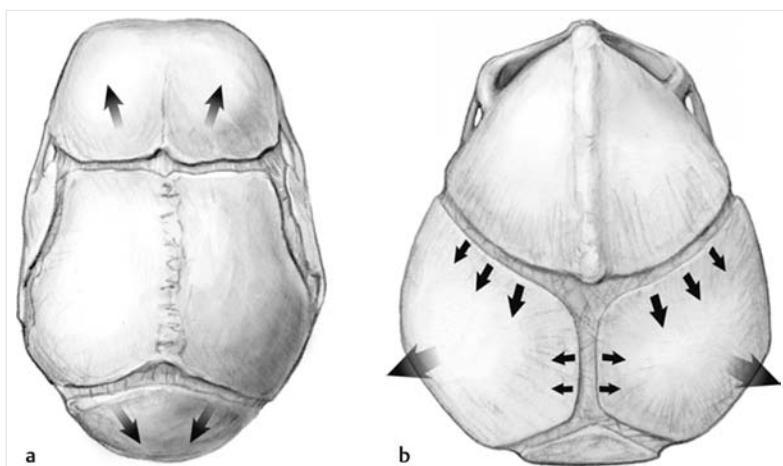
Abbreviation: CNS, central nervous system.

Source: Adapted from Bates' Guide to Physical Examination and History-Taking.<sup>11</sup>

## Evaluation of Head Shape

Craniosynostosis is the premature fusion of a cranial suture, with an incidence rate of approximately 4 in 10,000 live births.<sup>12</sup> While a number of genetic abnormalities may predispose to various abnormalities in cranial shape, craniosynostosis is most commonly a sporadic occurrence affecting a single suture. The most common is sagittal craniosynostosis.<sup>3,13,14</sup> The presence of craniosynostosis impacts skull growth perpendicular to the fused suture, and creates an abnormal shape to the head, with classic morphologies that are often seen with various fused sutures (► Fig. 14.1). Examination of the head shape from all angles may help to

differentiate craniosynostosis (a relatively rare condition) from positional plagiocephaly which develops secondary to positional molding of the skull and has an incidence of as high as 46.6%.<sup>15</sup> In addition, premature infants may demonstrate disproportional fronto-occipital growth, leading to a slightly scaphocephalic shape and which may also have a dramatic effect on overall head circumference.<sup>3</sup> Examination of a newborn and young infant may include palpation of sutures for mobility in any child with an abnormality of head shape. Infants with craniosynostosis benefit from early identification as intervention includes options for minimally invasive treatment or open repair. The exact incidence of elevated ICP



**Fig. 14.1 (a)** Sagittal craniosynostosis. The deformity includes a disproportionately long and narrow skull. Compensatory growth can occur at the coronal and metopic sutures, causing frontal bossing or at the lambdoid sutures, resulting in an occipital knob. **(b)** Metopic craniosynostosis. Characteristic skull morphology seen in patients with metopic craniosynostosis leads to trigonocephaly. Early metopic fusion causes restricted growth of the forehead with varying degrees of hypotelorism, recession of the lateral orbital rims, and bitemporal narrowing. (Reproduced from Goodrich J, *Pediatric Neurosurgery*, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>17</sup>



varies widely in the literature (between 4.5 and 24% and as high as 44% in one study) and exact attributable sequelae of nontreatment is controversial. Nevertheless, correction is typically recommended to improve head shape as well as prevent future sequelae of craniocephalic disproportion which may lead to elevated ICP, among other multifactorial concerns.<sup>16</sup>

### 14.1.3 Evaluation of Alertness

The evaluation of alertness in an infant is largely dependent on time of day, time since feeding, external stimuli at the time of examination, gestational age, and behavioral development (► Table 14.2).<sup>18,19,20,21</sup>

### 14.1.4 Cranial Nerve Evaluation

During the cranial nerve evaluation of infants, the physician must be more creative than during an adult examination due to the lack of verbal communication

from the patient. ► Table 14.3 summarizes the most common techniques used to assess the cranial nerves in infants and young children as compared to those used in adults.<sup>3</sup>

### 14.1.5 Motor Evaluation

The major components of the infant's neuromuscular examination serve to assess tone, strength, and reflex responses. Throughout gestation and in the postnatal months, these measures of neuromuscular function fluctuate and are an indication of the infant's development and maturity.<sup>3</sup> In addition to the primitive reflexes previously discussed (► Table 14.1), deep tendon reflexes are also an important component of the infant neurologic examination and are assessed in examination.

The observance of clonus upon eliciting the Achilles tendon reflex is a normal response in infants up to 3 months of age but should be considered abnormal after this period.<sup>3</sup>

**Table 14.2** Behavioral states of infancy

| Stage | Eyes     | Respiration | Movement | Vocalizations | Behavior                                       |
|-------|----------|-------------|----------|---------------|------------------------------------------------|
| 1     | Closed   | Regular     | Absent   | Absent        | Sleeping, often rapid eye movement (REM) stage |
| 2     | Closed   | Irregular   | Variable | Absent        | Drowsy                                         |
| 3     | Open     | Regular     | Absent   | Absent        | Awake, alert, calm                             |
| 4     | Open     | Irregular   | Present  | Absent        | Alert and irritable                            |
| 5     | Variable | Irregular   | Present  | Present       | Crying uncontrollably                          |

Source: Adapted from Behavioural states of the full-term newborn. The emergence of a concept. Psychobiology of the Human Newborn<sup>22</sup> and Continuity of Neonatal Function from Prenatal to Postnatal Life.<sup>19</sup>

**Table 14.3** Cranial nerve evaluation in infants and adults

| Cranial nerve             | Infant                                                                                                   | Adult                                                                                                                                          |
|---------------------------|----------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| I—Olfactory <sup>a</sup>  | Cannot be reliably tested                                                                                | Response to odorous cotton pad                                                                                                                 |
| II—Optic <sup>a</sup>     | Can observe blinking to light and indirectly through tracking                                            | Snellen’s chart of visual acuity                                                                                                               |
| III—Oculomotor            | Tracking, pupillary response, resting disconjugate gaze normal in young children                         | PR: Flashlight test<br>EOM: “H” test                                                                                                           |
| IV—Trochlear              | Same as CN III                                                                                           | EOM: “H” test                                                                                                                                  |
| V—Trigeminal              | V <sub>1</sub> : Glabellar tap<br>V <sub>2</sub> and V <sub>3</sub> : Pinprick<br>Motor: Sucking ability | V <sub>1</sub> : Corneal reflex<br>V <sub>2</sub> and V <sub>3</sub> : Symmetric light touch to face<br>Motor: contract muscles of mastication |
| VI—Abducens               | Same as CN III                                                                                           | EOM: “H” test                                                                                                                                  |
| VII—Facial                | Glabellar tap (efferent), observance of spontaneous facial expressions, or pinprick                      | Voluntary performance of facial expressions                                                                                                    |
| VIII—Vestibulocochlear    | Startle or blink in response to noise                                                                    | Weber’s test, Rinne’s test                                                                                                                     |
| IX—Glossopharyngeal       | Swallowing ability, gag reflex                                                                           | Gag reflex                                                                                                                                     |
| X—Vagus                   | Swallowing ability, gag reflex                                                                           | Gag reflex and observance of a central uvula                                                                                                   |
| XI—Accessory <sup>a</sup> | Best assessed by detecting decreased shoulder motion or shoulder droop                                   | Shrug shoulders and rotate the head against opposition                                                                                         |
| XII—Hypoglossal           | Atrophy, tongue deviation                                                                                | Protrude tongue and move laterally to both sides                                                                                               |

Abbreviations: CN, cranial nerve; EOM, extraocular movements; PR, pupillary response.

<sup>a</sup> Indicates cranial nerve is rarely evaluated in the infant physical examination.

Source: Data from Neurology of the Newborn.<sup>3</sup>

### 14.1.6 Sensory Evaluation

Beyond the scope of sensory stimulation used to test reflexes, the sensory evaluation is rarely performed in infants without

considerable suspicion of sensory deficit.<sup>23</sup> Pinprick tests of sensation will elicit withdrawal and crying in an infant greater than 28 weeks of gestation, if necessary to test for subtler sensory deficits.<sup>3,24</sup>

### 14.1.7 Examination of Toddlers and Older Children

While the neonatal examination requires a number of modifications due to lack of communication abilities, and physical development, the examination of older pediatric patients resembles that of an adult. In the neurologic examination in particular, it is important to follow head circumference and shape closely until preadolescence. Verbal children older than 2 years are typically capable of following simple commands and providing responses to examination questions (e.g., “follow my finger with your eyes,” “shrug your shoulders and don’t let me push them down”).

## 14.2 Developmental Anomalies

### 14.2.1 Arachnoid Cysts

Arachnoid cysts (ACs) are congenital abnormalities that arise from a separation of the layers in the arachnoid mater, typically filled with a fluid that is similar or identical in composition to CSF. The most common locations for ACs to develop are near CSF cisterns in the middle fossa, cerebellopontine angle, suprasellar region, posterior fossa, and in the spinal canal. Spinal ACs are rare in the pediatric population.<sup>25</sup>

### Diagnosis

Cysts may be an incidental finding on brain imaging and focal deficits may appear disproportionately mild relative to the size of the fluid collection. Symptomatic ACs almost always present in early childhood with variant symptoms relative to location of the cyst or elevation of ICP.<sup>26,27,28</sup>

### Treatment

Neurosurgical treatment, when indicated for symptomatic ACs, involves two primary techniques: fenestration and shunting. Fenestration is a treatment method by which an opening in the cyst membrane is created either by way of an open craniotomy or endoscopically through a burr hole.



Currently, endoscopic fenestration is the preferred method of treatment in pediatric patients due to the decreased invasiveness compared to craniotomy and the avoidance of shunt dependence and complications.<sup>29</sup>

In a cohort of pediatric patients, fenestration has showed further improved revision-free survival if accompanied by a simultaneous ventriculocystocisternotomy, a procedure that entails creating further fenestrations in the basal surface of the collapsed cyst.<sup>30</sup> Shunting has largely become an outdated practice due to the complications of long-term shunting and improvements in endoscopic technique.<sup>31</sup>

### 14.2.2 Chiari Malformations

#### Naming and Subtypes

Though seemingly nuanced, “Chiari malformation,” in reference to Hans Chiari, generally refers to the type I malformation, while the term “Arnold–Chiari malformation,” named for Julius Arnold, is in reference to the type II malformation. Though there are four total pathologies under the umbrella of “Chiari malformations,” types I and II are predominate as occurring most frequently. Type I Chiari malformation may be diagnosed during childhood or adulthood. However, given its relationship to myelomeningocele, type II Arnold–Chiari malformation is classically diagnosed in infancy.

General

The hallmark of Chiari I malformation is the impairment of CSF flow through the foramen magnum with an otherwise heterogeneous morphology of the posterior fossa obstruction. Distinction of the Chiari II (previously known as the Arnold–Chiari malformation) from the Chiari type I include the caudal displacement of the medulla and vermis (rather than the cerebellar tonsils which are displaced in the Chiari I malformation) as well as the presence of a myelomeningocele.<sup>32</sup> In both conditions, the downward displacement of the cerebellum poses some obstruction to the flow of CSF through the foramen magnum. A Chiari malformation may be primary when it is not associated with other intracranial abnormalities, or secondary as a result of

hydrocephalus or a mass lesion. ▶ Table 14.4 compares the subtypes of Chiari malformation and their associated symptoms.

Diagnosis

The best diagnostic tool for a Chiari malformation is magnetic resonance imaging (MRI) showing tonsillar herniation and caudal displacement of the cervicomedullary junction (▶ Fig. 14.2).

Treatment

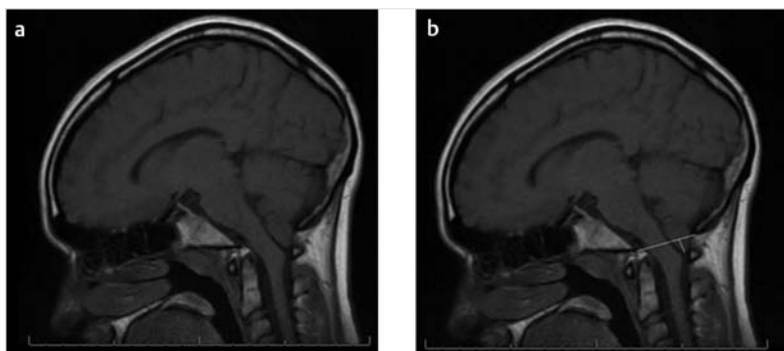
Chiari I Malformations

Treatment for Chiari I malformations in children is a decompressive procedure of the posterior fossa to allow release of

**Table 14.4** Classification of Chiari malformation and associated findings

| Subtype | Radiographic findings                                                                                                                                                                                                                                                                                                                | Associations                                                                                | Age of diagnosis                                  |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------|
| I       | Classically refers to cerebellar tonsil herniation > 5 mm below the foramen magnum in adults, but < 5 mm herniation may also be considered                                                                                                                                                                                           | Syringomyelia common; Hydrocephalus uncommon                                                | Adolescents and young adults (2nd or 3rd decades) |
| II      | Herniation of the cerebellar tonsils through and caudal displacement of the cervicomedullary junction with possible involvement of the 4th ventricle. Can also see, among many other features, shortening of the clivus, dysgenesis of corpus callosum, kinking of brainstem, beaking of tectum, and a low-lying tentorium cerebelli | Hydrocephalus in majority of cases; Myelomeningocele universally seen; Syringomyelia common | Infancy                                           |
| III     | Cerebellar herniation into the spinal canal and foramen magnum encephalocele                                                                                                                                                                                                                                                         | Encephalocele at foramen magnum                                                             | Usually incompatible with life                    |
| IV      | Cerebellar hypoplasia or total aplasia                                                                                                                                                                                                                                                                                               |                                                                                             | Incompatible with life                            |

Source: Adapted from Management of the Chiari Malformations in Childhood.<sup>33</sup>



**Fig. 14.2** (a) MRI of a patient with a Chiari I malformation showing the cerebellar herniation through the foramen magnum. (b) MRI image with superimposed measurements delineating the boundary of the foramen magnum and an 8-mm herniation through the foramen magnum from basion to opisthion. (Reproduced from Goodrich J, *Pediatric Neurosurgery*, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>17</sup>

pressure on the brainstem and improved CSF flow at the foramen magnum. A suboccipital craniectomy and C1 laminectomy is the general standard of care, additional laminectomy levels may be necessary depending on the extent of tonsillar descent.<sup>34</sup> Current controversy exists as to whether a bone-only decompression or decompression with duraplasty yields superior outcomes.

Posterior fossa decompression classically involves suboccipital craniectomy, cervical laminectomy to the level of the tonsillar herniation, and a Y-shaped dural opening from the tonsillar herniation to the foramen magnum.<sup>35,36</sup> Recently, it has been suggested that dural openings and suboccipital craniectomies may not be obligatory in pediatric patients, who often have more pliable meninges than adult patients and show no clinical benefit to more extensive bony decompressions.<sup>37,38</sup> Chiari I malformations in children are treated with a similar approach, but may also require the placement of a shunt or drain for the management of symptomatic syringomyelia if the syrinx does not

resolve and/or remains symptomatic after decompression.<sup>39,40</sup>

## Chiari II Malformation (Arnold–Chiari)

Chiari II malformations are present in patients with myelomeningocele. Conservative observational treatment is preferred in almost all cases of Chiari II malformation. Later in life, symptomatic Chiari II malformations may be indicative of shunt malfunction or tethering of the spinal cord, where treatment of the Chiari II malformation is accomplished by a shunt revision or detethering.<sup>41</sup> On the rare occasion that surgical decompression is indicated, surgical technique is identical to that of a Chiari I malformation.

### 14.2.3 Neural Tube Defects

Neural tube defects (NTDs) refer to abnormalities that occur during the closure of the embryonic elements of the central nervous system (CNS), disrupting

formation and function of the CNS. Early detection along with a comprehensive understanding of the genetic and environmental factors that cause NTDs are crucial for identifying their heterogeneous presentations and neurosurgical management.

## Prenatal Diagnostics

### Maternal Serum Alpha Fetoprotein Test

The maternal serum alpha fetoprotein (MSAFP) test is frequently elevated in NTDs, but is not specific.<sup>42</sup> Of note, when the level of MSAFP is low during gestation, the risk of the fetus having trisomy 21 is elevated.

### Ultrasound (US)

Prenatal US is a more definitive way to detect the presence of an NTD than MSAFP and is done later in pregnancy.

### Amniocentesis

Amniocentesis in the second trimester is used to determine the presence of a myelomeningocele (MMC) or other open NTD. AFP levels are elevated in the presence of an open NTD and may be indicated with a suspicious US despite a risk of pregnancy loss from the procedure.<sup>11</sup>

### Fetal MRI

MRI has historically been unfavorable due to the sedation required to avoid motion artifact from the fetus. In recent years, imaging technique has improved and offered more comprehensive fetal neuroimaging for complicated posterior fossa and spinal defects. This provides a more detailed view of the brain, hindbrain, and neural tube defect anatomy.<sup>43,44</sup>

## Prevention

Recurrence rates in subsequent pregnancies following a diagnosis of an NTD is between 2 and 4% with one affected sibling, and approximately 10% with two affected siblings.<sup>11,45,46,47</sup> Therefore, it is an important consideration when counseling women with potential future pregnancies on the ways in which this risk can be ameliorated.

NTDs are believed to be linked to a deficiency of folic acid in the early stages of pregnancy.<sup>48,49,50,51</sup> For this reason the Food and Drug Administration (FDA) approved fortification of many foods in the United States, however, these fortifications have not been definitively shown to be sufficient to prevent NTDs.<sup>52</sup> The Centers for Disease Control and Prevention (CDC) advises that pregnant women should take folic acid 400 to 800 µg/d, and those with a strong family history or prior pregnancy with NTD should take 4 mg/d.

## Open Neural Tube Defects

### Anencephaly



A lethal condition in which the cranial neural tube fails to close between days 25 and 27 postconception, causing a lack of skin and bone over the cranial neural tissue.<sup>53</sup>

The neural tissue may be underdeveloped or destroyed due to the lack of protective covering.<sup>54</sup> While often these pregnancies spontaneously terminate in utero, occasionally the fetus is born alive and may live for hours or rarely, days to weeks. The incidence of anencephaly in the United States was reported to be approximately 9.4/100,000 live births in 2001.<sup>55</sup>

**Diagnosis:** MSAFP and ultrasonography (see above).

## Encephalocele

Protrusion of the meninges and cranial tissue through an opening in the skull, usually, occurs in the occipital region. Though less common than MMC, encephalocele may occur in up to 20% of cases.<sup>13</sup> In some cases referred to as basal encephalocele, the defect may present as a craniofacial defect such as a nasal polyp causing recurrent meningitis or CSF leak.

**Diagnosis:** MSAFP, ultrasonography, postnatal evaluation  $\pm$  MRI/computed tomography (CT) imaging.

**Treatment:** In both cases of a basal and occipital encephalocele, surgical excision, when possible, of the protruding mass and dural closure is the definitive treatment. Occipital encephaloceles often extensively involve the posterior cranial vasculature, and extreme caution must be taken when excising the mass. If extracranial neural tissue is present, it should be preserved.

Management of basal encephaloceles usually requires combined intracranial and transnasal approaches to avoid hemorrhage, CSF leak, and/or infection. The prognosis is largely based on the size of the sac, type of extracranial tissue, hydrocephalus, and accompanying pathologies.<sup>56</sup>

## Myelomeningocele/Meningocele

Within the category of spina bifida aperta, a further division exists to describe the degree to which the defect has remained “open” with *meningocele* referring to a defect in the bony spine not affecting the underlying neural tissue and *myelomeningocele* referring to a defect that affects both the bony spine and underlying spinal cord.

**Risk factors:** All open NTDs have been linked to a low maternal folic acid level early in pregnancy.<sup>48,49,50,51</sup> The caudal neuropore closes at gestational day 28 (4 weeks), so it is crucial that folic acid

supplementation is begun at a very early stage of pregnancy. For this reason, pregnant women or women wishing to become pregnant in the near future are advised to take folic acid supplements to lower the risk of NTD formation prior to maternal knowledge that she is pregnant. Though no clear pattern of inheritance has been identified, the increased risk of myelomeningocele, within families with a history of NTDs suggests that multifocal genetic factors may be at play.<sup>45,46,47</sup>

**Diagnosis:** Frequently, the diagnosis of NTD is made prenatally. Elevated MSAFP between weeks 15 and 20 is highly suggestive of an open NTD. Ultrasound may also be helpful in the prenatal detection of spina bifida when the defect is large enough to be seen with sonographic imaging. Lastly, open NTDs cause an elevation of AFP in amniotic fluid. Amniocentesis between gestational weeks 13 and 15 is recommended for all women who have a family history or prior gestation resulting in an open NTD.<sup>11</sup> Exceptions to these diagnostic methods include spina bifida occulta, which can be difficult to detect prenatally. Occasionally, neonates with closed spinal dysraphism will have a small tuft of hair in the lumbosacral region, or the diagnosis will be made later when accompanying conditions become symptomatic.

**Treatment:**

Meningocele and MMC must be closed immediately due to risk of infection in the neonatal period.

While immediate closure is preferred, it is unlikely that time to surgical correction has an effect on the neurologic sequelae of the NTD. In the case of MMC, as many as 65 to 85% of children will develop hydrocephalus requiring eventual placement of a shunting device. If present at birth, hydrocephalus may be corrected simultaneously with the

NTD repair.<sup>57</sup> Recently, a prospective study on fetal surgery for the correction of open NTDs has shown to decrease the rates of CSF leakage, Chiari II malformation, and hydrocephalus in fetuses known to have meningocele or MMC.<sup>58</sup>

## Closed Neural Tube Defects

### Tethered Cord Syndrome

The term “tethered cord syndrome” (TCS) is typically used to describe a set of symptoms that describe a tethered cord. These symptoms may occur as a result of several etiologies including but not limited to a fatty filum, filar lipoma, diastematomyelia, lipomyelomeningocele, or a secondary tethered cord from scarring after repair of any of the preceding or an MMC.<sup>59,60</sup> Clinical symptoms tend to fall into three categories: neurologic, urologic, and orthopedic. Neurologic symptoms may include pain in the back or lower extremities, lower extremity weakness, sensory deficits, and muscle wasting. Urologic symptoms include bladder dysfunction and frequent urinary tract infections. Orthopaedic symptoms include gait instability, limb-length discrepancy, and scoliosis. There are known higher rates of occurrence in patients with spina bifida, particularly with MMC.<sup>61,62</sup>

### Fatty Filum

A fatty filum is typically described as a low-lying conus medullaris as a result of a short and thickened filum terminale, resulting in many of the aforementioned constellation of symptoms, which taken together are called TCS.

**Diagnosis:** MRI imaging showing a low-lying conus medullaris and thickened filum.<sup>59</sup>

**Treatment:** Lumbosacral laminectomy with division of the filum terminale is the definitive neurosurgical treatment for TCS when evidence exists that a shortened and thickened cord is the inciting factor.<sup>63</sup>



It is particularly important to correctly distinguish the filum terminale from nerve roots of the cauda equina. This is accomplished using intraoperative electrical stimulation of the lower extremities and anal sphincter.

Monitoring the onset or progression of symptoms is also an option in asymptomatic patients.<sup>64</sup>

### Lipomyelomeningocele

Subcutaneous lipoma that passes through all of the layers of the lumbar dorsum and enters the dura through a defect and attaches to the spinal cord. This is the most clinically relevant of the subtypes of lipomyeloschisis due to the incidence of TCS or spinal compression. Half of patients with lipomyelomeningocele present with no neurologic signs or symptoms and only complain of a back mass. In the other 50% the symptoms resemble TCS such as bladder difficulties, leg pain, gait abnormalities, and paralysis.<sup>65</sup>

**Diagnosis:** MRI imaging.

**Treatment:** Treatment can involve correction of two possible etiologies: (1) TCS (2) spinal cord impingement due to increased volume of the intradural fat. Surgical intervention is frequently performed in infancy to prevent development of neurologic defects and timing is weighed against the risks of anesthesia in young infants. The goal of surgery is primarily prevention of worsening symptoms, but many patients do not experience clinically significant improvement if they are symptomatic at the time of presentation. Complete isolation of the lipoma via resection and invagination of the pial surfaces surrounding the lesion is utterly critical. Partial resection has a low rate of progression-free survival and does worse than historical cohorts of patients that were observed without surgery.

### Spina Bifida Occulta

Often, spina bifida occulta is an incidental finding that is otherwise observed unless



symptomatic comorbidities arise later in life as the child continues to grow and develop.

### 14.2.4 Congenital Brain Disorders

#### Hydranencephaly

Complete or partial absence of the cerebral hemispheres with nearly the complete volume of the cranial vault being filled with CSF. The etiology of this disease is variable and may include bilateral internal carotid artery (ICA) infarct, infection, or agenesis of the neural wall.<sup>66,67</sup>

**Diagnosis:** From a neurosurgical standpoint, the most important consideration in patients with hydranencephaly is to rule out hydrocephalus, which is treatable with shunt placement or endoscopic third ventriculostomy and choroid plexus cauterization (ETV/CPC) which may be successful in up to 40% of patients.<sup>68</sup> The primary methods by which

hydranencephaly can be distinguished from hydrocephalus are electroencephalogram (EEG), radiographic imaging (CT, MRI, US), transillumination, or angiography.<sup>11</sup>

**Treatment:** Though there is no treatment for hydranencephaly, shunting or ETV/CPC may be used for controlling head size.

#### Holoprosencephaly

Failure of the cerebral hemispheres (prosencephalon) to split resulting in a range of presentations that depend on the severity. Holoprosencephaly is often lethal at a young age, however, survivors beyond infancy demonstrate severe mental delays that limit meaningful cerebral function and require neurosurgical intervention.<sup>69</sup> ▶ Table 14.5 shows potential craniofacial abnormalities associated with holoprosencephaly which can range from cyclopia to cleft lip.<sup>70</sup> Birth of a child with holoprosencephaly does increase the risk of incidence in a future pregnancy.

**Table 14.5** Five facies that are diagnostic of holoprosencephaly<sup>70</sup>

| Craniofacial abnormality          | Facial features                                                                                                    | Cranium and brain                                                            |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Cyclopia                          | Single eye or partially divided eye in a single orbit; Arhinia with proboscis                                      | Microcephaly; Alobar holoprosencephaly                                       |
| Ethmocephaly                      | Extreme orbital hypotelorism with separate orbits; Arhinia with proboscis                                          | Microcephaly; Alobar holoprosencephaly                                       |
| Cebocephaly                       | Orbital hypotelorism, proboscis-like nose; No medial cleft lip                                                     | Microcephaly; Usually alobar holoprosencephaly                               |
| Median cleft lip                  | Orbital hypotelorism; Flattened nose                                                                               | Microcephaly, sometimes trigonocephaly; Usually alobar holoprosencephaly     |
| Median philtrum-premaxilla anlage | Orbital hypotelorism, bilateral cleft lip with median process representing philtrum-premaxillary anlage, flat nose | Microcephaly, sometimes trigonocephaly; Semilobar or lobar holoprosencephaly |

## Dandy–Walker Malformation

Enlargement of the posterior fossa with cystic dilation of the fourth ventricle, and partial or complete agenesis of the cerebellar vermis.

Dandy–Walker malformation (DWM) may also present in the context of a syndrome which involves irregularities in the heart, face, limbs, gastrointestinal (GI) tract, and/or genitourinary (GU) tract. Further CNS deformation such as corpus callosum agenesis and occipital encephalocele may be present. The pathophysiology of this disease is not well understood, and genetic hypotheses have largely been disproven. Other hypotheses propose infection and illicit drug or medication exposures as a possible cause of DWM.

**Diagnosis:** Prenatal diagnosis of DWM can be made in more severe cases, but in milder cases, it is difficult to achieve.<sup>71</sup> Important findings to elucidate DWM from other CNS abnormalities (e.g., arachnoid cyst) on radiography are the presence of cerebellar hypoplasia and communication of the cystic malformation with the fourth ventricle.<sup>72,73,74</sup> Typically, in more severe cases, the radiographic findings of DWM are visible after the closure of the cerebellar vermis between 16 and 20 weeks.<sup>75</sup>

**Treatment:** Because of the high incidence of concomitant hydrocephalus, patients with DWM typically require placement of a shunt. If hydrocephalus is not present but the patient requires treatment for the posterior fossa cyst, a shunt may also be placed for adequate fluid drainage. Other techniques have fallen out of favor due to high rates of morbidity and mortality.

## 14.2.5 Sellar Lesions

### Rathke's Cleft Cyst

Sellar cysts that arise from Rathke's pouch and manifest in the posterior

portion of the anterior pituitary. Overwhelmingly, Rathke's cleft cyst (RCC) is more commonly found in adult patients. However, we have included it here to highlight the unique presentation of this anomaly in children so that on the infrequent occasion that it is the underlying pathology, it can be promptly recognized.<sup>76</sup> In the pediatric population, it is particularly important to distinguish a RCC from a malignant and aggressive craniopharyngioma that may be found in a similar region of the brain.

**Presentation:** When RCCs are symptomatic, patients may present with headache and signs of hypopituitarism.<sup>77</sup> In children, they may present with growth delay in addition to other signs of hypopituitarism such as deficits in the anterior pituitary hormones (follicle-stimulating hormone [FSH], luteinizing hormone [LH], adrenocorticotrophic hormone [ACTH], thyroid-stimulating hormone [TSH], prolactin, growth hormone [GH]). Structural compression may cause headache and visual disturbances as might be expected in other pituitary lesions. RCC is present two times more likely in female patients than male patients.<sup>76</sup>

**Diagnosis:** MRI of brain is used for RCC diagnosis in both children and adults.<sup>76</sup>

**Management:** Surgical management may be offered for patients with symptomatic RCCs. The typical approach for symptomatic RCCs is a transsphenoidal resection, which is typically performed endonasally. In patients who have undergone endonasal resection of RCC, they must be closely monitored for CSF leak postoperatively.

As imaging techniques have advanced and the use of MRI has become more prevalent, there has been a rise in the diagnosis of RCC as an incidental finding. Currently, surgical management is reserved for cases that present symptomatically, and asymptomatic lesions may be managed conservatively.<sup>78</sup>

## Craniopharyngioma

Benign sellar mass that arises from the remnants of Rathke's pouch usually appearing as cystic or solid masses on brain imaging that make up 5 to 10% of all childhood brain tumors.<sup>79</sup>

**Diagnosis:** MRI or CT brain imaging. Morphology of the tumor on imaging can vary widely from a solid mass to a cystic lobular structure in the sellar region. Pathognomonic imaging findings include calcifications within the mass.

**Treatment:** The treatment of craniopharyngiomas remains overwhelmingly surgical; however, the use of adjuvant treatments has altered current views on the surgical approach. Traditionally, an aggressive total resection was recommended due to the risk of recurrence particularly in those patients who had a diagnosis of childhood craniopharyngioma. At present, resection remains the gold standard, but subtotal resection with postoperative radiation therapy is advised to avoid damaging surrounding structures during removal of the mass which may result in severe symptomatic panhypopituitarism.<sup>80</sup> Endonasal transsphenoidal resection and pterional approach are the most common approaches used for surgical resection of craniopharyngioma.

The classic triad associated with KFS includes limited neck motion, low hairline, and short neck.<sup>81</sup>

**Diagnosis:** Patients typically present with neurologic complaints, pain, or limited range of motion. Plain film radiograph, followed by MRI for concern of stenosis or instability, is used for diagnosis in conjunction with history and physical examination.

**Treatment:** While fusion of the cervical vertebrae is the hallmark of Klippel–Feil syndrome, more concerning manifestations



**Fig. 14.3** X-ray showing Klippel–Feil syndrome. (Reproduced from Citow JS, Macdonald RL, Refai D, Comprehensive Neurosurgery Board Review, ©2010, Thieme Publishers, New York.)<sup>82</sup>

## 14.2.6 Spinal Disorders

### Klippel–Feil Syndrome

Congenital fusion of cervical vertebrae that typically causes profound neck stiffness and other bony anomalies throughout the body (► Fig. 14.3). Because of possible neurologic consequences and cervical instability, the patient must be evaluated for the severity and extent of cervical fusion.

include instability, hypermobility, and neurologic sequelae of stenosis and impingement. These patients are surgical candidates for spinal fusion, usually performed from a posterior approach and involve the placement of plates and screws for vertebral stabilization.<sup>83</sup>

## Scoliosis

Pathologic curvature of the spine in the coronal plane that is greater than 10 degrees, as measured by the Cobb angle (► Fig. 14.4).<sup>84</sup> This angle may be calculated by extending a



**Fig. 14.4** A 15-year-old adolescent girl with idiopathic scoliosis. Frontal plain film and computerized radiography (PF/CR) shows typical rightward thoracic lateral and rotatory curvature (breast shields in place). (Reproduced from Kim DH, Betz RR, Huhn SL, Newton PO. *Surgery of the Pediatric Spine*, ©2008, Thieme Publishers, New York.)<sup>86</sup>

line from the inferior-most border of the inferior bound of the spinal curvature and another line from the superior-most border of the superior bound of the spinal curvature.<sup>85</sup> When describing scoliosis curvature, the convex side of the spinal distortion is used for naming purposes. Dextroscoliosis delineates a curve with the convexity pointing to the right, whereas levoscoliosis delineates a curve with the convexity to the left. Scoliosis is classified by the etiology and age of presentation (► Table 14.6). Congenital scoliosis, secondary to abnormal formation of the vertebrae such as hemivertebrae or congenital fusion, is present at birth but may not be immediately evident. Neuro-muscular scoliosis arises secondary to abnormalities in innervation of the spine stabilizer musculature—found in cases of cerebral palsy, spina bifida and tethered cord, Chiari I malformation and syringomyelia, spinal muscular atrophy as well as other neurodegenerative conditions, and spinal cord injuries.

Adolescent scoliosis indicates onset between age 11 and 14; juvenile indicates onset from age 4 to 10; infantile indicates onset from age 0 to 3 years.

**Presentation:** Asymmetry in the shoulders, pelvic asymmetry, visible curve, rib hump with forward bending may be physical manifestations of scoliosis. In severe cases, pulmonary dysfunction may occur secondary to restrictive lung disease.

**Diagnosis:** Close physical examination paying particular attention to the neurologic examination and the Adam's forward bend test typically raises the suspicion for scoliosis. Radiographs (posteroanterior and lateral) help to determine the severity of the deformity and may guide subsequent treatment.<sup>88,89</sup> Patients with early-onset scoliosis (infantile or juvenile), neurologic symptoms (pain, numbness, weakness), or atypical curves (thoracic levoscoliosis) should be referred for advanced imaging including an MRI to rule out a neurologic etiology.

**Table 14.6** Summary of the risk factors and features of adolescent idiopathic scoliosis (AIS)

|            | Age                                                                                                                                                                                                                                   | Gender                                                                                                                                                                                              | Genetic factors                                                                                                                                                                                |
|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Prevalence | <ul style="list-style-type: none"> <li>• There is a higher prevalence of adolescents with scoliosis than for younger children</li> <li>• Higher prevalence after puberty than prior to puberty (&gt; 15 years)</li> </ul>             | <ul style="list-style-type: none"> <li>• Female to male ratio is 2:1 and increases with age</li> </ul>                                                                                              | <ul style="list-style-type: none"> <li>• 97% of AIS patients have family members with AIS</li> <li>• Patients with Prader–Willi syndrome may have up to 40% prevalence of scoliosis</li> </ul> |
| Curvature  | <ul style="list-style-type: none"> <li>• Infantile scoliosis has a higher prevalence of left-sided curves than juvenile scoliosis</li> <li>• Juvenile scoliosis showed equal prevalence of left- and right-sided scoliosis</li> </ul> | <ul style="list-style-type: none"> <li>• Males have a higher prevalence of thoracolumbar/lumbar curvatures</li> <li>• Females have a higher prevalence of thoracic and double curvatures</li> </ul> |                                                                                                                                                                                                |

Note: This subtype of scoliosis is diagnosed after ruling out all possible types of nonidiopathic scoliosis. AIS makes up approximately 90% of all adolescent scoliosis cases, and typically does not require surgical intervention.<sup>87</sup>

**Treatment:** Treatment method for scoliosis largely depends on the severity of deformation and the accompanying symptoms that result from the spinal distortion as well as the etiology. About 90% of adolescents with scoliosis do not require surgery and treatment consists of physical therapy and bracing to strengthen surrounding muscles and correct pathologic curvature. Patients with neuromuscular scoliosis secondary to Chiari I malformation, syringomyelia, or tethered cord may have arrest of their scoliosis progression after treatment of their primary cause.<sup>90,91</sup> However, of those with idiopathic scoliosis, the 10% that do show signs of severe scoliosis including signs of progression, Cobb angle greater than 50 degrees, or respiratory deficits due to compression of the thoracic spine, may necessitate surgical correction.<sup>89,92,93</sup> Goals of surgery involve preventing further progression of scoliosis

as well as achieving some correction of the existing deformity. A posterior approach is usually preferred to achieve stability by fusing regions of the spine using instrumented fusion with pedicle screws, hooks, and rods to fix the vertebrae in place.<sup>94</sup>

### 14.2.7 Hydrocephalus

Hydrocephalus is the leading cause of neurosurgical intervention in pediatric patients.<sup>95</sup> Despite the commonality of this disease, the treatments available remain imperfect, with complications often arising throughout life. Currently, the mainstay of hydrocephalus treatment remains shunting to divert CSF elsewhere in the body. This method is effective in decreasing the life-threatening effects of hydrocephalus, yet infection, shunt hardware malfunction, and overdrainage are constant burdens of care in children with

shunts. Etiology of hydrocephalus, age of patient at presentation, clinical signs and symptoms, and all treatment options available should be considered when determining the best method of treatment for pediatric patients with hydrocephalus.<sup>96</sup>

## Etiology

Etiology of the patient's hydrocephalus is an important factor in determining the treatment method that is likely to be successful. Patients with previous neoplasm, intraventricular hemorrhage, or congenital hydrocephalus show increased risk of shunt failure.<sup>96,97,98,99</sup> While these etiologies are likely to predispose to shunt complications or failure, they remain among the most common types to require lifelong shunting.<sup>100</sup>

## Diagnosis

A combination of examination findings and imaging studies are useful in the diagnosis of pediatric hydrocephalus. Particularly in infants prior to closure of fontanelles, macrocephaly may be an obvious and distinguishing feature of hydrocephalus and may be detected in the pre- or postnatal period. In older children and adults, hydrocephalus typically manifests with classical presentation of increased ICP with decreased consciousness, headache, nausea, vomiting, and blurry vision or diplopia. MRI remains the gold standard of imaging modalities by which to diagnose hydrocephalus.

## Treatment

**Shunting:** Shunting from the ventricle to the peritoneal cavity (ventriculoperitoneal [VP] shunt) remains the most common method for treating hydrocephalus in the pediatric patient. Particularly in pediatric patients, the ease of access to the

peritoneal cavity, absorptive capacity of the space, and additional volume in which to place excess catheter to account for the child's growth are all positive reasons that this method remains favored.<sup>96</sup> Furthermore, access into the peritoneal cavity has been made less invasive due to the widespread use of laparoscopy instead of laparotomy to place the catheter.<sup>96</sup> However, following VP shunt failure or other medical constraints that prohibit placement of the catheter in the abdomen, ventriculopleural, ventriculoatrial (VA), and ventriculogallbladder shunts are alternative options to the classic VP shunt.<sup>96</sup> Interestingly, a particular type of shunt called a lumbar peritoneal (LP) shunt is used in patients who present with idiopathic intracranial hypertension (usually young, overweight women) that can be placed percutaneously in cases when intraventricular shunt placement may carry additional risks due to anatomical considerations.<sup>96</sup>

**Alternative treatments:** ETV has been a mainstay of hydrocephalus treatment in cases in which a shunt is not an optimal or desired treatment method.<sup>96</sup> This method of treatment creates a new pathway for the CSF through the floor of the third ventricle creating a pathway into the interpeduncular cistern. Additionally, cauterization of the choroid plexus has proven to increase the success of the ETV procedure.<sup>101</sup> As this method of treatment for hydrocephalus is further refined in the future, it may be an avenue through which to prevent many of the shunt complications that burden hydrocephalus patients throughout their lives. The ETV Success Score can be utilized to help predict the the success of this intervention based on age, etiology of hydrocephalus, and history of a prior shunt.

## 14.3 Pediatric Tumors

See Chapter 13 on "Neurosurgical Oncology" for High-Yield Pediatric Tumors.

## 14.4 Pediatric Trauma

### 14.4.1 Growing Skull Fracture

The evaluation of pediatric head trauma does not differ greatly from that of an adult patient. Therefore, in this section of the chapter we have chosen to highlight the pathophysiology, evaluation, and treatment of a unique finding in pediatric head injury, the growing skull fracture (GSF). The incidence of this complication is estimated to occur in between

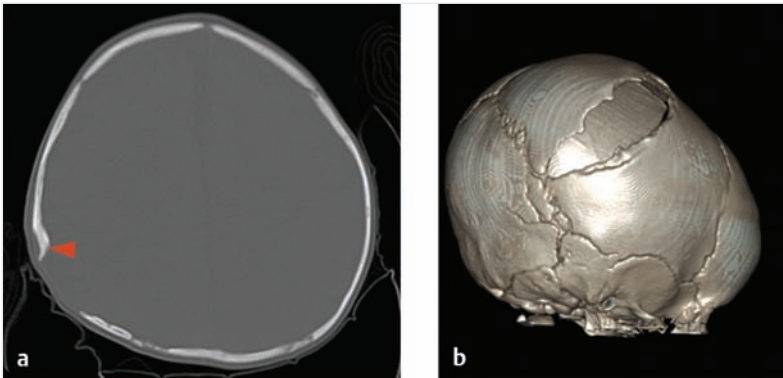
0.05 and 1% of linear skull fractures.<sup>107</sup> Most commonly, GSFs are seen in patients younger than 3 years, but may take days to years for definitive diagnosis.<sup>102,104,106,108</sup> Because of the defect in the dura tissue and the corresponding bone fracture, cranial contents may herniate through the opening wedging between the fractured calvarium. Eventually, this causes the brain tissue to necrotize, forming a fluid-filled cystic cavity (► Fig. 14.5).<sup>102,108</sup>

### Diagnosis

The four criteria that have been proposed for clinical diagnosis of a growing skull fracture are:

- Age less than 5 years with a cephalohematoma.
- Bone diastasis 4 mm or greater.
- Underlying brain contusion.
- Contrast MRI showing a dural tear.

Also known as a leptomeningeal cyst or posttraumatic encephalocele, a GSF is a rare and potentially lethal complication that can be seen in pediatric patients following a dural tear secondary to a fracture of the skull.<sup>102,103,104,105,106</sup>



**Fig. 14.5** Leptomeningeal cyst. **(a)** Axial bone algorithm computed tomographic image in a 6-month-old male infant with prior trauma shows a gap in the posterior right parietal bone with smooth margins, including the anterior margin of the bone gap, which flairs outward (red arrowhead). **(b)** Lateral projection of a three-dimensional rendering shows a wide gap from this “growing fracture” related to a leptomeningeal cyst. (Reproduced from Choudhri AF, *Pediatric Neuroradiology: Clinical Practice Essentials*, ©2017, Thieme Publishers, New York.)<sup>109</sup>

Meeting these criteria makes it highly likely that the child has a GSF and that he or she should be promptly managed with surgical intervention.

## Treatment

The gold standard for surgical management of growing skull fracture is repair of the dural tear and shunt placement if the defect has resulted in hydrocephalus.<sup>102,104</sup> The crucial aspect of surgical treatment is the necessity of early intervention, therefore, immediate recognition is essential.

### 14.4.2 Spinal Trauma

Spinal injuries in the pediatric population are common, making up approximately 1 to 5% of all injuries in children.<sup>110</sup> Overwhelmingly, pediatric spinal injuries occur in the cervical spine due to weak neck bones and muscles supporting a disproportionately large cranium. As children age, the cervical spine remains the most likely location of spinal injury overall, but older children are more likely than younger children to sustain injuries to the middle and lower spine.<sup>110,111</sup> When evaluating a pediatric patient with a potential spinal injury, it is important to consider the structural differences in anatomy between children and adults. As mentioned previously, children have disproportionately large heads as compared to adults. When a pediatric patient is being evaluated for a spinal injury, it is crucial to elevate the body in order to align the vertebrae and avoid forced flexion of the neck due to head circumference. Treatment is dependent on type and severity of injury, mechanism of injury, and other pertinent medical or surgical history.

## Pearls



- Examination of the infant should include a careful assessment of head shape and size which may be an early indicator of intracranial and calvarial pathology.
- Chiari I malformations in children may often present with syringomyelia, assessment and monitoring of the syrinx following treatment is recommended.
- Neural tube defects comprise a variety of open and closed pathologies which vary in severity however have common hallmarks of causing urologic, orthopedic and neurologic dysfunction when symptomatic.
- Hydrocephalus is a common pediatric neurosurgery pathology. Consideration of the etiology of the hydrocephalus will help to guide treatment options which currently include endoscopic treatment and shunting.

## 14.5 Top Hits

### 14.5.1 Questions

1. A newborn is evaluated in the NICU for a neural tube defect as evidenced by a lesion on his lower spine resembling a myelomeningocele without skin covering. He is moving around without significant fussiness and does not seem to be drowsy during your examination. During the work-up, an MRI of the brain is obtained which shows herniation of the cerebellar vermis and medulla through the foramen magnum approximately 5 mm below the boundary. What are the next steps in the management of this patient?



- a) Surgical decompression because of the potential for hydrocephalus to develop.
  - b) Repair of the myelomeningocele, monitoring for signs of hydrocephalus, conservative management, and observation for lower cranial nerve signs.
  - c) Schedule a cervical decompression when the child is 6 months old; by then his risks of having surgery will be lower.
  - d) Immediate EVD placement due to concerns for increased ICP.
2. A 15-year-old girl presents to your office for evaluation of short stature. She and her parents state that although the other kids in the girl's class have grown significantly over the last 2 years, she has grown only 1 to 2 cm. Additionally, she reports occasional headaches, and sometimes finds it difficult to "clearly focus her eyes." On MRI imaging of her brain, there is a mass in the sellar region that lacks any hyperdense signals. What is the most likely diagnosis?
    - a) Arachnoid cyst.
    - b) Craniopharyngioma.
    - c) Rathke's cleft cysts.
    - d) Growing skull base fracture.
  3. A 31-year-old G1P0 woman discovers at her 20 week US that her baby has massive hydrocephalus in utero due to aqueductal stenosis and decides to come to your office for consultation so that she may know what to expect when the baby is born. You tell her that:
    - a) She will likely not need surgery, the hydrocephalus will resolve within the first few months.
    - b) She will likely require shunt placement, and this will occur approximately 6 months after the baby is born.

- c) She will likely require shunt placement, and this will occur very soon after the birth of her child.

## 14.5.2 Answers

1. **b.** Open NTDs should be urgently repaired. Because of the high risk of hydrocephalus in this population, patients should be monitored for signs on increased ICP. Many Chiari II malformations remain asymptomatic with closure of the NTD and treatment of any arising hydrocephalus, so the Chiari II malformation should be managed conservatively.
2. **c.** Rathke's cleft cysts typically present with hypopituitarism (growth delay), blurred vision, diplopia, and headaches and do not demonstrate signs of calcification on imaging. They are two times as likely to be found in female than male patients.
3. **c.** She will likely need shunt placement for treatment of hydrocephalus which should occur as soon as possible so as to avoid prolonged increased ICP, resulting in other neurologic damage, or further expansion of the sutures or calvarial vault.

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# 15 Movement Disorders and Epilepsy

Pablo A Valdes, Garth Rees Cosgrove

## 15.1 Movement Disorders

### 15.1.1 Parkinson's Disease Diagnosis

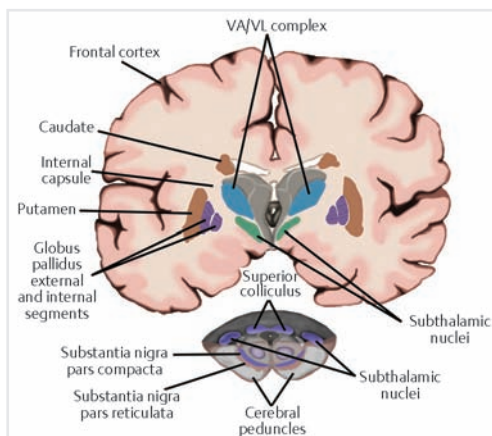
Parkinson's disease (PD) is the second most common progressive neurodegenerative disease characterized by motor and non-motor features affecting 2 to 3% of the population older than 65 years,<sup>1,2</sup> with men more likely than women. It is the most common and well-understood disorder of the basal ganglia (► Fig. 15.1).

PD is clinically defined by the presence of bradykinesia, and at least one additional cardinal feature and additional supporting/exclusion criteria. PD can display both motor and nonmotor symptoms.

Motors symptoms are numerous and include, but are not limited to, tremor, rigidity, akinesia/bradykinesia, postural instability, shuffling gait, micrographia, and masked facies. Resting tremor is the most common and easily recognized feature characterized as a "pill-rolling" tremor most prominent in the distal extremities. Rigidity is associated with a "cogwheel phenomenon" when performing a passive movement of the limb.<sup>1,2</sup> Nonmotor symptoms include cognitive impairment, depression, apathy, fatigue, dysautonomia, and sleep disorders.

The National Institute of Neurological Disorders and Stroke (NINDS) diagnostic criteria for PD are as follows:

- **Group A features (characteristic):** Resting tremor, bradykinesia, rigidity, asymmetric onset.
- **Group B features (suggestive of alternate diagnosis):** Prominent postural instability, freezing phenomenon, or



**Fig. 15.1** Coronal section highlighting key structures involved in movement disorder pathophysiology and treatments. (Reproduced from Kanekar S, *Imaging of Neurodegenerative Disorders*, ©2015, Thieme Publishers, New York.)<sup>3</sup>

hallucinations unrelated to medication in the first 3 years; dementia preceding motor symptoms in the first year; supranuclear gaze palsy, slow vertical saccades, or severe dysautonomia.

- **Definite PD:** All Group A and pathologic confirmation.
- **Probably PD:** At least four Group A, none group B, and substantial and sustained response to levodopa.
- **Possible PD:** At least two group A including tremor or bradykinesia, and none group B or symptoms less than 3 years and no features of group B, and substantial and sustained response to levodopa or no adequate trial of levodopa.

Error rates for clinical diagnosis can be as high as 24% which include multiple systems atrophy (MSA), progressive supranuclear palsy (PSP), corticobasal degeneration (CBD), essential tremor (ET), drug-induced parkinsonism, and vascular parkinsonism.

## Pathophysiology

PD is hypothesized to be a disease of the basal ganglia, with dopaminergic neuronal loss in the substantia nigra (SN) and intracellular protein accumulation ( $\alpha$ -synuclein) known as Lewy bodies.<sup>2</sup> Multiple mutations including *PARKIN*, *PINK*, *LRRK2*, and *SCNA* have been associated with approximately 20% of cases.<sup>4</sup> Net loss of dopaminergic input (> 70% dopaminergic neuronal in the SN) causes opposing effects within the motor striatum with increased activity in the *indirect pathway* by net disinhibition of the globus pallidus interna (GPi) and subthalamic nucleus (STN), decreased activity of the *direct pathway*, and net tonic gamma-aminobutyric acid-ergic (GABAergic) inhibition of thalamic output to the cortex.

Overall, the STN and GPi are noted to be overactive and as such have been the target of ablative treatments, for example, pallidotomy, and deep brain stimulation (DBS) (► Fig. 15.2).<sup>2,4,5,6</sup>

## Treatment

### Medical Therapy

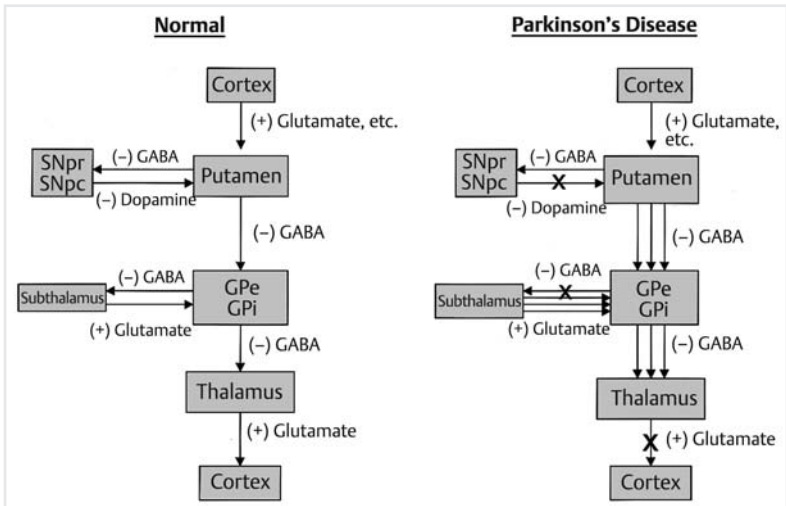
The mainstay of pharmacologic treatment for PD involves dopaminergic targets; that is, given loss of dopaminergic neurons in the substantia nigra pars compacta (SNpc) leading to dopamine depletion in the striatum as the core mechanism for motor symptoms in PD.

L-Dopa is a precursor of dopamine and was introduced in the 1960s and is the gold standard for PD and parkinsonism.<sup>5,6</sup>

Patients eventually develop resistance to L-dopa therapy and develop motor response oscillations and drug-induced dyskinesias. Common preparations including enzyme inhibitors, for example, carbidopa, that prevents peripheral metabolism of dopamine; monoamine oxidase (MAO) inhibitors, for example, selegiline, to inhibit a major postsynaptic clearance mechanisms of dopamine and dopamine agonists on striatum, for example, ropinirole, serve as adjunct therapy given their long half-life.<sup>2</sup> Dyskinesia is a major side effect of L-dopa with amantadine currently used for treatment of such.

### Surgical Therapy

- **Deep Brain Stimulation (DBS):** The ideal DBS patient is a generally healthy patient, with no significant psychiatric disorder, who is levodopa responsive, and



**Fig. 15.2** Basal ganglia in Parkinson's disease. Basal ganglia circuitry including key nuclei and neurotransmitters in Parkinson's disease. (Reproduced from Citow J, Macdonald R, Refai D, Comprehensive Neurosurgery Board Review, 2nd edition, ©2009, Thieme Publishers, New York.)

an idiopathic PD patient with disabling symptoms and/or significant side effects such as on/off fluctuations.<sup>7</sup>

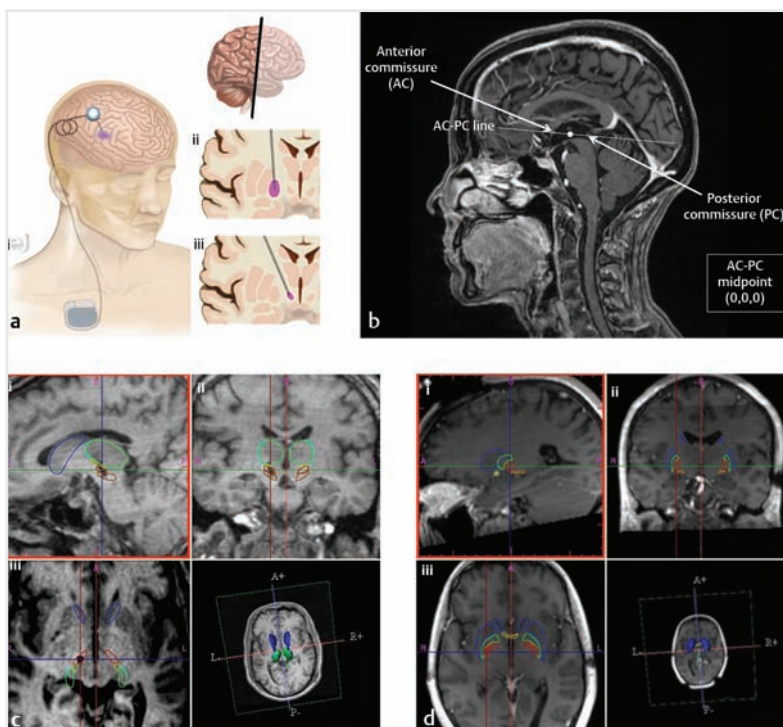
DBS involves placement of deep subcortical electrodes into the STN or GPi using stereotactic techniques, with or without intraoperative electrophysiologic monitoring, and which are connected to an implantable pulse generator (IPG) (► Fig. 15.3).

Both demonstrate comparable efficacy in addressing the cardinal motor symptoms (tremor, bradykinesia, gait, rigidity) of PD; reduced off time, on/off fluctuations, and on-medication time dyskinesias; and less marked on-medication state.<sup>7,8</sup>

STN over GPi is currently the preferred target based on evidence noting greater reduction of medication requirements (> 50% at 12 months) and lower stimulation voltage, yet with more notable cognitive and behavioral side effects.

Multiple techniques can be used including frame-based approaches, frameless neuronavigation-guided approaches, or frameless approaches with intraoperative magnetic resonance imaging (MRI).<sup>8</sup> Most stereotactic techniques use known atlas-based distances of the different nuclei (i.e., STN, GPi) in relation to the





**Fig. 15.3** DBS in Parkinson's disease. (a) Schematic of DBS with (i) intracranial and extracranial components of complete DBS system; (ii) coronal views of GP and (iii) STN targeting. (b) AC/PC line and MCP point in sagittal MR image. (c) STN targeting in DBS surgery. STN (red), caudate (blue), zona incerta (yellow), and thalami (green) in (i) sagittal, (ii) coronal, (iii) and axial views.<sup>3</sup> (d) GPi targeting in DBS surgery. GPi (red), GPe (green), caudate/putamen (blue), and AC (yellow) in (i) sagittal, (ii) coronal, and (iii) axial views. (Reproduced from Kanekar S, Imaging of Neurodegenerative Disorders, ©2015, Thieme Publishers, New York.)<sup>3</sup>

midcommissural point (MCP), anterior commissure (AC), and posterior commissure (PC) (► Table 15.1). MRI images with specific volumetric T1-weighted sequences and T2-weighted sequences delineate the GPi/STN very well.<sup>9</sup> Direct techniques use MRI and/or computed tomography (CT) to visualize the nuclei in relation to known atlas coordinates and as such their strength lies in accounting for

patient's anatomical variability usually in the order of millimeter differences. Indirect techniques are based on atlas coordinates and usually accompanied by intraoperative monitoring of patients' neurophysiologic responses during stimulation and recording. Multiple stereotactic frames are available (e.g., Leksell's, Cosman-Roberts-Wells), and are user and institution dependent, providing the



**Table 15.1** DBS coordinates for movement disorders<sup>7,10</sup>

| Target | Lateral to MCP                        | Vertical to AC/PC line | Anterior/posterior to MCP |
|--------|---------------------------------------|------------------------|---------------------------|
| STN    | 11–13 mm                              | 4–5 mm ventral         | 3–4 mm posterior          |
| GPI    | 19–21 mm                              | 4–5 mm ventral         | 2–3 mm anterior           |
| VIM    | 11 mm lateral to 3rd ventricular wall | 0 mm                   | 5–6 mm anterior to PC     |

Abbreviations: AC, anterior commissure; DBS, deep brain stimulation; GPI, globus pallidus interna; MCP, midcommissural point; PC, posterior commissure; STN, subthalamic nucleus; VIM, ventral intermediate.

surgeon millimeter accuracies. Entry points are chosen to avoid cortical, sulcal, subcortical, and periventricular vessels to reduce the risk of hemorrhage. Most common complications include intracranial hemorrhage (2.1%), infection within 6 months (4.5%), and hardware complications (as high as 8.4%).<sup>8</sup>

- **Technique:** Place patient in a frame fixed to the table. Merge CT/MRI with calculated coordinates correlated with the frame. Make a bicoronal incision with uni-/bilateral burr holes 2 to 4 cm from midline at 1 to 2 cm anterior to the coronal suture. Open dura and coagulate pia. If electrophysiologic monitoring is performed, insert electrodes at defined offset and perform microelectrode recordings with stepwise movement with physiologic identification of targets based on nuclei specific frequency and pattern of activity. Once confirmed, placement of macroelectrode is performed and macrostimulation to determine benefits and side effect of stimulation. DBS electrode(s) is affixed to the skull and distal tips placed in the subgaleal space for future connection to an IPG. An IPG can be placed concurrently or at a later date, and involves placing patient supine, head tilted to the opposite side of the IPG. An infraclavicular subcutaneous pocket is created,

IPG placed, and connecting wires tunneled to the subgaleal pocket for connection to the distal electrode(s) tip (► Fig. 15.4).<sup>6,8</sup>

Unilateral pallidotomy has similar efficacy as unilateral DBS, since pallidotomy currently can be only safely performed on one side.

- **Pallidotomy:** GPI discharge is abnormal PD and GPI pallidotomy helps address these abnormalities to relieve PD symptoms.

Good candidates for unilateral pallidotomy are patients with asymmetric symptoms, and those unable to comply with DBS follow-up and management.<sup>8</sup> Main advantages include decreased infection risk given no hardware. Disadvantages include irreversible damage to GPI and surrounding structures, for example, corticospinal and optic tracts and if bilateral, a high risk of permanent speech and cognitive dysfunction.<sup>8</sup> Pallidotomy uses the same localization techniques as those for DBS-GPI. Lesioning is most commonly performed using radiofrequency (RF) ablation, focused ultrasound (FUS) is currently under development for performing pallidotomy noninvasively.<sup>11</sup> During pallidotomy, two key steps involve identification of the optic tract by eliciting



**Fig. 15.4** DBS surgery. (a) Placement of Leksell's frame under local anesthesia. (b) OR table frame placement. (c) Sterile operative frame setup. (d) Full sample DBS OR setup. (Reproduced from Sekhar L, Fessler R, Atlas of Neurosurgical Techniques: Brain, Volume 2, 2nd edition, ©2016, Thieme Publishers, New York.)<sup>9</sup>

phosphenes in the contralateral visual field, and contralateral tetanization with macrostimulation near the internal capsule.<sup>12</sup>

## 15.1.2 Essential Tremor

### Diagnosis

Essential tremor (ET) is the most common movement disorder and is characterized as a benign, primarily postural, and/or kinetic tremor at a frequency of 4 to 12 Hz (higher than PD).<sup>13</sup>

In making the diagnosis of ET, careful characterization of the form of tremor needs to be undertaken: resting tremor, which occurs with a relaxed and stationary limb (e.g., PD); postural tremor, which

occurs during voluntary held positions or substantial limb extension (e.g., ET); and intention tremor, which occurs as a limb approaches a target and is a coarse terminal tremor. ET is a clearly postural and/or intention tremor without resting tremor characteristics, with usual age of onset greater than 70 years, progressive in nature and mostly distal in location with greatest amplitude at the wrist and hand and with some form of asymmetry.<sup>14</sup> It is more likely in women than men with prevalence of 0.4 to 6%,<sup>8,15,16,17</sup> and has autosomal dominant transmission.<sup>14</sup> ET can be exacerbated by anxiety and improved by alcohol.<sup>16</sup> Careful characterization of a patient with intention tremor can help distinguish ET from physiologic tremor and associated exacerbating factors (e.g., caffeine, smoking, drugs,

hyperthyroidism), other diseases (e.g., Parkinson's tremor, dystonia, Wilson's disease), and from secondary tremors (e.g., multiple sclerosis, stroke, trauma).<sup>7,13</sup>

Diagnostic criteria for ET include the Movement Disorder Society and the Washington Heights Inwood Genetic Study of Essential Tremor criteria, which include the following criteria.

Inclusion criteria consist of bilateral postural tremor with or without intentional component of arms and forearms, and duration more than 5 years.

Exclusion criteria consist of other abnormal signs, known causes for increased physiologic tremor, current or recent use of tremor inducing drugs or drug withdrawal state, nervous system trauma within 3 months before onset of tremor, evidence of psychogenic signs, and evidence of sudden onset or stepwise deterioration.<sup>13</sup>

## Pathophysiology

The pathophysiologic basis of ET is not as well understood as PD but consensus suggests mediation by a neuronal loop involving cerebellothalamocortical fibers with the ventral intermediate (VIM) nucleus of the thalamus as a key therapeutic target.<sup>13</sup> The VIM contains two sets of tremor cells, whose input is primarily cerebellar and not striatal, and its output in part is hypothesized to target the pallidal tracts, serving as a major component of tremor circuitry connecting the cerebellum with cortical motor pathways.<sup>7,15</sup> These VIM cells fire in synchronous bursts with timing similar to peripheral tremor, with intraoperative stimulation noted to temporarily arrest tremor and as such have been posited as "tremorigenic pacemakers."<sup>10,16</sup> ET is traditionally thought of as an autosomal dominant transmission with susceptibility loci at chromosomes 2, 3, and 6. Postmortem studies note significant cerebellar degenerative changes as well as brainstem Lewy bodies.

## Treatment

### Medical Therapy

Patients with severe ET are significantly impacted in their activities of daily living and are candidates for medical treatment.

First-line treatments for ET alone or in combination include  $\beta$ -blockers, (i.e., propranolol) and anticonvulsants (i.e., primidone) with class I evidence noting tremor reduction of up to 60% in 50% of patients.<sup>15</sup>

If failure of first-line agents occurs, patients can try second-line agents including benzodiazepines (e.g., clonazepam, alprazolam), gabapentin, calcium channel blockers (e.g., nimodipine), theophylline, and even botulinum toxin A, but additional treatments are rarely sufficient and at such point patients should undergo surgical evaluation.<sup>6,13,15,17</sup>

### Surgical Therapy

Patients with medically refractory ET have two surgical options available with patients notable for distal extremity tremor benefiting most from surgery.<sup>6,15</sup>

Current surgical options include VIM targeting via DBS or thalamotomy using either RF, SRS, or FUS.

- **Deep brain stimulation:** Unilateral or bilateral DBS of the VIM is a surgical option for upper extremity tremor control with success rates greater than 70%. A recent randomized controlled trial (RCT) of DBS VIM noted suppression of drug-resistant tremor with fewer ad-

verse effects than thalamotomy.<sup>6</sup> DBS techniques are equivalent to those for PD noted above, but coordinates used to target the VIM are 11 mm lateral to the third ventricular wall, 5 to 6 mm anterior to the PC, and at the level of the AC/PC line (► Table 15.2).

- **Thalamotomy:** There are currently three available means of performing VIM thalamotomy: the more common, invasive RF ablation approach, SRS, and a new, noninvasive FUS approach. Of note, irreversibility of thalamotomy is the major downside of such ablative procedures compared to DBS. Thalamotomy has been shown to reduce contralateral tremor in more than 85% of patients with notable transient (60%) versus mild permanent (23%) neurologic deficits

including weakness, dysarthria, ataxia, and sensory deficits.<sup>10</sup> In addition, bilateral thalamotomy is associated with greater than 50% cognitive and bulbar deficits, which makes bilateral DBS a preferred means of treating patients with severe bilateral tremor.<sup>7</sup>

FUS is performed by placing a patient in an MRI, followed by stereotactic targeting using known coordinates and MRI localization of the VIM target. The patient then undergoes sonication with acoustic energy to tissue ablative temperatures of 55 to 60°C, meanwhile undergoing real-time monitoring with MRI thermometry. FUS thalamotomy in a recent RCT showed almost 50% improvement in tremor scores in patients<sup>15</sup> and is now a powerful option for treatment of ET in

Table 15.2 Key features of movement disorders

| Disease             | Key clinical features                                                                                                        | Pathology                                            | Genes                     | Medical treatment                                                                    | Surgical targets |
|---------------------|------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|---------------------------|--------------------------------------------------------------------------------------|------------------|
| Parkinson's disease | Bradykinesia, resting tremor, rigidity, shuffling gait                                                                       | Loss of dopaminergic neurons in SN                   | PARKIN, PINK, LRRK2, SCNA | L-dopa/carbidopa MAOI, dopamine agonists                                             | STN, GPi         |
| Essential tremor    | Postural/kinetic tremor at 4–12 Hz frequency                                                                                 | Cerebello-thalamo-cortical loop with VIM involvement | Chromosome 2,3,6          | Propranolol, primidone, benzodiazepines, calcium channel blockers, botulinum toxin A | VIM              |
| Dystonia            | Hyperkinetic disorder with sustained muscle contractions generating abnormal postures, repetitive movements, and/or twisting | Gpi overactivity with thalamo-cortical activation    | DYT1                      | Levodopa, trihexyphenidyl, neuroleptics, baclofen, botulinum toxin A                 | GPI              |

Abbreviations: GPi, globus pallidus interna; MAOI, monoamine oxidase inhibitor; SN, substantia nigra; STN, subthalamic nucleus; VIM, ventral intermediate.

a noninvasive manner. SRS thalamotomy is also noninvasive and has similar clinical outcomes compared to DBS or RF ablation. However, the clinical benefit is delayed and there is no opportunity for intraoperative clinical monitoring for side effects.

### 15.1.3 Dystonia Diagnosis

Dystonia is a heterogeneous hyperkinetic movement disorder notable for sustained muscle contractions generating abnormal postures, repetitive movements, and/or twisting movements.<sup>6,7,17</sup>

Dystonia is a clinical diagnosis with key characteristics including abnormal postures with or without tremor and specific features. First, the clinician is tasked with recognition of abnormal movements as dystonic, which are characteristically consistently directional, patterned, repeatedly involve the same muscle groups, causing sustained twisting of body parts of either trunk, extremities, or both. Dystonic movements usually involve both agonist and antagonist muscle contraction and are usually aggravated by voluntary movement.<sup>18</sup>

Dystonia can be understood based on several classification schemes including location of body affected (generalized, focal, multifocal, segmental, hemidystonia), etiology (primary or idiopathic, secondary or symptomatic), or age of onset (early < 26 years or late > 26 years). Dystonia has a bimodal distribution with modes at 9 (presenting usually with appendicular symptoms) and 45 (presenting usually with axial symptoms) years.<sup>6,7,17</sup> Secondary dystonias are a heterogeneous group which include those caused by other central nervous system (CNS) insults (e.g., drugs, infarcts); dystonia plus syndromes associated with neurochemical, nondegenerative disorders associated with another movement disorder (e.g., dopa-responsive dystonia, myoclonus dystonia syndrome); and herodegenerative dystonias which are part of a known neurodegenerative disorder

(e.g., PD, Huntington's disease, Wilson's disease, Lesch–Nyhan syndrome).<sup>5,6,17,18</sup>

## Pathophysiology

Primary dystonias have no clear etiologic factor (e.g., trauma, stroke, known neurologic disorder, normal brain imaging, and laboratory studies).



A subset of primary dystonias are autosomal dominant and are associated with *DYT1* which encodes the *TorsinA* gene.

This gene is mapped to a GAG deletion in chromosome 9, is expressed prominently in the SNpc, and is the most common mutation leading to childhood-onset primary dystonia.<sup>5,6</sup> Secondary dystonias are associated with multiple etiologies as noted previously.

The pathophysiologic basis of dystonia is complex including loss of motor inhibitory function leading to excessive cocontraction of agonist and antagonist muscles; abnormal somatosensory input; motor cortex overexcitability and loss of intracortical inhibition; and finally, given the data from DBS, the basal ganglia is posited as a major site of dysfunction. Abnormal basal ganglia circuitry results in imbalance of direct and indirect pathways, leading to overactivity of the direct pathway, an overall net decrease in GPi activity, and overall increase in thalamocortical activation.<sup>7,19</sup>

## Treatment

### Medical Therapy

Medical options for dystonia are aimed at controlling symptoms and are broadly focal or generalized. These include anticholinergics, levodopa, neuroleptics, and baclofen as generalized forms of treatment. Botulinum toxin has become a drug of choice for focal

treatments with response rates of 70 to 100%.<sup>5,7,17</sup> Patients are initially trialed on L-dopa and if unsuccessful, a trial of the anticholinergic, trihexyphenidyl is used with benefit in more than 40% of patients. Clozapine, an atypical neuroleptic blocking primarily D4 receptors has shown greater than 30% improvement in dystonia scales. Baclofen and benzodiazepines are useful as adjunct therapies.<sup>5,18,19</sup>

## Surgical therapy

Patients undergoing surgical treatment for dystonia must have failed standard medical therapy. Every patient should undergo a trial of levodopa to rule out those with dopamine-responsive dystonia.<sup>5,17</sup>



Further, the best candidates are patients with primary generalized dystonia, specifically those with the *DYT1* gene mutation; segmental or idiopathic cervical dystonia; or hemidystonia not responsive to medication with profound disability.

Patients with secondary dystonias do not have the same success with surgical treatment.<sup>5,7,17</sup>

- **Deep brain stimulation:** Bilateral GPi-DBS is the surgical treatment of choice for dystonia, which has shown improvements 45 to 75% in dystonia rating scales in patients with primary dystonia compared to rates 10 to 30% in those with secondary dystonias.<sup>6,7</sup> Predictors of good outcome include primary dystonia, *DYT1* mutation, age of onset greater than 5 years, lack of multiple orthopaedic deformities with improved response in appendicular compared to axial symptoms. Of note additional, less popular targets included the Voa/Vop and VIM of the thalamus.<sup>5,6</sup>
- **Lesionectomy:** Historically, both thalamotomy and pallidotomy have been targeted for treatment of dystonia. Unilateral

pallidotomy of the posterovental GPi as demonstrated by Leksell has shown good results but is currently not a preferred treatment of choice for dystonia.<sup>5</sup>

## 15.2 Epilepsy

Epilepsy surgery is indicated in cases of drug resistance despite an adequate trial of two antiepileptic drugs (AEDs). Approximately 30% of epilepsy patients will have drug-resistant epilepsy,<sup>20</sup> which significantly impacts quality of life (QOL) and mortality (0.9 per 100 person years) and up to 20 times greater in those with uncontrolled convulsive seizures and AED polypharmacy. Epilepsy surgery is the most effective way to control drug-resistant epilepsy and thus improving QOL and mortality. Delineation of the “epileptogenic zone” (EZ, i.e., the proposed necessary and sufficient cortical area for seizure generation whose complete removal is required for seizure control) is limited by the lack of a gold standard biomarker, which has led to the current paradigm of phases 1 and 2 investigations in the work-up for selective patients most likely to benefit from epilepsy surgery.<sup>21</sup>

### 15.2.1 Presurgical Investigations

#### Phase 1: Noninvasive

The main components of phase 1 investigations include seizure semiology, imaging studies, electroencephalogram (EEG)/video EEG, and neuropsychological assessment. Seizure semiology has been described for different seizures and can help guide an initial hypothesis, for example, fear and rising epigastric sensation suggest mesial temporal sclerosis; visual auras suggest an occipital focus; or sympathetic symptoms suggest insular focus.<sup>22</sup> All patients are required to have a high-resolution MRI to help identify any underlying lesion or pathology as the

possible cause of epilepsy (e.g., mesial temporal sclerosis) which include T1, T2, and fluid-attenuated inversion recovery (FLAIR) sequences and dedicated coronal sequences for temporal pathologies.<sup>22</sup> EEG and video EEG monitoring provides interictal and ictal data to localize areas of correlating to the seizure phenomenology. Finally, neuropsychological assessment is used to evaluate for functional roles of the identified regions and more broadly for generic functions like language dominance (e.g., > 95% of right-handed and > 15% of left-handed subjects have left hemisphere language dominance), and baseline neurocognitive assessment.<sup>21,22</sup>

During phase 1 investigations, clinicians have numerous tools to help both (1) better localize the EZ and (2) assess the risk of postoperative deficits in planning for epilepsy surgery.

Additional morphometric analysis on MRI can help improve detection of structural lesions on MRI (e.g., focal cortical dysplasia). Areas of interictal dysfunction and epileptiform discharges can be investigated by neuropsychology, scalp EEG, magnetoencephalography (MEG), functional MRI (fMRI) coupled with EEG and positron emission tomography (PET). MEG, EEG, or EEG-fMRI can show strong spatial concordance with the EZ based on interictal epileptiform discharges data. The most important determinant of the EZ is ictal EEG recordings. Assessment of glucose metabolism with fluorodeoxyglucose (FDG) PET in interictal brain dysfunction may show hypometabolism in the epileptogenic lobe and is associated with better outcome in temporal lobe epilepsy and in MRI-negative patients. Metabolism is correlated with hyperperfusion during seizures, and areas of ictal onset can be further characterized by hyperperfusion on single-photon emission computed tomography (SPECT) (and as part of phase 2 investigations using

intracranial EEG).<sup>22</sup> These techniques are limited in spatial or temporal resolution and the relationship between ictal and interictal findings are surrogate markers of the EZ zone but none are ideal imaging biomarkers for the EZ.<sup>21, 22</sup>

Assessment of preoperative deficits and risk of postoperative deficits can be performed by use of validated memory tests (e.g., Battery of Learning and Memory), fMRI, Wada test, and MEG to help determine language dominance; fMRI or Wada for memory evaluation; diffusion tensor imaging (DTI) for reduction of visual field deficits (contralateral superior quadrantanopia) to localize Meyer's loop and fMRI and DTI to reduce risk of postoperative motor deficit. Language dominance in clear cases is highly reliable with fMRI, but in cases of atypical dominance or severe developmental delay a more invasive Wada test can be useful for lateralization of language. Lateralization of memory deficits can be performed with various memory tests to help localize a memory deficit to the EZ as corroborated by clinical, EEG, and imaging studies.<sup>21,22</sup>

Phase 2 investigations should only be performed if noninvasive data do not enable clinicians to proceed to surgery with confidence.

## Phase 2: Invasive

Phase 2 investigations involves invasive intracranial electrodes, which include placement of subdural grids or strips, stereotactic EEG (sEEG) intracerebral electrodes, and/or foramen ovale electrodes.<sup>22</sup> These are most common in patients with simple or complex partial seizures (with or without secondary generalization), without structural lesion(s) on imaging, bilateral ictal and interictal activity, discordant data between seizures, EEG and imaging, and EZ localization near or involving eloquent areas.<sup>21,22,23</sup>



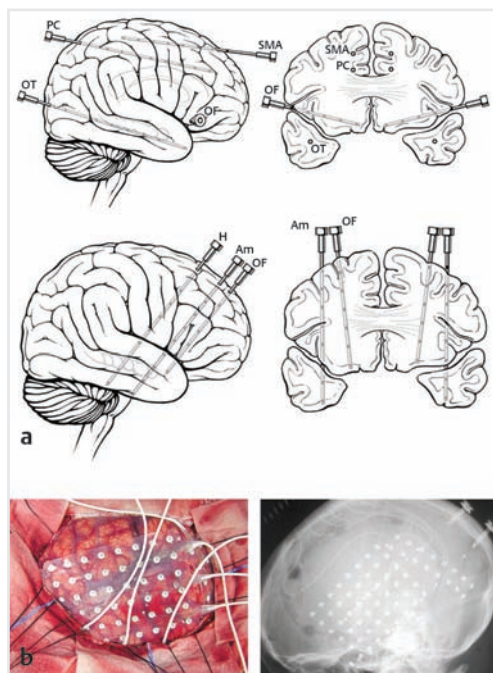
Foramen ovale electrodes are placed under fluoroscopic imaging by percutaneous placement of electrodes through the foramen ovale medial to the temporal lobes intradurally, and are useful to help clarify the side of mesial temporal EZ in cases of equivocal EEG findings (e.g., intracranial electrodes can be both in the form of subdural grids and strips with 4–64 contacts per strip or grid).<sup>22</sup>

Subdural grids and strips electrodes are placed subdurally by means of a craniotomy usually regarding broad exposure for visualization, mapping, and placement of electrodes over the convexity, under the brain or in an interhemispheric location (► Fig. 15.5).<sup>22,23</sup>

Depth electrodes are tubular electrodes with multiple contacts placed with stereotactic techniques into cortical and

subcortical locations. Depth electrodes are less prone to artifacts and enjoy higher spatial resolution with high specificity for ictal onsets. Ictal data are the gold standard for EZ localization, and in addition, the use of high-frequency oscillations, known as ripples and fast ripples, is now used to help further localize the EZ as they are found in higher rates (► Fig. 15.6).<sup>22,23</sup> Major possible complications for such invasive investigations include hemorrhage and infection that can be minimized by careful planning with preoperative imaging to avoid major vessels during electrode passage and with cerebrospinal fluid (CSF) tight closures when tunneling electrodes.<sup>23</sup>

Electric currents can be applied through intracranial electrodes to perform brain mapping of eloquent motor and

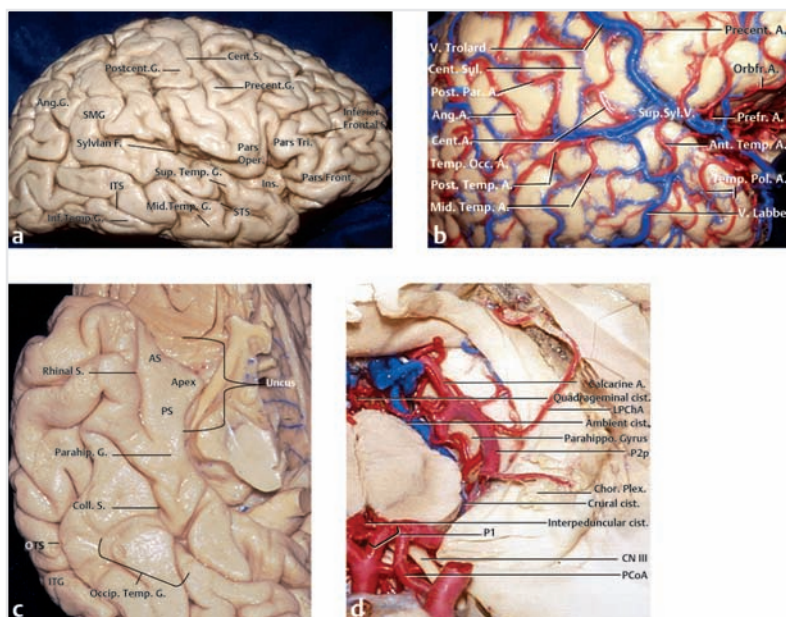


**Fig. 15.5** Commonly used intracranial electrodes.

**(a)** Depth electrodes at various common trajectories.

**(b)** Subdural grids and stripes electrodes with intraoperative and radiographic views. H, hippocampal; Am, amygdala; OF, orbitofrontal; OT, amygdalohippocampal; PC, cingulate; FSMA, supplementary sensorimotor area. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>23</sup>





**Fig. 15.6** Temporal lobe anatomy. (a) Lateral view of the cortical surface with superior temporal gyrus, middle temporal gyrus, inferior temporal gyrus of temporal lobe noted. (b) Lateral view of cortical vessels with special note of the sylvian vessels and posterior lateral course of vein of Labbe. (c) Inferior view of temporal lobe and cross-section of midbrain with parahippocampal gyrus, fusiform (occipitotemporal) gyrus, ITG, uncus, optic nerve and cerebral peduncle noted. (d) Inferior view of temporal lobe and cross-section of midbrain with main vasculature and cisterns noted including interpeduncular, crural, ambient, and quadrigeminal cisterns, and posterior cerebral artery and cranial nerve III. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>24</sup>

speech areas with excellent spatial resolution. Electrocorticography (ECoG) can be performed intraoperatively with concurrent EZ resection, extraoperatively during long-term intracranial electrode monitoring, or during second craniotomy at removal of intracranial electrodes and EZ resection.<sup>21,22,23</sup>

## 15.2.2 Epilepsy Surgery

### Temporal Lobe Epilepsy

Mesial temporal lobe epilepsy (MTLE) is the most common focal epilepsy syndrome with seizure-free rates as high as 70% following surgical resection.<sup>25,26,27</sup>

Patients who have undergone a careful preoperative evaluation and deemed good surgical candidates for remediable syndrome of MTLE undergo an anterior temporal lobectomy (ATL). The most common scale for seizure control/reduction is the Engel Outcome Classification (► Table 15.3). A landmark RCT demonstrated 64 versus 8% Engel I outcomes in patients with MTLE undergoing ATL versus medical management, respectively. Subsequent meta-analyses further support an Engel class I outcomes of approximately 70% for ATL in MTLE.<sup>25,26,27</sup>

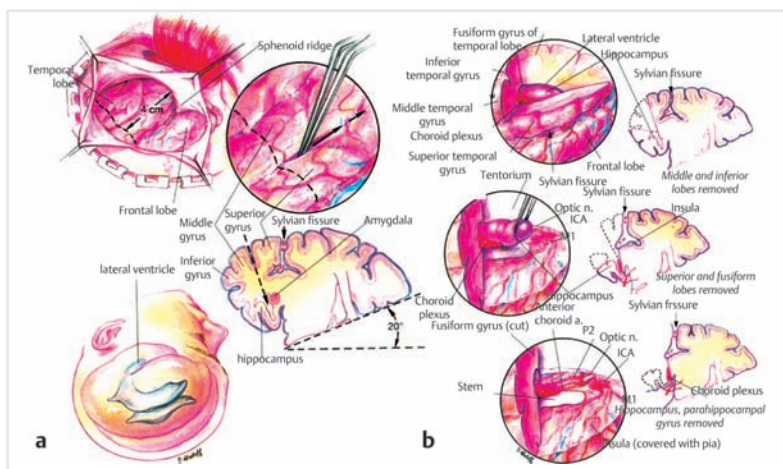
Anterior temporal lobectomy can be performed with various approaches including but generally involve en bloc resections of the lateral neocortical and mesial structures in two parts (► Fig. 15.7).<sup>25,26,27</sup> Patient is placed supine to undergo a temporal craniotomy with or without use of ECoG. A question mark incision from the root of zygoma and 1.5 cm anterior to tragus is made and carried to the superior temporal line with care to preserve the superficial temporal artery (STA) if possible. Two burr holes are made at the upper and lower end of the incision and craniotomy is carried out. Afterwards, the sphenoid ridge and inferior aspect of craniotomy are trimmed with rongeurs to further expose the temporal pole and floor of middle fossa, respectively. Dura is opened in C fashion and retracted anteriorly to expose the sylvian fissure, superior temporal gyrus (STG), middle temporal gyrus (MTG), inferior frontal gyrus (IFG), and the vein of Labbe. Resection

proceeds with removal of the neocortical portion followed by the mesial structures, with resection of 4 or 6 cm from anterior tip of the temporal lobe of neocortex in dominant or nondominant cases, respectively, without significant impact on memory, cognitive function, or language.<sup>25,26,27</sup>

Spencer et al developed a more conservative technique to minimize lateral resection and maximize mesial resection, in which most of the STG is spared with only 3 to 3.5 cm removed from MTG, ITG, most of the amygdala, and 3 to 4 cm of hippocampus and parahippocampal gyrus (PHG).<sup>27</sup> The surgeon performs careful cautery of MTG and dissection to the floor of the middle fossa, traversing the MTG and ITG around the basal surface to include the fusiform gyrus, and directed medially toward the collateral sulcus approximately 2 to 3 cm deep toward the temporal horn. After removal of neocortical structures, attention to the mesial structures can proceed with removal of the PHG, hippocampus, and amygdala by first identifying the ventricle which is usually 3 to 4 cm posterior to the temporal pole and 3.5 cm deep to surface of MTG. The hippocampus comprises the inferomedial wall of the temporal horn of the lateral ventricle; choroidal fissure is the superomedial boundary; and the amygdala is the superomedial cap of the ventricle. Once the ventricle is entered, CSF or choroid plexus is noted and the hippocampal surface identified inferiorly; the cleft between amygdala and hippocampus is noted anteriorly, and medial procession is used to identify the mesial temporal lobe arachnoid membrane as our medial-most boundary, which should never be violated. Deep to arachnoid membrane lie the ambient cistern and key structures including anterior choroidal artery (AchA), posterior cerebral artery (PCA) (posteriorly around midbrain), CN III (anteriorly), and CN IV (along and below the edge of the tentorial incisura). PHG and hippocampus are

**Table 15.3** Engel outcome classification

| Class | Description                     |
|-------|---------------------------------|
| I     | Seizure free                    |
| II    | Rare disabling seizures (< 2/y) |
| III   | Worthwhile and variable         |
| IV    | No worthwhile change            |



**Fig. 15.7** Anterior temporal lobectomy. (a) Open dura with initial neocortical resection deep to ventricle, and (b) deeper resection at inferior and mesial components of temporal lobe leaving the medial most arachnoid intact with visualization of CN III, cerebral peduncle, and PCA. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>25</sup>

removed with care not to penetrate the medial arachnoid membrane and carried 2 cm back from the head of the hippocampus and a hippocampectomy is carried posteriorly to the point where the hippocampus starts to curve medially and superiorly at approximately at the level of the quadrigeminal plate. Finally, the amygdala is resected ensuring the superior limit of the resection (line between choroidal point and limen insula). A selective amygdalohippocampectomy can be employed in cases of clearly defined unilateral mesial temporal EZ, thus limiting the lateral neocortical resection. No RCT has compared selective amygdalohippocampectomy to ATL, with scattered, yet inconsistent evidence regarding better outcomes with selective amygdalohippocampectomy on some neuropsychological measures.<sup>25,26,27</sup>

Complications are rare, with mortality at zero in modern reports; permanent hemiparesis less than 1% secondary to damage to middle cerebral artery (MCA), posterior communicating artery (Pcomm), or AchA; and cranial nerve deficits less than 1% with CN III more common than CN IV or CN VII.

Contralateral superior quadrantanopia is the most common deficit and usually subclinical secondary to disruption of Meyer's loop coursing over the temporal horn of the lateral ventricle.

A more severe homonymous hemianopsia can occur with damage to the lateral geniculate nucleus and/or optic tract. Aseptic meningitis can present with

headache, nausea, lethargy, fevers, and neck stiffness at approximately 3 to 7 days postoperatively. Psychiatric disturbances occur in up to 20% of patients including depression. Neuropsychological changes can include decrements in verbal and nonverbal short-term memory as high as 25 to 30% with higher rates in dominant resections. Transient postoperative dysnomia as high as 25% in dominant cases and fewer than 1% severe persistent dysphasia. Patients can be noted to have improvements in cognitive function likely secondary to seizure control. Seizures at more than 48 hours postoperatively with adequate AED levels are a poor prognostic factor in terms of long-term seizure control.<sup>25,26,27</sup>

Radiosurgery can play a role in management of temporal lobe epilepsy, with a recent RCT on patients with MTLE noting that 77% of patients were seizure free at 12 months. It is still associated with visual field deficits, memory deficits, and headaches in 70% of patients and most significant severe edema in 3% of patients requiring a temporal lobectomy.<sup>21</sup> Stereotactic laser ablation is another nonresective option for epilepsy with seizure-free rates up to 60 to 67% in MTLE.<sup>28</sup>

### Extratemporal Lobe

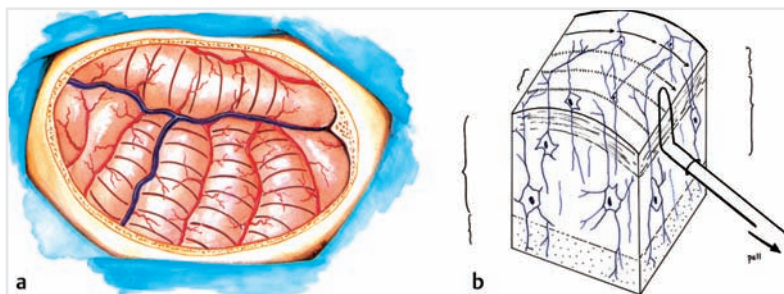
Extratemporal lobe epilepsy includes a heterogeneous group of conditions and symptomatology that can coexist with mesial temporal sclerosis, and often involve eloquent areas with unacceptable postoperative deficits if resected. Extratemporal surgery represents fewer than 50% of all epilepsy surgeries but include hemispherectomies, lobectomies, cortical resection, or palliative options such as corpus callosotomy, multiple subpial transections, DBS, and vagus nerve stimulation.<sup>29, 30</sup>

Cortical resections can be curative with the frontal lobe being the most common location. Complete lobectomies or more

limited cortical resections in any lobe can be very successful especially if a lesion can be defined and implicated in the EZ (i.e., low-grade tumor, focal cortical dysplasia, post-stroke, posttrauma). Care should be taken in frontal resections with respect to location of motor cortex and language cortex during dominant resections. Similarly, during parietal resections, care should be taken when approaching either sensory or language cortex in dominant resections.<sup>29, 30</sup>

Multiple subpial transection is a technique used to treat EZ located in eloquent cortex (e.g., most commonly for pre- and postcentral gyrus, Wernicke' and Broca's), with Engel I to III outcomes of up to 80%, and recent meta-analysis greater than 95% seizure reduction in 71% of patients.<sup>31</sup> This technique is based on the idea that the functional unit in the cortex is a vertically oriented column such that disruption of the horizontal fibers does not eliminate function but will control conduction of epileptic discharges, thus decreasing synchronized cell discharge necessary for an epileptic spike.<sup>30</sup> The surgeon uses a small transector to make cuts perpendicular to the pial surface 5 mm apart and 4 mm deep just above white matter, leaving the vertical column intact, preserving function, and reducing discharge conduction horizontally (► Fig. 15.8).<sup>30,31</sup>

Hemispherectomy is the procedure of choice in unilateral, diffuse hemispheric epileptic syndromes or catastrophic infantile epilepsy, for example, Rasmussen's encephalitis, trauma, meningoencephalitic processes, Sturge-Webber syndrome, hemimegalencephaly, perinatal infarct, MCA/internal carotid artery (ICA) occlusion ischemic insults.<sup>32,33,34</sup> Anatomical hemispherectomy was first introduced in the early 20th century with various flavors including complete removal of a hemisphere including full hemisphere, or partial resection leaving the caudate and thalamus behind, or cortical resection with preservation of underlying white matter. Functional



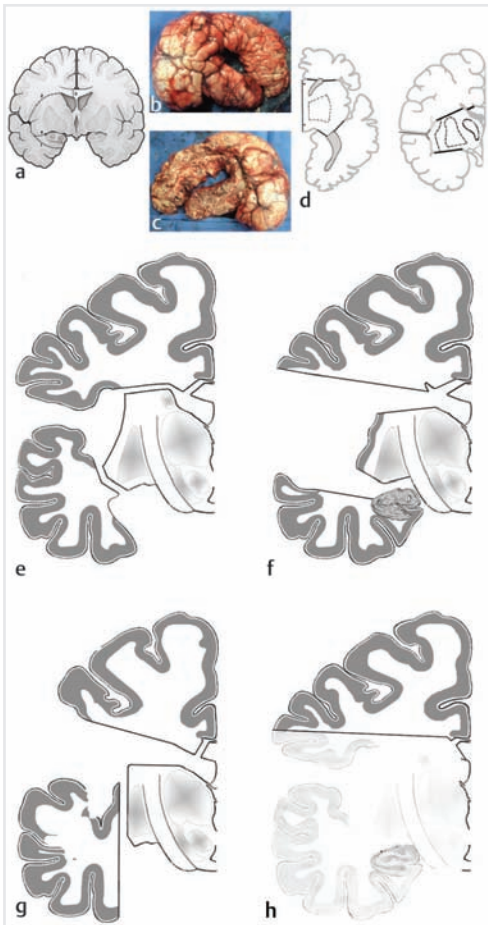
**Fig. 15.8** Multiple subpial transection. (a) Cortical appearance following transections 5 mm apart and (b) subpial transection during disruption of horizontal fibers at 5mm intervals and 4 mm deep. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>30,31</sup>

hemispherectomy (or hemispherotomy) was introduced in the late 20th century as a disconnective technique to decrease the risk of delayed hydrocephalus and superficial cerebral hemosiderosis compared to traditional, anatomical hemispherectomy (► Fig. 15.9). Reported Engel class I ranges from 74 to 90% in disconnective surgeries compared to traditional hemispherectomy with rates of 52 to 78%, but is highly dependent on pathology (e.g., Engel I in 81% of postischemic etiology versus 40% in hemimegalencephaly).<sup>32,34</sup> Only patients with congenital hemiplegia and no useful finger or toe movement should be considered for hemispherectomy; in these cases, no new neurologic deficit would be expected from surgery.

DBS for epilepsy surgery includes bilateral anterior thalamic nucleus (up to 60% seizure rate reduction in patients with partial or secondarily generalized epilepsy), centromedian thalamic (Lennox-Gastaut syndrome with accruing data), and STN stimulation with studies providing preliminary data suggesting decreases in seizure rate.<sup>29</sup> All forms of generalized seizures (e.g., tonic and tonic-clonic generalized seizures) and clinical syndromes like Rasmussen's encephalitis and Lennox-Gastaut have noted positive response rates.<sup>35,36</sup>

Corpus callosotomy is particularly useful for treatment of secondarily generalized seizures and drop attacks, with 80 to 100% reduction in drop attacks.

The length of callosotomy is usually the anterior two-thirds as a first-stage procedure, and in cases of failed anterior callosotomies patients can undergo a complete callosotomy of the posterior one-third.<sup>36</sup> The brain is exposed at the midline and an interhemispheric dissection performed with initial identification of callosomarginal arteries at the level of the cingulum, followed by careful dissection to identify the surface of the corpus callosum and paired pericallosal arteries. Following careful identification of these key structures, the corpus callosum can be sectioned in the anterior-posterior direction, down to the cleft between the leaves of the septum pellucidum, thus avoiding entry into the lateral ventricles (► Fig. 15.10).<sup>35,36</sup> An interhemispheric sensory disconnection can occur with posterior or complete callosotomy, which leads to inability of the dominant hemisphere to recognize



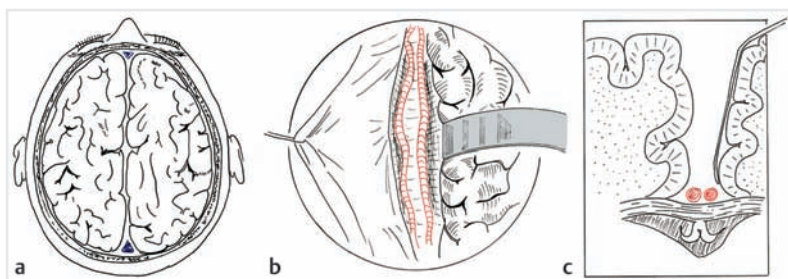
**Fig. 15.9** Hemispherectomy techniques. (a) Cortical appearance following transections 5 mm apart and 4 mm deep. (b–d) Axial and coronal schematic for a transylvian transventricular technique. Four different functional hemispherectomy techniques including (e) the transylvian transventricular approach, (f) peri-insular window, (g) combined peri-insular and temporomesial resection, and (h) modified lateral hemispherectomy with temporal lobe, insular, and basal ganglia resection. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>33,34</sup>

Two possible syndromes can occur after a corpus callosotomy which include a decrease in spontaneous speech and associated varying degrees of paresis of the contralateral side similar in nature to a supplementary motor area syndrome, which is noted to resolve within days to weeks.

tactile or visual inputs originally presented to the nondominant hemisphere.<sup>35,36</sup>

Vagus nerve stimulation (VNS) is FDA indicated as an adjunct for intractable epilepsy in patients older than 12 years with partial seizures but is used off-label for cases of generalized seizures in younger patients and is an important adjunct for intractable epilepsy.<sup>37,38</sup>





**Fig. 15.10** Corpus callosotomy. (a) View of operative site at vertex of field with (b) corpus callosum exposed following interhemispheric dissection and (c) coronal view with paired pericallosal vessels superior to body of corpus callosum. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>36</sup>

The vagus nerve has greater than 80% afferent visceral fibers with a vast number of cortical, subcortical, deep nuclei, and brainstem projections involved in epileptogenesis. Although the exact mechanism is not understood, VNS uses electrical stimulation at the left vagus nerve that is transmitted rostrally throughout the CNS, leading to positive effects in seizure rate reduction.

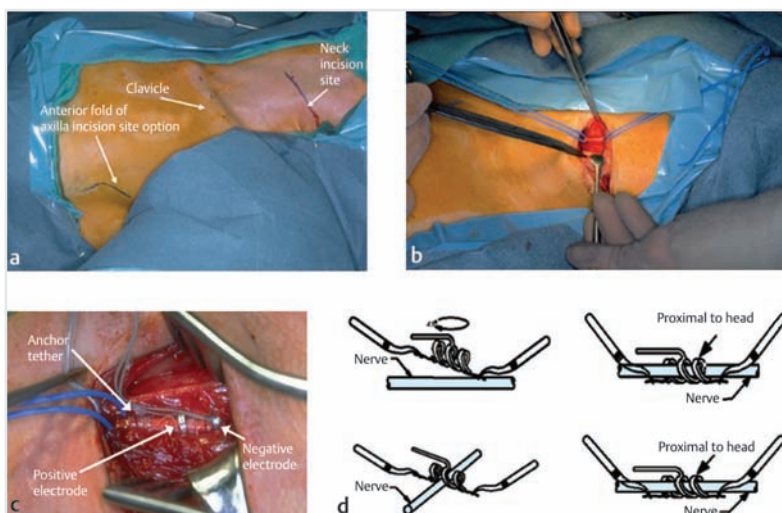
Studies show that many patients will have seizure frequency reductions of 50% in about 50% of patients.<sup>37</sup>

VNS placement is not first-line treatment, and is reserved for patients who failed multiple treatments, EZ in eloquent cortex, and/or failed prior epilepsy surgery with no restrictions on seizure type (e.g.,

comparable efficacy in generalized and partial seizures).

Vagus nerve is approached on the left side and located in the carotid sheath between the carotid and jugular vein below the carotid bifurcation, and is exposed over a distance of 3 cm. Helical electrodes are placed around the vagus nerve and are connected to an infraclavicular or axillary pulse generator in a fashion similar to DBS (► Fig. 15.11).<sup>37,38</sup>

Adverse events with use of VNS are usually transient with patients experiencing voice alteration (20–30%), cough (6%), or paresthesias (10%), which diminish over time. Surgical complications are rare including infection requiring removal of system (1%), vocal cord injury (< 1%), and lower facial weakness (1%), with the most common reason for repeat surgery being replacement of a depleted pulse generator.<sup>38</sup>



**Fig. 15.11** Vagus nerve stimulation. (a–c) Typical positioning and anatomical landmarks noted with neck and axillary markings. (d) Technique for placement of helical electrodes around vagus nerve. (Reproduced from Starr P, Barbaro N, Larson P, Functional Neurosurgery, 2nd edition, ©2008, Thieme Publishers, New York.)<sup>38</sup>

## Pearls

- Common DBS Targets:
  - PD: STN, GPi
  - Essential Tremor: VIM
  - Dystonia Target: GPi
- Engel Outcome Classification: class I, seizure free; class II, rare disabling seizures (> 2/yr); class III, worthwhile and variable; class IV, no worthwhile change.
- Mesial temporal lobe epilepsy with Engel class I outcomes of approximately 70% following anterior temporal lobectomy.
- Extratemporal lobe epilepsy can be treated via multiple approaches including:
  - Cortical resections (can be curative).
  - Multiple subpial transections (Engel I to III outcomes up to 80%).

- Hemispherectomy (Engel I outcomes up to 74–90%).
- Corpus callosotomy (80–100% reduction in drop attacks).
- Vagus nerve stimulation (seizure frequency reductions of 50% in about 50% of patients).

## 15.3 Top Hits

### 15.3.1 Questions

1. What are the main targets for PD, essential tremor and dystonia?
  - a) PD: VIM, ET: VIM, Dystonia: GPi.
  - b) PD: GPi, ET: GPi, Dystonia: STN.
  - c) PD: GPi/STN, ET: VIM, Dystonia: GPi.
  - d) PD: STN, ET: VIM, Dystonia: STN.



2. What are the stereotactic coordinates for STN, GPi, and VIM?
3. What are the cardinal motor symptoms of PD?
  - a) Resting tremor, bradykinesia, shuffled gait, rigidity.
  - b) Masked facies, on/off fluctuations, bradykinesia.
  - c) Rigidity, bradykinesia, on/off fluctuations.
  - d) Action tremor, rigidity, on/off fluctuations.
4. What is the main difference between STN and GPi-DBS in PD?
  - a) STN has improved outcomes in cardinal motor symptoms over GPi.
  - b) GPi has improved reduction in on/off fluctuations compared to STN.
  - c) They are both equivalent in every outcome measure.
  - d) STN noted greater reduction in medication requirements and more cognitive and behavioral side effects over GPi.
5. Dystonia can be classified as which of the following:
  - a) Location of body affected (generalized, focal, multifocal, segmental, hemidystonia), etiology (primary or idiopathic, secondary or symptomatic), or age of onset (early < 26 years or late > 26 years).
  - b) Location of body affected (generalized, focal, multifocal, segmental, hemidystonia), etiology (primary or idiopathic, secondary or symptomatic), or age of onset (early < 9 years or late > 9 years).
  - c) Tremor type (resting, postural, kinetic), etiology (primary or idiopathic, secondary or symptomatic), or age of onset (early < 26 years or late > 26 years).
  - d) Location of body affected (generalized, focal, multifocal, segmental, hemidystonia), etiology (primary or idiopathic, secondary or symptomatic), or age of onset (early < 26 years or late > 26 years).
6. Which of the following is first-line treatment for ET:
  - a) Benzodiazepines, botulinum toxin A.
  - b) Alcohol, primidone, benzodiazepines.
  - c) Propranolol, primidone.
  - d) Primidone, botulinum toxin A.
7. What are the main components of phase 1 investigations?
  - a) Seizure semiology, imaging studies, EEG, neuropsychological assessment.
  - b) Seizure semiology, intracranial electrodes, fMRI.
  - c) EEG, imaging studies.
  - d) Seizure semiology, EEG, intracranial electrodes, functional studies.
8. Phase 2 investigations include which of the following?
  - a) Subdural grids and strips electrodes, sEEG intracerebral electrodes, foramen ovale electrodes.
  - b) Neuropsychological assessments, Wada, MEG, fMRI.
  - c) Scalp EEG, Wada, fMRI, MEG.
  - d) Seizures semiology, imaging studies, EEG, intracerebral electrodes.
9. What are typical measurements for an anterior temporal lobectomy?
  - a) A 6 and 6 cm from anterior tip of the temporal lobe of neocortex in both dominant and nondominant cases.
  - b) A 6 or 4 cm from anterior tip of the temporal lobe of neocortex in dominant or nondominant cases.
  - c) A 4 or 6 cm from anterior tip of the temporal lobe of neocortex in dominant or nondominant cases, respectively.
  - d) No typical standard is used.

10. Which technique is based on the idea that the functional unit in the cortex is a vertically oriented column such that disruption of the horizontal fibers does not eliminate function but will control conduction of epileptic discharges, thus decreasing synchronized cell discharge necessary for an epileptic?
  - a) Anterior temporal lobectomy.
  - b) Hemispherectomy.
  - c) Vagus nerve stimulation.
  - d) Multiple subpial transection.
11. \_\_\_\_\_ is a disconnective technique that decreases the risk of delayed hydrocephalus and superficial cerebral hemosiderosis compared to \_\_\_\_\_.
  - a) Functional hemispherectomy, anatomical hemispherectomy.
  - b) Anatomical hemispherectomy, functional hemispherectomy.
  - c) Anatomical hemispherectomy, multiple subpial transection.
  - d) Multiple subpial transection, functional hemispherectomy.
2. **See ► Table 15.1.** The stereotactic coordinates for the major movement disorders targets are: STN: 11–13 mm lateral to MCP, 4–5 mm ventral to AC/PC line, and 3–4 mm posterior to the MCP; GPi: 19–21 mm lateral to MCP, 4–5 mm ventral to AC/PC line, and 2–3 mm anterior to MCP; VIM: 11 mm lateral to 3rd ventricular wall, at the level of the AC/PC line, and 5–6 mm anterior to the PC.
3. **a.** The cardinal motor symptoms of PD are resting tremor, bradykinesia, shuffled gait, and rigidity due to imbalances in the basal ganglia direct and indirect pathways including STN and GPi overactivity following net loss of dopaminergic input.
4. **d.** The main difference between STN and GPi DBS for the treatment of PD is that STN is noted to have a greater reduction in medication requirements (>50% at 12 months) but with more cognitive and behavioral side effects, making it the preferred target.
5. **a.** Dystonia can be understood based on several classification schemes to help guide clinicians in their treatment of disease and symptoms management, which include: location of body affected (generalized, focal, multifocal, segmental, hemidystonia); etiology (primary or idiopathic, secondary or symptomatic); or age of onset (early > 26 years or late > 26 years).

## Answers

1. **c.** The main targets for the major movement disorders are as follows: PD targets both the STN and GPi likely due to overactivity following net loss of dopaminergic input. Essential tremor targets VIM likely due to mediation by a neuronal loop involving the cerebello-thalamocortical fibers with tremors cells in the VIM. Dystonia targets the GPi likely due to complex mechanisms involving loss of motor inhibitory function leading to excessive contraction of agonist and antagonist muscles, abnormal somatosensory input, motor cortex overexcitability and loss of intracortical inhibition with imbalance of direct and indirect pathways in the basal ganglia.
2. **See ► Table 15.1.** The stereotactic coordinates for the major movement disorders targets are: STN: 11–13 mm lateral to MCP, 4–5 mm ventral to AC/PC line, and 3–4 mm posterior to the MCP; GPi: 19–21 mm lateral to MCP, 4–5 mm ventral to AC/PC line, and 2–3 mm anterior to MCP; VIM: 11 mm lateral to 3rd ventricular wall, at the level of the AC/PC line, and 5–6 mm anterior to the PC.
3. **a.** The cardinal motor symptoms of PD are resting tremor, bradykinesia, shuffled gait, and rigidity due to imbalances in the basal ganglia direct and indirect pathways including STN and GPi overactivity following net loss of dopaminergic input.
4. **d.** The main difference between STN and GPi DBS for the treatment of PD is that STN is noted to have a greater reduction in medication requirements (>50% at 12 months) but with more cognitive and behavioral side effects, making it the preferred target.
5. **a.** Dystonia can be understood based on several classification schemes to help guide clinicians in their treatment of disease and symptoms management, which include: location of body affected (generalized, focal, multifocal, segmental, hemidystonia); etiology (primary or idiopathic, secondary or symptomatic); or age of onset (early > 26 years or late > 26 years).
6. **c.** First line treatments alone or in combination for Essential Tremor include  $\beta$ -blockers like propranolol and anticonvulsants like primidone with class I evidence noting tremor reduction up to 60% in 50% of patients.
7. **a.** The main components of phase 1, or noninvasive investigations in the work up of epilepsy include seizure semiology, imaging studies (e.g., MRI, PET, SPECT), EEG (video), and neuropsychological assessment (memory tests,

language evaluation including fMRI, Wada test, and/or MEG). These tools are geared to help clinicians both better localize the epileptogenic zone and assess the risk of postoperative deficits in planning for epilepsy surgery.

8. **a.** Phase 2 investigations should only be performed if noninvasive studies do not enable the clinician to proceed to surgery with confidence, and they include: subdural grids and strips electrodes, sEEG intracerebral electrodes, foramen ovale electrodes. Phase 2 investigations are most in patients with simple or complex partial seizures (with or without secondary generalization), without structural lesion(s) on imaging, bilateral ictal and interictal activity, discordant data between seizures, EEG and imaging, and EZ localization near or involving eloquent areas.
9. **c.** Typical measurements for an anterior temporal lobectomy are: a 4 or 6 cm from anterior tip of the temporal lobe of neocortex in dominant or non-dominant cases respectively, with resection of neocortical portion followed by mesial structures without significant impact on memory, cognitive function, or language. A more conservative technique developed by Spencer et al minimizes lateral resection and maximizes mesial resection, with sparing most of the STG, removal of 3 to 3.5 cm of the MTG, ITG, most of the amygdala, and 3 to 4 cm of the hippocampus and parahippocampal gyrus.
10. **d.** Multiple subpial transections are most commonly used to treat EZ located in eloquent cortex with Engel I to III outcomes of up to 80%. This technique is based on the idea that the functional unit in the cortex is a vertically oriented column such that disruption of the horizontal fibers does not eliminate function but will

control conduction of epileptic discharges, thus decreasing synchronized cell discharge necessary for an epileptic spike.

11. **a.** Functional hemispherectomy (or hemispherotomy) is a disconnective technique introduced in the late 20th century decreasing the risks associated with anatomical hemispherectomies, including delayed hydrocephalus and superficial cerebral hemosiderosis. Outcomes for functional hemispherectomy are highly dependent on pathology with Engel class I outcomes in 81% of patients with a postischemic etiology compared to 40% in patients with hemimegalencephaly.

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# 16 Stereotactic Radiosurgery

Rachel Jacobs, Daniel Tonetti, L Dade Lunsford

## 16.1 Introduction

The use of ionizing radiation in the treatment of malignancy is well established across medical specialties. In the field of neurologic surgery, external beam radiation therapy (XRT) has broad application in treating vascular abnormalities and neoplasms. Dr. Lars Leksell developed radiosurgery with the use of a stereotactic frame at the Karolinska Institute in Stockholm, Sweden (► Fig. 16.1). The initial North American Gamma Knife Surgery instrument experience of 207 patients from the University of Pittsburgh was published in 1990, demonstrating that the treatment of brain tumors and arteriovenous malformations (AVMs) was associated with no patient mortality and very little morbidity within the first 6 months after surgery.<sup>1</sup> Furthermore, the average length of hospital stay and hospital charges were both significantly lower for Gamma Knife than the average length of hospital stay and hospital charges for traditional operative measures (craniotomy).<sup>1</sup> Throughout this chapter, the



**Fig. 16.1** Lars Leksell at the console surrounded by colleagues with the prototype noninvasive Leksell's Gamma Knife. (Reproduced from Lunsford L, Sheehan J, *Intracranial Stereotactic Radiosurgery*, 2nd edition, ©2015, Thieme Publishers, New York.)

achievements associated with the clinical implementation of stereotactic radiosurgery (SRS) will be described.

## 16.2 Radiation Background

Fractionated radiotherapy refers to the daily administration of small radiation doses to a large treatment target. This process of fractioning the total dose increases the killing of tumor cells and lessens damage to healthy tissues by allowing time for repair of damage to DNA.<sup>2</sup> SRS, by contrast, is the delivery of a single or limited number of doses to a small, precisely defined treatment target via an array of nonparallel radiation beams.<sup>2,3</sup> Damage via photons in electromagnetic waves is initiated via the Compton effect in which the initial photon–atom interaction discharges an electron, which then ionizes other atoms and breaks chemical bonds.<sup>4</sup>

The two most critical clinical considerations in the use of radiosurgery are a sharp dose gradient and accurate target positioning.

A margin is included around the target lesion to account for positioning uncertainties.

## 16.3 Types of Radiation

### 16.3.1 Conventional Radiotherapy

Conventional radiotherapy involves delivering radiation in one or two beams without highly conformal treatment techniques,

unlike SRS.<sup>5</sup> This is of particular use in the spine, where most tumors are metastases, and many cases may involve spinal cord impingement or effacement. Conventional radiotherapy is a widely accepted treatment for spinal metastatic disease. The goals of this therapy are effective pain palliation, preservation of neurologic function and ambulation, spinal stability to prevent progression of disease, and improved quality of life.<sup>6</sup>

### 16.3.2 Stereotactic Radiosurgery

SRS and its derivative stereotactic radiotherapy (SRT) are the main focuses of this chapter. SRS refers to the delivery of a single large dose of radiation, while radiotherapy generally refers to fractionated radiation therapy, delivering several small doses of radiation across several treatment sessions. While these strict definitions may be of academic interest, the following practical definition of SRS is utilized: “Stereotactic radiosurgery typically is performed in a single session, using a rigidly attached stereotactic guiding device, other immobilization technology, and/or a stereotactic image-guided system, but can be performed in a limited number of sessions, up to a maximum of five.” Therefore, the

more general term SRS will be used in this review.

## 16.4 Main SRS Modalities

### 16.4.1 Gamma Knife Surgery

Gamma Knife radiosurgery (GKRS) contains 192 to 201 individual cobalt-60 radiation sources in a donut ring array in a heavily shielded assembly (► Fig. 16.2).<sup>8</sup> A stereotactic frame is surgically fixed to the patient's skull, allowing for precise positioning within the source array. While each individual source is not biologically active on its own, the intersection of these sources produces an ablative dose of radiation capable of inactivating or damaging the cells within the target. Volumetrically accurate dose calculation tools allow the clinician to control the specific three-dimensional shape of the ablative area while minimizing the dose of radiation delivered to surrounding tissues (sharp dose gradients). The newest Gamma Knife model is the Icon, a model that contains 192 cobalt-60 sources and does not require a frame for treatment (► Fig. 16.3).



**Fig. 16.2** Gamma Unit 5, installed at Presbyterian University Hospital, began clinical operation on August 14, 1987. (Reproduced from Lunsford L, Sheehan J, Intracranial Stereotactic Radiosurgery, 2nd edition, ©2015, Thieme Publishers, New York.)



**Fig. 16.3** Leksell Gamma Knife® Icon™. (Image is provided courtesy of Elekta, Inc. 2018.)

## Linear Accelerators

The principle underlying a linear accelerator (LINAC) system is similar to that of Gamma Knife; a small volume of tissue receives an ablative dose of radiation as a result of the intersection of multiple X-ray beams.<sup>9</sup> While the Gamma Knife uses multiple cobalt-60 sources emitting gamma rays, LINAC generate X-rays and rotates about the patient's head, delivering high-energy photon beams to a precise location throughout the rotation. Each beam passes through other brain tissues only momentarily. CyberKnife is a mobile LINAC affixed to an image-guided robotic arm. When this device is used, the use of a stereotactic head frame is no longer required. Other versions include the Varian True Beam linear accelerator and the Novalis linear accelerator adapter for various LINACs.

## Proton Beam SRS

Proton beam SRS uses a magnet to accelerate a proton through a magnetic field, targeting the beam to a specific region of interest. The dose distribution affected by proton beam therapy is different from that

of GKRS and LINAC systems. Specifically, the dose slowly increases followed by a rapid dose increase to the Bragg peak, beyond which the dose falls to zero.<sup>10</sup> While the energy is delivered by heavy charged particles, the ability to induce ionization is similar to that of the electromagnetic waves employed in other SRS modalities.

## 16.5 Dosing

Biologically effective dose (BED) is a measure of the true biological effect of any radiotherapy treatment,<sup>11</sup> and is often modeled by the following equation:

$$\text{BED (Gy)} = n \times d \times \left[ 1 + \frac{d}{\alpha/\beta} \right]$$

Where  $n$  = the number of doses,  $d$  = dose per fraction, and the factors  $\alpha$  and  $\beta$  describe the cell response to radiation.<sup>4</sup>

### 16.5.1 Tolerance

Based on early Radiation Therapy Oncology Group (RTOG) guidelines, 24 Gy is recommended for tumors less than or equal to 2 cm, 18 Gy for tumors 2.1 to 3 cm, and 15 Gy for tumors greater than 3 cm in size.<sup>12</sup>

Subsequent experience has found that such doses are not necessary for malignant tumor control, and much smaller doses are used for benign tumors. For the brainstem, typical practice is to limit the lateral brainstem to no more than 12 Gy.<sup>13</sup> For the optic nerves and chiasm, most studies suggest that the maximum point dose should be 8 Gy in a single fraction.<sup>14</sup> Most of the data determining tolerance to the cochlea arises from the vestibular schwannoma literature, and average cochlear doses of 3.5 to 5 Gy can be utilized to improve hearing preservation rates.<sup>15</sup> At our institution, we use 4.2 Gy. Regarding the spinal cord, Sahgal et al documented radiation-induced myelopathy following SRS and found that no more than 12.4 Gy is recommended in a single fraction.<sup>16</sup>

### 16.5.2 Dose Limitations

Special sensory nerves, such as the optic and vestibulocochlear nerves, are the most radiosensitive. This is in contrast to motor nerves including those of the parasellar region and the lower cranial nerves, which are able to tolerate higher doses, though the exact dosage tolerance of cranial nerves is uncertain.<sup>4</sup> The brainstem is also considered radiosensitive because of the critical neural structures and pathways. It is particularly susceptible to edema from SRS treatment in conjunction with its clinical importance. In general, the most critical radiation-sensitive regions include the optic nerve, optic chiasm, the brainstem, pituitary gland, and the cochlea.

### 16.5.3 Compressive Tumors of the Spinal Cord, Brainstem, or Optic Structures

Surgical removal should be emphasized in these situations, especially for benign lesions

in a younger population or those lesions symptomatic due to mass effect, as substantial risk of neurologic injury may result from edema following SRS delivered within a few millimeters of the margins of the isocenter in these regions.<sup>4</sup> Furthermore, the latency interval after SRS may allow for some interval growth before tumor response.

## 16.6 Occupational Exposure

The U.S. Nuclear Regulatory Commission advises taking every reasonable effort to keep the radiation dose as far below the limits as possible, as is consistent with the purpose of the licensed activity, with recommendations to keep exposure less than or equal to 2 rem (roentgen equivalent man)/y averaged over 5 years.<sup>4</sup> Steps to reduce occupational radiation dose during surgery include increasing the distance from the radiation source, shielding, and keeping “boost” mode usage, which can double radiation output, to a minimum. In general, medical personnel are monitored and are not physically present during radiation delivery.

## 16.7 Adverse Reactions

The mechanism by which XRT causes side effects is not confirmed, however, the etiology may include immune system effects, damage to vascular endothelium and resultant breakdown of the blood–brain barrier (BBB), and glial injury.

### 16.7.1 Radiation Vasculopathy

Vascular endothelium and oligodendroglial cells are the most susceptible to radiation necrosis, as radiation is selectively toxic to more rapidly dividing cells.<sup>4</sup> Radiation



vasculopathy can mimic recurrent or new tumor from both clinical and radiological standpoints, and computed tomography (CT) and magnetic resonance imaging (MRI) cannot reliably differentiate some cases of adverse radiation effects (in the most major form leading to tissue necrosis) from tumor, though doing so is important for prognosis and treatment. Multiple authors have attempted to define imaging characteristics that can assist in differentiating tumor progression from radiation effect after SRS. At our institution, we have found the concept of “T1/T2 match,” an association between the low signal-defined lesion margin on T2-weighted images and the contrast-enhanced volume on T1-weighted images, to be particularly useful.<sup>17</sup>

### 16.7.2 Edema

Adverse radiation effects such as increased brain edema may develop after SRS, occurring in 15 to 28% of cases and causing symptoms in 3 to 15%.<sup>18,19</sup> Increased risk for edema following SRS includes a larger tumor volume, location within the hemisphere, and higher prescribed dose.

### 16.7.3 Cyst Formation

Another side effect is cyst formation, defined as a fluid-filled cavity at the site of treatment. In one large series, the incidence of cyst formation in 1,203 consecutive patients with AVMs who underwent Gamma Knife was 1.6%.<sup>20</sup> In the AVM population, a predisposing factor for cyst formation post SRS is history of prior bleeds. Cysts can usually be managed with observation, but may necessitate surgical intervention including drainage, cyst shunting, or fenestration. An even rarer complication than cyst formation is the complication of a chronic encapsulated expanding hematoma, which can develop many years after Gamma Knife surgery for an AVM patient.<sup>21</sup>

## 16.8 Indications

### 16.8.1 General Considerations

SRS is generally useful for well-circumscribed lesions less than 3 cm in diameter.

Published indications will be discussed below.

The latency period/latency interval is an important consideration for radiosurgery. Unlike surgery, the effect of radiosurgery is not realized immediately. For trigeminal neuralgia (TN), for example, it can take 2 to 3 months for clinical relief.

For AVM, the latency period has been established as 2 to 3 years.

Brain metastases are the most common form of brain tumor. In addition to surgical resection, metastatic tumors can be managed with adjuvant whole-brain radiation, immediate postoperative SRS treatment of the resection cavity, or SRS if tumors recur. It has been shown that postoperative SRS management of unresected metastases provides equivalent survival, but better preservation of cognitive function and quality of life and less toxicity than whole-brain radiation.<sup>22,23,24</sup>

In the setting of a peripheral primary neoplasm with metastases to the brain, SRS has also been combined with systemic chemotherapy. Remote treatment failure with adjuvant SRS and whole-brain radiation remains a problem, suggesting that micrometastases escape treatment. It has been suggested that the addition of systemic chemotherapy may prevent recurrence from these undetectable metastases.<sup>25</sup> The relatively nascent addition of immunologic checkpoint inhibitors and its coincident use with radiosurgery remains to be seen.

## 16.8.2 Vascular Indications

### Arteriovenous Malformations

AVMs are congenital vascular anomalies comprised of abnormally constructed shunts from the high-pressure arterial input system to the low-pressure venous system. Anatomical and flow disturbances lead to increased risk of rupture and intracranial hemorrhage. The patient's age, medical history, prior management, risk factors (particularly for hemorrhage), and AVM characteristics (e.g., volume, morphology, compact vs. diffuse vascular architecture) are considered when deciding to pursue SRS.<sup>26</sup> As discussed above, the effect of radiosurgery is not realized immediately. Based on angiography or MRI criteria, the median time to total obliteration for AVMs after SRS is 30 months, with obliteration rates noted as 58, 87, 90, and 93% at 3, 4, 5, and 10 years, respectively (► Fig. 16.4).<sup>27</sup>

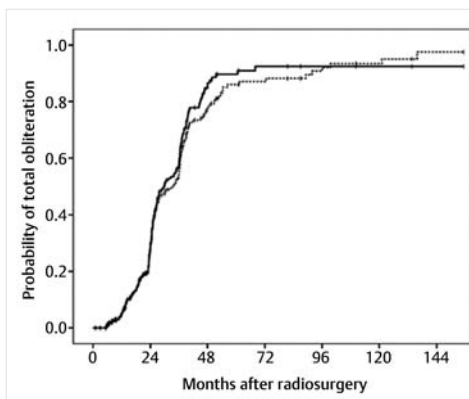
### Cavernous Malformations

Cerebral cavernous malformations (CCMs) are vascular anomalies that are comprised of blood vessels devoid of muscular and elastic

tissue. The role of SRS in the management of CCMs remains controversial due to the varied natural history, the inability to image malformation vessels, and the lack of an imaging technique that defines “cure,” unlike an AVM.<sup>28</sup> There is evidence supporting the use of SRS for high-risk CCMs that bleed in the brainstem, thalamus, basal ganglia, or internal capsule.<sup>29</sup>

### Dural Arteriovenous Fistulas

Dural arteriovenous fistulas (DAVFs) are fistulas within the dura mater where meningeal arteries channel blood straight into the dural sinus and/or other dural and leptomeningeal venous channels. Treatment with SRS is primarily indicated based on morphology and symptomatology. Initial treatment with an endovascular procedure or open surgery is indicated for DAVFs that are considered aggressive in behavior due to their retrograde cortical venous drainage. This is in contrast to those with only antegrade sinus drainage which are clinically regarded as benign, and radiosurgery may be indicated as an initial treatment for those harboring these lesions with benign symptoms.<sup>30</sup>



**Fig. 16.4** Kaplan-Meier curves for total obliteration by MR imaging or angiography after single radiosurgery for small-volume AVMs with corrected time (solid line) and uncorrected time (broken line).<sup>27</sup>

## 16.8.3 Tumors

### Primary Malignant

The properties of gliomas often do not fulfill the common criteria for tumor treatment with SRS as they are not well-circumscribed and are frequently greater than 3 cm in size. Decisions to accept or reject the use of SRS treatment in these cases will be made at the individual clinician level or the individual institutional level based on histological subtype and grade, though most literature does not substantiate the use of SRS for gliomas.<sup>12</sup> In practice, SRS is rarely used in these circumstances and usually as a salvage therapy in the face of progression of a glioma that has failed initial management with radiation and chemotherapy.

### Metastasis



SRS plays a dominant role in the management of brain metastases.

While SRS has been historically reserved for patients with one to four brain metastases, a prospective Japanese Leksell Gamma Knife Society 0901 trial in 2009 showed that patients with 5 to 10 brain metastases had similar outcomes to those with 2 to 4 brain metastases.<sup>31</sup> In practice, SRS is often used to manage patients with oligometastases to the brain.

### Primary Benign

#### Meningiomas

Meningiomas are the most frequent primary brain tumor with an incidence of approximately 7/100,000, and resection is the treatment of choice.<sup>32</sup> SRS is indicated for meningiomas that are unable to be completely resected due to proximity of

integral vascular and neural structures, or those with recurrence after resection.

#### Pituitary Adenomas

Pituitary adenomas comprise 10 to 20% of all intracranial tumors. They are classified by hormonal secretory status and size. SRS offers tumor control for both functioning and nonfunctioning types, however, a higher dose is necessary to achieve remission in functioning pituitary adenomas.<sup>33</sup> The highest remission rates post SRS are accomplished in patients with Cushing's disease, whereas the lowest rates for control are in prolactinomas.<sup>33</sup>

#### Chordomas

Chordomas are locally aggressive tumors of the spine and skull base of mesenchymal derivation that have an extremely high likelihood for recurrence if not resected in total. SRS is used most often for recurrent or residual tumor, with surgical management as the initial treatment of choice. When comparing SRS to conventionally fractionated radiotherapy, SRS has the advantage of increased relative biological effectiveness.<sup>34</sup>

#### Chondrosarcomas

Chondrosarcomas are primarily tumors of bone, though they are of mesenchymal origin, and thus can arise from the dura in rare circumstances. They are difficult to distinguish on imaging from chordomas, which leads to their frequent misdiagnosis.<sup>34</sup> SRS can be considered as an adjuvant option for these tumors after initial surgical removal as SRS appears to provide a high rate of local tumor control.<sup>35</sup>

#### Glomus Tumors

Glomus tumors are benign, highly vascular tumors that arise from paraganglionic

chemoreceptors, particularly of cranial nerves (CNs) IX and X. SRS can be used as a primary or adjunct treatment after surgical resection as it has a modest risk of neurologic complications combined with a high rate of local tumor control.<sup>37</sup>

### Nonvestibular Schwannomas

Nonvestibular schwannomas are similar to vestibular schwannomas in their growth patterns and biological behavior, and can arise from any cranial nerve, though arising from the trigeminal nerve and jugular foramen most frequently. In a study by Pollock et al, of six patients with trigeminal schwannoma treated with SRS, none exhibited tumor growth during a mean follow-up of 21 months, and only one out of five patients with a jugular foramen region schwannoma had an increase in tumor size after radiosurgery.<sup>38</sup> There has been a paradigm shift in the management of these skull base tumors, with SRS becoming the primary method, and surgical resection being reserved for large tumors and those inducing symptoms from mass effect.

### Vestibular Schwannomas

Vestibular schwannoma (VS), also known as acoustic neuroma, is a benign tumor of the cerebellopontine angle derived from Schwann's cells of the eighth cranial nerve. Multiple studies have exhibited the superior safety efficacy of SRS over microsurgery for schwannomas without significant mass effect on the brainstem or hydrocephalus, focusing on the preservation of facial motor and hearing function.<sup>39,40,41</sup> The 3-year rate of hearing preservation post SRS is at 65%, though it varies depending on the quality of the hearing initially, a past history of hearing loss. SRS dose and the interval of elapsed time after diagnosis. The best hearing results are found in

patients with small tumors treated within two years of diagnosis.

### Hemangioblastomas

Hemangioblastomas are rare and highly vascular tumors that often present as manifestations of von Hippel-Lindau disease, although they can also occur sporadically. Though resection is the treatment of choice for symptomatic lesions, SRS has been used as an adjuvant or salvage option for over 25 years. Though the role of SRS here is not as well defined as is surgical resection, in a retrospective multicenter study in 2015, Kano et al found SRS provided tumor control in 79 to 92% of intracranial hemangioblastomas.<sup>42</sup>

### Pain

#### Trigeminal Neuralgia

TN is a severe facial pain in the trigeminal nerve distribution of a paroxysmal nature. Microvascular decompression is the preferred treatment of choice over SRS due to greater duration of pain relief, however, SRS acts as an alternative for those patients not suitable for open neurosurgical procedures. SRS outcomes for TN are measured by pain relief, ability to halt medications, and improved quality of life. Marshall et al found in a cohort that in more than 400 patients, 86% had an initial improvement in pain control within the first 3 months after SRS.<sup>43</sup>

### Functional Disorders

#### Movement Disorders

The treatment of functional movement disorders has shifted away from lesional techniques, such as radiosurgery, to technologies like deep brain stimulation (DBS) due to its reversibility and ability to

modulate effect. Because of the imprecision associated with confirming the physiologic target through anatomical MRI, radiosurgery is generally reserved as an option for patients who decline DBS. Radiosurgical thalamotomy has shown control of tremor, with rates similar to those achieved using other methods.<sup>44</sup>

## Psychiatric Disorders

Neurosurgical interventions for treatment refractory obsessive-compulsive disorder (OCD) date back to the 1950s, with lesioning primarily designed to disrupt frontal-striatal-thalamic circuitry that is thought to be overactive in patients with severe OCD. Twenty-seven patients described in the literature had undergone radiosurgery for OCD, 20 (74%) of which had a 25% reduction in Yale-Brown Obsessive-Compulsive Scale score.<sup>8</sup> Because of the low number of studies that have looked at SRS for medically refractory OCD as well as the not well-understood nature of the neuroanatomy and neurobiology behind OCD, multiple questions remain to be answered.

## Epilepsy

SRS is utilized most frequently for epilepsy when it is one of several presenting symptoms secondary to a tumor or vascular malformation. In practice, SRS is generally reserved for the treatment of mesial temporal lobe epilepsy (the most frequent cause of treatment refractory epilepsy in adults) only in patients unable to tolerate a surgery or inoperable epileptic lesions like hypothalamic hamartomas, with differences in outcomes attributed to dosage and patient selection. Encouraging results came from a 2004 European prospective multicenter trial, demonstrating a 2-year postoperative seizure remission rate of 62%.<sup>45</sup>

## 16.8.4 Ocular Disorders

Uveal melanoma is the most common indication for treatment of ocular disorders with radiosurgery as the eye can often be preserved. Challenges of SRS for this specific use include movement of the eye during the treatment procedure and limitations in the radiosurgery coordinate system for this unusual target location, although the former can be relatively controlled with proper eye fixation. In a group of 35 patients, Toktas et al found that the 3-year local control rate for uveal melanoma was 83%, with retinal detachment as the most prevalent complication.<sup>46</sup> Though SRS for ocular tumors acts as a legitimate treatment option, further clinical studies are warranted.

## 16.8.5 Pediatric Tumor Indications

The literature for the use of SRS in the pediatric population is comprised of exclusively single-institution experiences. SRS use is complicated by incomplete characterization of normal tissue toxicities related to central radiation exposure.

## Ependymomas

Ependymomas, arising from ependymal cells lining the cerebral ventricles, account for 5 to 10% of all pediatric brain tumors.<sup>47</sup> They are well suited for SRS due to their well-delineated nature from the surrounding brain parenchyma, however, prognosis primarily depends on the extent of surgical resection prior to SRS.

## Low-Grade Astrocytomas

World Health Organization (WHO) grade I and II astrocytomas are both known as low-grade astrocytomas. Maximal surgical resection is the primary technique of

treatment, although complicated by the diffuse nature of these tumors. Because of this characteristic, low-grade astrocytomas are not ideal targets for SRS, as substantial normal brain tissue would be affected while trying to encompass the entirety of known disease, limiting both the safety and efficacy.<sup>51</sup>

### High-Grade Gliomas

High-grade gliomas comprise 15% of primary brain tumors in children and, like high-grade gliomas in the adult population, usually carry a discouraging prognosis. Data regarding the use of SRS for high-grade gliomas in the pediatric population are limited and unfavorable. In Hodgson et al, 18 patients with grade III or IV astrocytomas received SRS, 4 of which survived after 50 to 119 months.<sup>48</sup> In a similar study at the University of Pittsburgh, 7 out of 12 children treated with SRS had a median survival of 6 months.<sup>49</sup>

### Medulloblastomas

Medulloblastomas are small-cell embryonal tumors of the cerebellum and the most common pediatric brain malignancy, comprising 15 to 20% of all childhood primary brain tumors.<sup>50</sup> SRS is primarily indicated here as a boost after XRT or salvage after recurrence, providing reasonable local control for recurrence, though insufficient data are available to suggest this treatment as routine practice.<sup>51</sup>

### Meningiomas

In adults, SRS has become one of the mainstays for treatment of meningiomas, however, data for the pediatric population are limited. Meningiomas are rare in children without neurofibromatosis type 2 (NF2), and gross total resection remains the treatment of choice when feasible.

### Vestibular Schwannomas

Though vestibular schwannomas usually occur in adults, bilateral acoustic neuromas are often seen in children with NF2. VS make for ideal targets for SRS due to their delineation from the surrounding normal brain parenchyma, though the data in the pediatric population are still scarce. Compared with sporadic VS,<sup>8</sup> Preservation of serviceable hearing is of utmost importance in the pediatric population, as deficits in early childhood can result in speech and learning impairment.

### Craniopharyngiomas

Craniopharyngiomas are benign brain tumors, common in children, that arise from epithelium derived from Rathke's pouch and generally involve suprasellar region although some may arise within the third ventricle.<sup>4</sup> They are commonly characterized by having both solid and cystic components. Though maximal surgical resection is the goal for treatment, SRS as a salvage therapy for recurrent tumor has been demonstrated in the literature. Kobayashi et al showed that the 10-year survival rate for a group of 107 patients, 38 of which were under the age of 15, who had craniopharyngiomas treated with Gamma Knife, was 91%.<sup>52</sup>

### Pituitary Adenomas

Pituitary adenomas are relatively rare in children, and though the data on the use of SRS for pituitary adenomas are much more limited in the pediatric population, the available literature is suggestive that the tumor control rates are similar to that of adults. Thorén et al from the Karolinska Institute found that in eight children with Cushing's disease treated with Gamma Knife, seven showed complete endocrine remission.<sup>53</sup>

## Pineal Tumors

Pineal tumors are relatively rare and have a wide variety of histologies, which is a critical factor when determining treatment strategy.<sup>8</sup> In a retrospective study of 147 cases of pineal region tumors treated with Gamma Knife from 1999 to 2009, Li et al reported that the tumor completely disappeared in 57 patients 1 year post SRS.<sup>54</sup> Despite encouraging results from a few studies, it is difficult to draw any substantial conclusions regarding the role of SRS for pineal tumors due to the lack of good outcome data and the varying histologies of the tumor in both pediatric and adult populations. Further, the dosing guidelines for SRS for pineal tumors are not well defined.

## 16.9 Treatment Procedure

### 16.9.1 Basic Overview

The treatment procedure consists of treatment planning/defining the target, preoperative imaging, placement of the stereotactic frame, and execution of treatment.

### 16.9.2 Planning



Treatment planning consists of defining isocenters or "shots" in order to create a dose distribution that treats the target areas while simultaneously minimizing radiation to normal surrounding structures.

In order to shape the dose distribution of irregular targets, one or more beams from the full complement being utilized can be blocked, and each beam can have a different diameter.

## Preoperative Imaging

Preoperative imaging for SRS generally utilizes MRI due to the superiority of its soft tissue and tumor contrast when compared to CT. In practice, the use of CT, with reported accuracy never better than 0.6 mm,<sup>4</sup> is limited to those patients who cannot undergo MRI and in certain cases in conjunction with MRI where bony imaging may be of benefit for radiosurgical planning. For example, the ability to visualize the cochlea on CT may be beneficial for dose calculation prior to treatment. Stereotactic angiography remains the best tool for definition of an AVM nidus and can be fused with an MRI for radiosurgical planning.

### 16.9.3 Preoperative SRS Frame Placement

Frame-based radiosurgery has been considered the standard for radiosurgery treatment from its outset. The frame has a multifaceted role, acting as a localizer for the treatment's isocenter as well as an immobilization device for the patient to remain still during the treatment. Pins are used to tighten the frame, which is then securely fixed to the patient's skull (► Fig. 16.5). A geometric relationship is established utilizing the patient's intracranial anatomy, the geometry of the frame, and the lesion of interest.<sup>55</sup> An external marker (fiducial) is secured to the frame, such as a localizer box (► Fig. 16.6). A CT scan is taken, the positions of the external markers are identified in each slice of the axial CT scan, and a coordinate system is created.<sup>4</sup> Using the Gamma knife ICON device a mask based immobilization system can be used to provide stereotactic work space.



**Fig. 16.5** Stereotactic head frame. (Reproduced from Lund V, Howard D, Wei W, Tumors of the Nose, Sinuses, and Nasopharynx, 1st edition, ©2014, Thieme Publishers, New York.)

## 16.9.4 Procedural Considerations

Procedural considerations mainly involve limiting doses to critical structures and maximizing conformational dose to the desired target.

For example, doses exceeding 12 Gy to the optic nerve and/or optic chiasm have markedly increased toxicity,<sup>56</sup> though other authors cite 8 Gy.<sup>14</sup> Similarly, a central cochlear dose of less than 3.5 Gy during the treatment of VS has been correlated with hearing preservation after stereotactic radiosurgery.<sup>57</sup> Sensory structures such as the optic nerves and cochlea are more easily affected than efferent neurons including motor fibers.



**Fig. 16.6** Fiducial box. (Reproduced from Lunsford L, Sheehan J, Intracranial Stereotactic Radiosurgery, 2nd edition, ©2015, Thieme Publishers, New York.)

## 16.9.5 Perioperative Care

Perioperative care of the patient undergoing radiosurgery is predicated on patient safety while administering appropriate anesthesia during frame placement. At our institution, a combination of intravenous analgesic and amnestic medications is titrated. Typically, a nurse certified in anesthetic administration is responsible for ensuring vital signs remain within normal limits for that patient and that the patient is ultimately both comfortable and safe.



## 16.10 Clinical Outcomes

### 16.10.1 Mortality

Perioperative and immediate postoperative mortality is approximately 0%.

### 16.10.2 Morbidity

#### Immediate

Only a paucity of patients is not discharged home within 24 hours of the procedure, and many centers will not admit patients overnight. Immediate adverse reactions include headaches and nausea/vomiting, which may require analgesics and antiemetics, respectively.

#### Long Term

The chances of long-term morbidity increase with larger doses and treatment volumes, as is the case with traditional XRT.

## 16.11 Radiation-Induced Changes

These changes may appear as low density on a CT or high intensity on a T2-weighted MRI, and are usually seen at a mean of 13 months posttreatment for AVMs with an incidence of 34%.<sup>4</sup> These changes may be attributed to breakdown of the BBB, damage to glial cells, and early venous thrombosis.

## 16.12 Vasculopathy

With an incidence of approximately 5%, radiation-induced vasculopathy can be seen on angiography as narrowing and ischemia on imaging.<sup>4</sup>

## 16.13 Cranial Nerve Deficits

Cranial nerve deficits are most often seen in the setting of parasellar tumors. The rate of new cranial nerve deficit after SRS for cavernous sinus lesions has been reported as approximately 11%.<sup>58</sup> Cranial nerve deficits can also occur with tumors of the cerebellopontine angle or skull base. Taking all procedures for all indications, the overall incidence has been reported as 1%.<sup>4</sup> Optic neuropathy can be reduced to a risk of less than 1% of patients if the optic nerve and chiasm average dose is less than 8–10 Gy.

## 16.14 Radiation-Induced Tumors

Only a few case reports have shown malignant induction of a tumor such as a glioblastoma after AVM radiosurgery or the malignant transformation of a vestibular schwannoma. Radiation related meningiomas developing after SRS has a risk estimated at 0.7% 20 years after treatment for AVM.<sup>59</sup> Our institution has previously reported that in over 14,000 Gamma Knife procedures, not one patient can fit the Cahan requirements for a radiation-induced tumor, which is defined as a histologically confirmed sarcoma in a previously irradiated field with a relatively long, asymptomatic latency period of 5 years.<sup>60</sup>

## 16.15 Future Directions

As recent investigations look at the further development of SRS, it can be advantageous to contemplate these

surfacing opportunities. In 2014, AANS and ASTRO started a prospective SRS registry modeled after the AANS spine surgery registry, with the aim to provide beneficial knowledge regarding patient-reported outcomes, cost-effectiveness, quality assurance, and patient selection.<sup>61,62</sup> It has been speculated that SRS will be combined with molecular agents and nanoparticles to reduce side effects and enhance therapeutic efficacy.<sup>8</sup> In order to enhance therapeutic efficacy while simultaneously allowing for dose escalation, agents could be added that would provide normal brain tissue protection.<sup>63</sup> Along similar lines, gold nanoparticles have been postulated to be used as radiosensitizers.<sup>64</sup> While these speculations have yet to be adopted in clinical practice, exciting work remains ongoing in an effort to optimize patient care and clinical benefit from stereotactic radiosurgery.

### Pearls

- SRS is one tool in a neurosurgeon's skill set that can be used to noninvasively treat a wide range of pathologies spanning the subdisciplines of tumor, vascular, skull base, pediatric, and functional neurosurgery to reduce neurologic morbidity and mortality.
- SRS has been proven safe and effective with long-term data available for the great majority of indications.
- While patient-specific and pathology-specific characteristics dictate care, SRS can play an effective role as part of a comprehensive treatment strategy for a given patient either as the sole treatment or as part of a multimodal treatment plan.

## 16.16 Top Hits

### 16.16.1 Questions

1. Complications from stereotactic radiosurgery include all of the following EXCEPT:
  - a) Cyst formation
  - b) Radiation necrosis
  - c) Hair loss
  - d) Edema
2. Cerebrovascular indications for radiosurgery include all of the following EXCEPT:
  - a) Dural arteriovenous fistula
  - b) Arteriovenous malformation
  - c) Middle cerebral artery (MCA) aneurysm
  - d) Cavernous malformation
3. Which of the following is the upper limit of the radiation dose in a single fraction tolerated by the optic nerve?
  - a) 5 Gy
  - b) 8 Gy
  - c) 15 Gy
  - d) 20 Gy
4. Which of the following latency period is generally accepted after SRS before AVM obliteration?
  - a) 1 to 2 months
  - b) 6 to 12 months
  - c) 2 to 3 years
  - d) 5 to 6 years

### 16.16.2 Answers

1. **c.** Stereotactic radiosurgery alone does not cause significant hair loss or alopecia with extremely rare exception. Cyst formation, radiation necrosis, and radiation-induced edema are all potential adverse effects of radiosurgery.
2. **c.** Though the treatment of cavernous malformations with SRS remains

controversial, intracranial aneurysms are not treated with radiosurgery and is the better answer choice. AVMs and dural AV fistulae are well-described indications for radiosurgery.

3. **b.**

4. **c.** During this latency period prior to obliteration, the AVM continues to function as a shunt and there remains a stable chance of hemorrhage.

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# 17 Neurological Infectious Diseases

Divyansh Agarwal, Harvey Rubin, Ali Naji

## 17.1 Introduction

For centuries, infectious diseases have afflicted humanity, be it in the form of the plague in the mid-1400s, cholera in the 1820s, polio in the early 1900s, or acquired immunodeficiency syndrome (AIDS) in the 1980s. From 1980 through 2014, infectious diseases comprised more than 5% of overall mortality rates in the United States, with a majority of the deaths being due to pneumonia and influenza.<sup>1</sup> In this chapter, we will review the framework for microbiological diagnoses of central nervous system (CNS) infections and consider a few important pathogens including flavivirus, meningococcus, and two common parasites—*Taenia solium* and *Naegleria fowleri*—that cause neuroinfectious disease. These organisms, although by no means exhaustive, provide examples of pathogen-mediated brain infection. We will further review common postsurgical infections, and the microbiological diagnoses of other CNS infections. Lastly, we include a brief section on the interpreting statistics in the medical literature as it relates to infectious diseases because Big Data analytics will be essential for the next generation of medical researchers, and we believe that infectious diseases provide a good avenue for discussing the basics of ongoing computational work in the field.

## 17.2 Microbiological Diagnosis

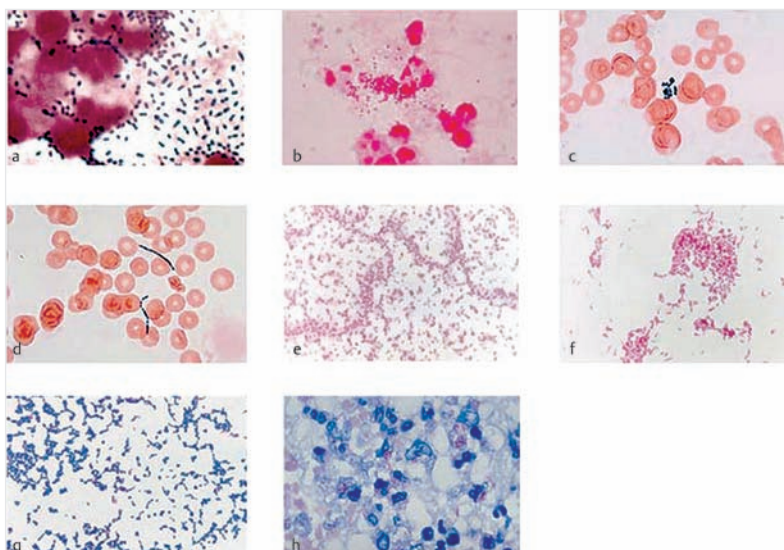
Lumbar puncture (LP) with cerebrospinal fluid (CSF) analysis is essential to diagnose CNS infections (►Fig. 17.1). In adults, the normal CSF opening pressure ranges from 50 to 190 mm H<sub>2</sub>O, and an elevated opening pressure is suggestive of bacterial

meningitis. Typical CSF findings in patients with selected infectious causes of meningitis are shown in ►Table 17.1.<sup>2</sup>

Two important markers acute-phase reactants are commonly used as markers for inflammation—erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP). The ESR corresponds to how much a vertical column of anticoagulated blood falls in 1 hour. If a condition affects red blood cells or fibrinogen levels, the ESR would be affected.<sup>3</sup> The ESR rises within 1 to 2 days of the onset of inflammation and falls back slowly. CRP, which is better at measuring acute-phase response, is primarily produced by the liver in response to interleukin-6 (IL-6).<sup>4</sup> Another predictive marker of surgical morbidity is impaired perioperative nutritional status, and prealbumin is useful to assess nutritional deficiency.<sup>5,6</sup> Similarly, serum procalcitonin has demonstrated its utility in distinguishing bacterial from viral meningitis, and in conjunction with other inflammatory markers, Procalcitonin levels can be useful in differentiating postoperative infection from inflammation.

## 17.3 Flavivirus-Mediated Neurological Disease

Flaviviruses are a family of positive, single-stranded, enveloped RNA viruses. They are transmitted by ticks and mosquito bites. Viruses in this family, such as yellow fever, dengue fever, and ZKV can cause widespread morbidity and mortality.<sup>7</sup> In light of the large outbreak starting in Brazil in 2015 that revealed a strong association between maternal ZKV infection and fetal microcephaly, we will focus on ZKV as an example for neurological infectious agent in the flavivirus family.



**Fig. 17.1** Microscopic detection of important pathogens in the CSF. (a) Pneumococci (*S. pneumoniae*), Gram stain. (b) Meningococci (*N. meningitidis*), Gram stain. (c) Staphylococci, Gram stain. (d) Streptococci, Gram stain. (e) *Haemophilus influenzae*, Gram stain. (f) *Enterobacteriaceae*, Gram stain. (g) *Listeria*, Gram stain. (h) *Mycobacterium tuberculosis*, Kinyoun carbolfuchsin stain. (Reproduced from Wildemann B, Oschmann P, Reiber H, Laboratory Diagnosis in Neurology, 1st edition, ©2010, Thieme Publishers, New York.)

- The most common malformations reported in fetuses and newborns with congenital Zika virus (ZKV) infection include agenesis of corpus callosum, macular chorioretinitis, cerebral calcifications, microcephaly, oligohydramnios, intrauterine growth restriction, atrophy of the ventricles, hydrops, and ventriculomegaly.
- ZKV is transmitted through the bite of female *Aedes* mosquitoes.
- The first trimester of pregnancy is considered the period of major risk for microcephaly.

The World Health Organization (WHO) declared ZKV as a public health emergency of international concern in 2016.<sup>8,9</sup> ZKV infection most commonly presents with initial low-grade fever, arthralgia, myalgia, fatigue, and conjunctival changes.<sup>10,11</sup> Several cases of acute meningoencephalitis and myelitis where ZKV RNA was detected and/or isolated in cell culture from CSF of the patients have also been reported. Definitive diagnosis of acute ZKV infection relies on the use of molecular tests for the direct detection of viral nucleic acids in blood and other biological specimens.<sup>12,13</sup>

Although specific antiviral drugs are not available for use in humans to treat any

**Table 17.1** Typical CSF findings in patients with selected infectious causes of meningitis

|                                    | WBC count (cells/mL) | Primary cell type            | Glucose (mg/dL)            | Protein (mg/dL) |
|------------------------------------|----------------------|------------------------------|----------------------------|-----------------|
| Normal range                       | 0–5                  | –                            | 2/3 of blood glucose level | < 50            |
| Acute bacterial                    | 1,000–5,000          | Neutrophilic                 | < 40                       | 100–500         |
| Acute viral                        | 50–1,000             | Mononuclear                  | > 45                       | < 200           |
| Neurosyphilis                      | > 10                 | Mononuclear                  | < 50                       | > 50            |
| Lyme                               | < 500                | Mononuclear                  | Normal                     | < 620           |
| Tuberculosis                       | 50–300               | Mononuclear                  | < 45                       | 50–300          |
| Cryptococcus                       | 20–500               | Mononuclear                  | < 40                       | > 45            |
| Coccidioides                       | < 700                | Mononuclear and eosinophilic | < 50                       | > 50            |
| <i>Naegleria</i>                   | > 100                | Neutrophilic                 | < 50                       | > 50            |
| <i>Angiostrongylus cantonensis</i> | > 100                | Eosinophilic                 | Normal                     | > 50            |

virus in the flavivirus family, including ZKV, compounds such as mycophenolic acid have been shown to be active against these viruses.

## 17.4 Meningococcal Disease

*Neisseria meningitidis* infection was first reported by Vieusseux in 1805, who described it as a “noncontagious malignant cerebral fever.”<sup>14</sup> The immunologic reactivity of capsular polysaccharides forms the basis for classification of meningococci into serogroups. Meningococci, best isolated on Thayer–Martin agar medium, change their cytoskeletal structures when they come in contact with cells.<sup>15</sup> The  $\alpha$ -chain structure of meningococcal lipo-oligosaccharides mimics that of human polysaccharides, which helps the bacteria escapes a host's immune mechanisms.

- Meningococcal disease is caused by *Neisseria meningitidis*, a gram-negative, aerobic, oxidase-positive, diplococcus bacterium.
- An important mechanism of virulence that provides sero-group-specific protection is called capsule switching.
- Acute meningitis most commonly presents with headache, neck stiffness, nausea, fever, and altered mental status; in infants, a bulging fontanelle is commonly noticed (► Fig. 17.2).
- Adrenal hemorrhage is a manifestation of fulminant meningococemia (Waterhouse–Friderichsen syndrome), which also causes diffuse thrombotic lesions or purpura.
- Chemoprophylaxis with rifampin should be given to all household contacts, child care/nursery school contacts, and contacts with exposure to secretions within 7 days of onset.





**Fig. 17.2** Diffuse leptomeningeal enhancement seen on a contrast-enhanced magnetic resonance image from a 4-month-old girl infant with meningococcal meningitis. (Reproduced from Hall W, Kim P, Neurosurgical Infectious Disease. Surgical and Nonsurgical Management, 1st edition, ©2013, Thieme Publishers, New York.)

*Neisseria meningitidis* is transmitted by secretions and multiplies in the nasopharynx.<sup>16</sup> Meningococcal disease occurs within 2 weeks of exposure.<sup>15,17</sup> A significant proportion of cases of meningococcal disease present with meningococcal septicemia, also known as meningococcemia. Abrupt onset of fever, hypotension, disseminated intravascular coagulation (DIC), multiple organ failure, and osteonecrosis due to DIC are some of the consequences of severe meningococcemia. People with deficient terminal complement-mediated immune activity (failure of the C5–C9 membrane attack complex), functional

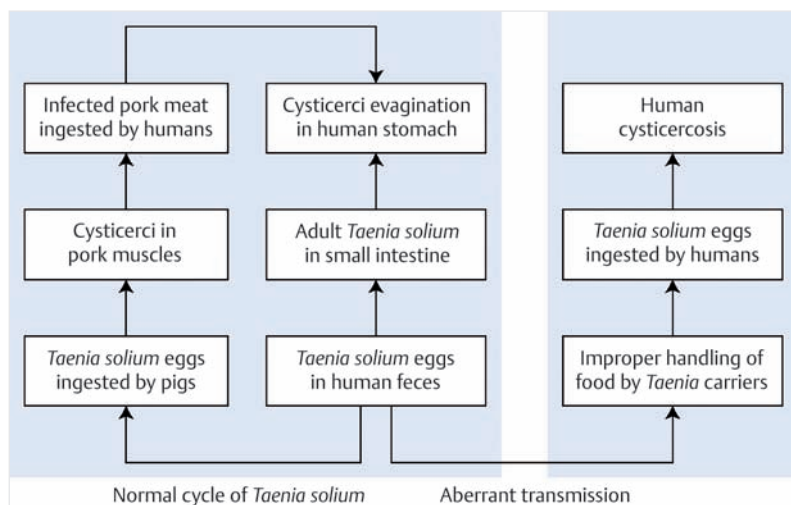
asplenic, or those living in crowded living conditions, such as college dormitories, are highly susceptible to infection.<sup>18</sup>

Blood and CSF cultures are commonly used for diagnosis. Management of the systemic circulation, respiration, and intracranial pressure (ICP) is vital for improving the prognosis.<sup>17</sup> Third-generation cephalosporins like ceftriaxone are the antimicrobial agents of choice against *N. meningitidis*. Steroids have also been investigated as an adjunct to antibiotic therapy in bacterial meningitis, and should be considered in patients with irreversible hemodynamic instability. A meningococcal vaccine has been developed and is recommended for entering college freshman, particularly those living in dormitories.

## 17.5 Neurocysticercosis

- Neurocysticercosis (NCC) is caused by the larval form of the pork tapeworm—*T. solium*.
- Inflammation of the meninges secondary to cysticercosis can present as a combination of visual impairment and several nerve palsies.
- Albendazole, an imidazole that impairs glucose uptake and metabolism in the parasite, is generally considered to be the drug of choice.

NCC is one of the most common parasitic diseases of the human CNS. When food or water contaminate with *T. solium* eggs is ingested, the eggs hatch in the intestine and spread throughout the body, particularly being avid for the CNS (► Fig. 17.3).<sup>19</sup>



**Fig. 17.3** Lifecycle of *Taenia solium* showing the normal cycle of transmission—in which humans act as definitive hosts and pigs act as intermediate hosts—and the aberrant cycle of transmission, in which humans become intermediate hosts and develop cysticercosis. (Reproduced from Cohen A, Pediatric Neurosurgery. 1st edition, ©2015, Thieme Publishers, New York.)

NCC can present with signs of increased ICP as well as acute seizures and diffuse cerebral edema. The brain parenchyma is commonly infected, and cysts often deposit at the gray matter–white matter junction.<sup>20, 21</sup> CSF and blood flow can also be disrupted due to high parasite burden. Spinal NCC should be suspected if the patient presents with motor and sensory dysfunction such as paresthesia and radicular pain along the nerve roots into the lower extremities.<sup>21</sup> The diagnosis of NCC can be made by direct visualization of the parasite from brain biopsy. Immunoassays which use targeted antigens to detect antibodies to *T. solium* in patient serum also provide sensitive and specific diagnostic information.<sup>20</sup> In addition to albendazole, praziquantel—an isoquinolone that causes parasite paralysis by disrupting calcium pathways and homeostasis—can also be used to treat NCC.

## 17.6 Primary Amoebic Meningoencephalitis

- The CNS infection caused by *N. fowleri* is mediated by the amoeba's entry along the olfactory neuroepithelial route via the cribriform plate and nasal mucosa.
- Infection of the olfactory lobes results in alteration of taste, smell, and vision.
- The diagnosis can be made by CSF enzyme-linked immunosorbent assay (ELISA) or immunofluorescence studies.
- The Centers for Disease Control and Prevention (CDC) recommended treatment regimen includes amphotericin B, fluconazole, azithromycin, rifampin, and dexamethasone.

Primary amoebic meningoencephalitis (PAM) is a hemorrhagic, necrotizing meningoencephalitis, caused by the thermophilic amoeba *N. fowleri*.<sup>22</sup> The *N. fowleri* infection is mainly contracted through contaminated water and hot springs. The parasite enters the human body through the nose, and the incubation period between exposure and development of the disease can be days to several weeks.<sup>23</sup>

The most common presenting symptoms of patients with PAM include headache, fever, nausea, and vomiting, and signs of meningeal irritation, such as confusion, irritability, and seizures.<sup>24</sup> The meningoencephalitis can be extremely severe and cause cerebral edema with focal white matter demyelination. In patients who present with neurological changes and have had a recent contact with freshwater or have a history of swimming in hot springs, PAM should be strongly considered on the differential diagnosis. The CSF Gram stain is often negative in these patients, but polymerase chain reaction (PCR) can be used to make the diagnosis of PAM.

## 17.7 Postsurgical Infections

- Staphylococci and facultative or aerobic gram-negative bacilli are responsible for majority of the cases of postsurgical meningitis, especially in patients who are hospitalized for a prolonged period after penetrating trauma.
- Careful surgical techniques and an effort to minimize CSF leakage can lower the risk of postoperative meningitis.
- In patients with obstructive hydrocephalus and a lack of communication between ventricular and lumbar CSF; lumbar CSF may not be reflective of ventricular infection.

Postoperative meningitis, although rare, is a serious complication of neurosurgery. The use of devices for therapeutic drainage of CSF or for ICP monitoring, such as external ventricular drains (EVD), external spinal drains (ESD), and shunts, correlates with a relatively high rate of postoperative meningitis.<sup>25</sup> Nosocomial meningitis can also be seen secondary to a complicated head trauma, and metastatic infection in the setting of hospital-acquired bacteremia. Bacterial meningitis occurs in 1 to 2% of patients who undergo craniotomy. Two important risk factors that increase the risk of postsurgical meningitis are (1) a duration of surgery of more than 4 hours, and (2) a concomitant infection at the site of the incision.<sup>26</sup>

Patients who require the use of foreign bodies, for example, internal ventricular drains, are susceptible to infections from cutaneous organisms such as *Staphylococcus epidermidis*.<sup>27</sup> *Streptococcus pneumoniae* is associated with complications after a basilar skull fracture or after head, neck, and/or ear surgery.<sup>26</sup> Infections associated with an internal ventricular catheter are best addressed by a combination of antimicrobial therapy, removal of all components of the infected catheter, and placement of an external drain as they are successful measures to address the underlying infection.<sup>26</sup> In the case of shunt infections caused by *Staphylococcus aureus* or gram-negative bacilli, multiple negative cultures and a 10-day course of antimicrobial therapy are recommended before placing a new shunt.<sup>28</sup>

Common clinical findings in patients with postsurgical meningitis include fever, malaise, and a decreased level of consciousness. The clinician should use neuroimaging modalities to evaluate ventricular size and possible CSF leaks. In patients who undergo neurosurgery, a lactate concentration of 4 mmol/L or more in the CSF has also been shown to have an excellent sensitivity and specificity, a positive predictive value of 96%, and a negative

predictive value of 94% for diagnosing bacterial meningitis.<sup>29</sup>

The pathogenesis of infection guides a clinician's choice of empirical antimicrobial therapy. For patients who are hospitalized for an extended period after penetrating head trauma, the most frequently used regimen consists of vancomycin in combination with either meropenem, cefepime, or ceftazidime.<sup>30</sup> Therapy should be optimized once a specific pathogen has been isolated. Antimicrobials are directly infused into the ventricles through a catheter if infections are difficult to eradicate with parenteral antimicrobial therapy alone. Treatment should be withdrawn after 72 hours if the results of CSF cultures are negative. This recommendation has been shown to be effective in a prospective study,<sup>31</sup> and is in accordance with the British Society for Antimicrobial Chemotherapy.

## 17.8 Additional Neurological Infections

### 17.8.1 Subdural Empyema

A subdural empyema (SDE) is a rare, suppurative infection that forms in the subdural space. It most often occurs due to the direct extension of local infection. Spread of the intracranial compartment may occur through the diploic veins and is associated with thrombophlebitis. SDE is often associated with paranasal sinusitis and chronic otitis media. Consider SDE on your differential diagnosis in a patient with fever, meningismus, hemiparesis, speech difficulty, papilledema, seizures, altered mental status, nausea, and sinus tenderness or swelling.<sup>32</sup> Common organisms that cause SDE include aerobic *Streptococcus*, Staphylococci, aerobic gram-negative rods, and other anaerobes. Treatment involves emergent

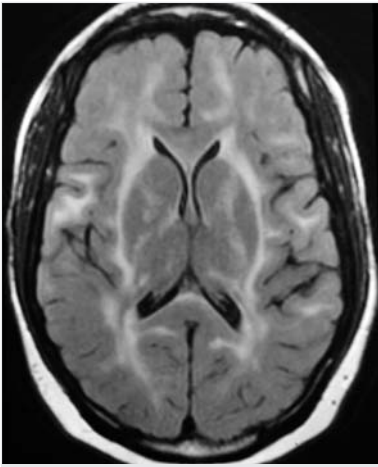
surgical drainage and broad-spectrum antibiotics.

### 17.8.2 HIV and AIDS

Half the patients with AIDS develop neurological symptoms. Toxoplasmosis, primary CNS lymphoma (associated with Epstein-Barr virus), progressive multifocal leukoencephalopathy (PML), and cryptococcal abscess are the most common conditions that produce focal CNS lesions in AIDS. CNS toxoplasmosis usually occurs when CD4 counts are fewer than 200, and can present as a mass lesion, meningoencephalitis, and encephalopathy. PML is caused by a polyomavirus, called the JC virus, and leads to focal myelin loss which results in mental status changes, blindness, aphasia, and ultimately coma.<sup>32</sup> Magnetic resonance imaging (MRI) with gadolinium is the preferred screening modality for AIDS patients with CNS symptoms because of lower false-negative rate compared with computed tomography (CT) (► Fig. 17.4).

### 17.8.3 Creutzfeldt-Jakob

When a normal prion protein becomes misshapen into an infectious prion, it can build up in the brain and disrupt normal brain function (► Fig. 17.5). Creutzfeldt-Jakob disease (CJD) is a rare disorder that is fatal, usually within 6 months of diagnosis. About 300 new cases per year are reported in the United States. There are three main forms of prion disease—sporadic, genetic, and acquired—categorized by how the disease occurs. Rapid neurocognitive decline in the form of memory loss, confusion, difficulty with coordination, and balance and personality changes are hallmark of CJD. Electroencephalography (EEG) recordings commonly show periodic sharp wave complexes. The 14–3–3 protein, which appears after neuronal destruction, is a useful surrogate CSF marker. There is no known



**Fig. 17.4** Primary human immunodeficiency virus infection of the brain that shows diffuse abnormal high signal, mostly in the central cerebral white matter bilaterally. (Reproduced from Meyers S, *Differential Diagnosis in Neuroimaging: Brain and Meninges*, 1st edition, ©2016, Thieme Publishers, New York.)

treatment or cure for CJD yet; management is focused on comfort care.

### 17.8.4 Tuberculous Vertebral Osteomyelitis

Pott's disease, also known as tuberculous spondylitis, is the most common type of skeletal tuberculosis (TB). The presentation of Pott's disease may be insidious over a long period and concomitant pulmonary involvement may not be present. Neurological deficits develop in majority of the patients due to medullary and radicular artery inflammation.<sup>33</sup> Paraplegia in Pott's disease is predominantly due to inflammatory compression of the cord of varying degrees, by edema,

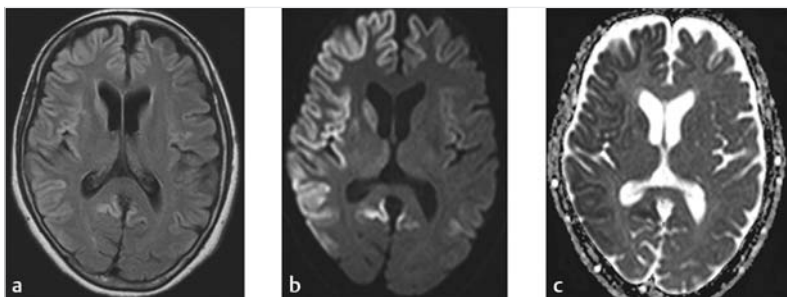
inflammatory cells, tubercular pus or debris, and early granulation tissue (► Fig. 17.6). An MRI is the imaging procedure of choice, although obtaining appropriate specimens for culture of acid-fast bacilli is essential to establish a definitive diagnosis and recover *Mycobacterium tuberculosis* for susceptibility testing. Management includes the RIPE regimen of antitubercular drugs: rifampicin, isoniazid, pyrazinamide, and ethambutol, which treat spinal tuberculosis as well as additional primary tubercular foci in the body. Surgical decompression of the cord is recommended with debridement of the lesion through anterior or anterolateral approach for high-grade paraplegia.<sup>34</sup>

### 17.8.5 Skull Osteomyelitis

The skull is normally resistant to osteomyelitis, and most infections are due to contagious spread or penetrating trauma. The most common causative organisms in adults are *S. aureus* and *S. epidermidis*. In neonates, *Escherichia coli* infection is relatively more common.<sup>18</sup> Imaging findings often show bony resorption, contrast enhancement, and periosteal reaction. Surgical debridement of the infected skull is critical; antibiotics alone are not sufficient. In the case of an infected craniotomy bone flap, the flap must be removed and discarded, and the edges of the skull ringed back to healthy bone. Cranioplasty may be performed 6 months postoperatively if there are no signs of residual infection.

### 17.8.6 Spinal Epidural Abscess

Spinal epidural abscess should be considered in a patient with back pain, spinal tenderness, and fever, sweats, or rigors.



**Fig. 17.5** A 68-year-old woman had memory problems and behavioral changes, subsequently found to have Creutzfeldt-Jakob disease. (a) Fluid-attenuated inversion recovery image demonstrates asymmetric cortical hyperintensity and mild hyperintensity in the right caudate head. Diffusion-weighted imaging (b) clearly shows asymmetric restricted diffusion in the cortex (cortical ribbon sign) and right caudate associated with decreased apparent diffusion coefficient (c). (Reproduced from Kanekar S, *Imaging of Neurodegenerative Disorders*, 1st edition, ©2015, Thieme Publishers, New York.)

The classic furuncle associated with an abscess presents only in a handful of cases. Early identification of an abscess is important because it can result in progressive myelopathy with precipitous deterioration. Major risk factors for an abscess include diabetes, intravenous (IV) drug use, chronic renal failure, and alcoholism.<sup>32</sup> Patients with vertebral osteomyelitis present with similar symptoms and risk factors as a spinal abscess. A percutaneous needle biopsy is often required, and most cases can be managed with appropriate antibiotics such as ceftriaxone, vancomycin, and metronidazole. Surgical intervention is considered in cases of neurological compromise or spinal instability. In general, abscesses affecting lumbar spine are amenable to medical management, while those affecting cervical or thoracic may require surgical intervention for decompression to prevent neurological decline that would occur due to septic thrombophlebitis or other complications.

### 17.8.7 Viral Encephalitis

Encephalitides may cause imaging findings that mimic a mass lesion, which is often the reason why they come to the attention of a neurosurgeon. The most important hemorrhagic viral encephalitis that the neurosurgeon in-training must be aware of is a multifocal necrotizing encephalomyelitis caused by herpes simplex virus type 1 (HSV1). HSV1 has a predilection for temporal and orbitofrontal lobes as well as the limbic system (► Fig. 17.7). Patients commonly present with altered mental state, personality changes, fever, hemiparesis, irritability, and occasionally, seizures.<sup>35</sup> CSF findings can guide diagnosis as explained in the section above. Additionally, EEG from the temporal lobe may demonstrate periodic lateralizing epileptiform discharges and imaging findings would be consistent with edema localized in temporal lobes. IV acyclovir is the drug of choice for HSV encephalitis.



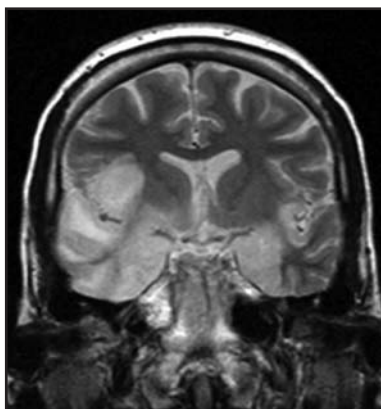
**Fig. 17.6** Tuberculous spondylodiskitis in a 29-year-old woman with microbiologically confirmed tuberculosis. She had complained of chest and back pain for the past several weeks. **(a)** Sagittal T2W image of the thoracic and lumbar spine. The T8 to T11 vertebral bodies show a patchy texture. The T8 and T9 vertebral bodies show decreased height with slight anterior wedging. The T8–T9 disk space is narrowed. **(b)** Short inversion time inversion recovery image corresponding to panel **(a)**. **(c)** Sagittal fat-saturated T1W image of the thoracic and lumbar spine shows patchy enhancement of the T8 to T11 vertebral bodies. A slight concomitant epidural reaction is noted at the level of the T10 and T11 vertebral bodies. (Reproduced from Forsting M, Jansen O, MR Neuroimaging: Brain, Spine, Peripheral Nerves, 1st edition, ©2016, Thieme Publishers, New York.)

## 17.9 Empiric Treatment

The most common empiric treatment regimen for meningitis comprises of vancomycin and ceftriaxone. For patients at risk for HSV encephalitis, IV acyclovir is often added. Similarly, for patients at risk for infection due to *Listeria*, ampicillin is commonly added. In neonates less than 56 days of age, ceftriaxone is

contraindicated because it displaces bilirubin from the albumin-binding site and is therefore associated with an increased risk of kernicterus. Thus, for a febrile neonate at risk for meningitis, the empiric regimen comprises of ampicillin/cefotaxime/acyclovir from birth to 21 days, ampicillin/cefotaxime from 22 to 28 days and cefotaxime alone from 29 to 56 days.<sup>36</sup>





**Fig. 17.7** Coronal T2-weighted MR image from a 33-year-old female patient with HSV-encephalitis. High signal can be seen in the temporal lobes. (Image has been provided courtesy of Dr Laughlin Dawes [radpod.org].)

Another class of drugs that is used to reduce the inflammation caused by infection is corticosteroids. Corticosteroids decrease nuclear factor kappa B (NF- $\kappa$ B) and are associated with an increased risk of hearing loss and neurological sequelae. Additionally, patients with meningitis due to *S. pneumoniae* treated with corticosteroids have been shown to have a lower death rate, although no effect on mortality was seen in patients with *Haemophilus influenzae* and *N. meningitidis* meningitis.<sup>37</sup>

## 17.10 Big Data

Computational and data analysis skills are critical now more than ever. This chapter lends itself naturally to a discussion of computational biology because both surgery- and infection-related

research can benefit tremendously from an understanding of how to find and understand useful signals in tremendously large sets of unsorted, noisy data. For example, large-scale data analysis is being used by the U.S. Geological Survey (USGS) to investigate the distribution of *N. fowleri*.<sup>38</sup> We now know that *N. fowleri* is a thermophile that causes PAM, a fatal disease. Big data has allowed bioinformatics researchers to understand the thermal and geochemical gradients that influence pathogens in warm waters. Geomapping and geographic information system (GIS) models collected a wide range of environmental variables, which showed that the lethal amoeba infections were reported in areas of low levels of copper and high levels of zinc.<sup>38</sup> Imagine that you are the researcher from USGS who is investigating whether *N. fowleri* is more likely to be found in soil with elevated zinc. You have recorded how long it takes for the amoeba to grow in soil with no zinc versus soil with zinc and have calculated the mean time to grow and the standard deviations. Scenario 1: You conduct your data analysis and find that growth time is faster in soil with zinc, but the difference is not “statistically significant,” say  $p = 0.3$ . Nevertheless, it may still seem sensible to check the zinc levels in the soil of the freshwater pool next to your house in Washington County, Minnesota. Scenario 2: You find strong evidence that amoeba grows faster with zinc, say  $p = 0.002$ . Although “significant,” it is important to consider the magnitude of the difference—*how much faster was the growth?*<sup>39</sup> Your clinical judgement and scientific conclusions should not be based only on whether a  $p$ -value passes a specific threshold. *Statistically significant* is not the same as *clinically important*.<sup>40</sup>



## Pearls



- Although viral and immune-mediated disorders of the nervous system are among the most challenging neurological disorders, remember to look for the common problems before you go for the "zebras." The most common neuroimmune disorder is multiple sclerosis, and HIV is the most common viral infection of the nervous system. Common to both disorders is the progressive loss of neurons, resulting in significant cognitive and motor dysfunction.
- Periodic postoperative follow-up is of utmost importance, and give special attention to the nutritional needs of your patient.
- As a neurosurgeon concerned about infection, take a minute to reflect on the pathophysiology of neuronal injury associated with an infection. This reflection will be critical in making meaningful consult requests.
- Never forget that p values do not measure the probability that the studied hypothesis is true, or the probability that the data were produced by random chance alone. A p value is an expression of the probability of getting results at least as extreme as what was observed, under the assumption that the null hypothesis is true. It carries no information about the magnitude of an effect.

patient is accompanied by her roommate, who has noted no confusion or personality changes. On physical examination she is awake, alert, and conversant. Her neck is supple and oropharynx shows thrush. An MRI of the brain is normal and ophthalmological examination shows bilateral papilledema. A rapid HIV test is positive. Which of the following is most likely to establish a diagnosis?

- a) Cytomegalovirus (CMV) IgG testing
  - b) Serum *Toxoplasma gondii* antibody
  - c) HSV1 PCR of the CSF
  - d) Cryptococcal antigen testing of CSF
  - e) JC virus PCR of CSF
2. A 36-year-old man is brought to the emergency department (ED) by his roommate with confusion and agitation for the last 2 days. While in the ED, he has generalized tonic-clonic seizures. His temperature is 40°C (104°F), blood pressure (BP) is 120/80 mm Hg, pulse is 105/min. There is no neck stiffness but a neurological examination shows upgoing plantar reflexes bilaterally. CT of the head reveals no abnormalities. An LP is performed and shows the following:
- Opening pressure:<sup>14</sup>
- Protein: 85 mg/dL
  - Red blood cells (RBCs): 25/mL
  - White blood cells (WBCs): 90/mL
  - Lymphocytes: 90%
- Which of the following is the next best step in management of this patient?
- a) IV amphotericin B
  - b) IV acyclovir
  - c) IV ceftriaxone and vancomycin
  - d) MRI of the brain, with and without contrast

## 17.11 Top Hits

### 17.11.1 Questions

1. A 38-year-old woman comes to the emergency department with 7 days of fatigue and headache that has worsened in intensity today. She also reports an episode of vomiting. The
3. A 15-year-old adolescent girl is brought to the emergency department (ED) due to 18 hours of headache and lethargy. The headache began last

night after she returned from 3 days of camping with friends. Temperature is 39.6°C (103.3°F), BP is 90/60 mm Hg, pulse is 120/min, and respirations are 22/min. The patient is obtunded and responds only to deep, painful stimulus. Physical examination shows resistance to passive neck flexion. Several petechiae are noted on the lower extremities. CSF results are as follows:

Glucose: 20 mg/dL

Protein: 475 mg/dL

Leukocytes: 2,000/mL

Neutrophils: 90%

Which of the following is the most likely cause of this patient's condition?

- a) Arboviral encephalitis
  - b) Acute Lyme's disease
  - c) Meningococcal infection
  - d) Pneumococcal meningitis
  - e) Rocky Mountain spotted fever
4. A 31-year-old man is brought to the ED due to 2 weeks of daily headaches and progressive confusion. He has a history of HIV. The patient appears unkempt and disoriented. Temperature is 38.6°C (101.4°F), BP is 118/75 mm Hg, pulse is 110/min. Neurological examination shows ataxia and right-sided hemiparesis. Brain MRI shows multiple ring-enhancing lesions. Which of the following would have most likely prevented this patient's condition?
- a) Acyclovir
  - b) Azithromycin
  - c) Trimethoprim-sulfamethoxazole
  - d) Isoniazid
  - e) Ganciclovir
  - f) Fluconazole
5. A 28-year-old man comes to the office due to trouble with his arm and face over the last week. He has had 1- to 2-minute episodes of twitching of the left arm and left side of the face. He has also had daily headaches for several weeks that are associated with nausea. The patient has a history of HIV but does not take his medications regularly. Three months ago, his CD4 count was 46/mL. Left arm motor strength is 4/5 and deep tendon reflexes (DTRs) are 3+. MRI of the brain reveals several ring-enhancing lesions at the gray-white junction and basal ganglia. Which of the following is the next step in management?
- a) Albendazole
  - b) Stereotactic brain biopsy
  - c) Clarithromycin and ethambutol
  - d) Sulfadiazine and pyrimethamine
  - e) Amphotericin B and flucytosine
  - f) Vancomycin and ceftriaxone
6. A 35-year-old woman comes to the physician for the evaluation of increasing weakness and numbness of the upper extremities for 5 days. During the past 2 days, she has had urinary incontinence not related to sneezing or laughing. Last summer, she had numbness and weakness of her lower extremity transiently for 3 weeks. She has had 10 male sexual partners in her lifetime and uses condoms inconsistently. Examination shows an impaired tandem gait, DTRs are 4+ bilaterally. There is mild spasticity and muscle strength is decreased in both upper extremities. Sensation to vibration and fine touch is decreased in upper extremities. What is the most appropriate next step in management?
- a) Check serum vitamin B12 level
  - b) Rapid plasma reagin (RPR)/Venereal Disease Research Laboratory (VDRL) test
  - c) MRI of the brain and spine
  - d) Lumbar puncture
  - e) Electromyography
  - f) Muscle biopsy

7. A 22-year-old primigravid woman comes to the physician for her initial prenatal visit at 12 weeks' gestation. She reports a tingling sensation in her legs for the past month. She follows a vegetarian diet since the age of 13. Examination shows pale conjunctivae, shiny tongue, and decreased sensation to vibration and position over the upper and lower extremities. When asked to stand, hold her arms in front of her, and close her eyes, she loses balance and takes a step backward. Which of the following is most likely to have prevented this patient's condition?
  - a) Folic acid supplementation
  - b) Calcium supplementation
  - c) Iron supplementation
  - d) Penicillin G therapy
  - e) Vitamin B12 supplementation
8. A 38-year-old woman comes to the physician for the evaluation of progressive weakness and numbness for 3 months. The symptoms started in her lower legs and gradually progressed up to her arms. During the past week, she has also had bilateral facial weakness and headaches. She is sexually active and uses condoms inconsistently. There is generalized weakness of the muscles, DTRs are 1+ bilaterally. Further evaluation is most likely to show which of the following findings?
  - a) Positive *Campylobacter* stool culture
  - b) Positive acetylcholine receptor (AChR) antibodies
  - c) RPR titer of 1:128
  - d) Positive GM1 ganglioside autoantibodies
  - e) Positive serum botulinum neurotoxin
  - f) Elevated thyroid-stimulating hormone (TSH) and decreased T<sub>4</sub> levels
9. A 71-year-old man comes to the physician because of a 2-week history of fatigue and 10-lb weight loss. Eight months ago, he underwent a kidney transplant. His current medications include prednisone and mycophenolate mofetil. While in the doctor's office, the patient has a seizure and difficulty coordinating movements with his left hand. An MRI of the brain shows an intraparenchymal lesion with peripheral ring enhancement. A tissue aspirate yields weakly acid-fast, gram-positive bacteria with branching, filamentous shapes. What is the most appropriate initial pharmacotherapy?
  - a) Trimethoprim-sulfamethoxazole
  - b) Vancomycin
  - c) Rifampin, isoniazid, pyrazinamide, and ethambutol
  - d) Erythromycin
  - e) Amikacin
10. A 7-year-old boy is brought to the ED due to high-grade fever and lethargy for 4 days. He has sickle cell disease and has not gotten any vaccines due to parental religious beliefs. Examination shows nuchal rigidity with positive Kernig's and Brudzinski's signs. An LP is performed and shows decreased glucose concentration, increased protein concentration, and numerous segmented neutrophils. A Gram stain of the CSF shows gram-negative coccobacilli. This patient is at an increased risk for which complication?
  - a) Cerebral palsy
  - b) Hearing loss
  - c) Adrenal insufficiency
  - d) Brain abscess
  - e) Communicating hydrocephalus

## 17.11.2 Answers

1. **d.** Cryptococcosis is the most common fungal disease in HIV-infected persons, and it is the AIDS-defining illness for 60 to 70% of HIV-infected patients. The insidious onset of this patient's symptoms together with bilateral papilledema supports a possible *Cryptococcus* infection. Cryptococcal disease usually develops only when CD4+ lymphocyte counts fall below 100 cells/mL.
2. **b.** Tonic-clonic seizures and lymphocyte-predominant CSF indicate a viral meningitis. The most common cause of viral meningitis in the United States is HSV. Thus, the correct and appropriate treatment is IV acyclovir.
3. **c.** This patient's physical examination findings of lethargy, neck stiffness, and petechiae point toward a *Neisseria gonorrhoeae* infection. The CSF findings of neutrophil predominance, elevated protein, and low glucose further strongly support a bacterial meningitis.
4. **c.** Trimethoprim-sulfamethoxazole is the first-line treatment for ring-enhancing lesions caused by *Nocardia*. The three most common causes of ring-enhancing lesions include toxoplasmosis, *Nocardia*, and CNS lymphoma. In this patient, the findings of unilateral hemiparesis, ataxia, and slow-onset confusion support *Nocardia* as the most likely cause.
5. **d.** MRI of the brain revealing multiple ring-enhancing lesions at the gray-white junction and basal ganglia is virtually pathognomonic for toxoplasmosis infection. The first-line treatment for toxoplasmosis is sulfadiazine and pyrimethamine. Other features of unilateral twitching and low CD4 count support an infectious etiology that causes neurological symptoms in the immunocompromised.
6. **c.** This woman has relapsing neurological symptoms that suggest lesions of the pyramidal tract (weakness, spasticity, increased DTR), the dorsal spinal column (loss of vibration and fine touch), and the autonomic nervous system that are disseminated in time and space, which is indicative of multiple sclerosis (MS). MRI of the brain and spine is the test of choice to confirm the diagnosis, showing multiple sclerotic plaques (most commonly seen in periventricular, juxtacortical, infratentorial, or spinal cord white matter) with finger-like radial extensions.
7. **e.** This patient presents with conjunctival pallor, fatigue, shortness of breath, and glossitis, which together indicate a nutrient-deficiency anemia. The patient's vegetarian diet and pregnancy are important risk factors for vitamin B<sub>12</sub> deficiency. Given the concomitant neurological signs and symptoms (paresthesias, loss of vibratory sensation and proprioception, positive Romberg's test), the most likely nutrient deficiency is that of vitamin B<sub>12</sub>.
8. **d.** Anti-GM1 autoantibodies are seen in patients with chronic inflammatory demyelinating polyneuropathy (CIDP). In the most typical form of CIDP, patients present with ascending symmetric sensory and motor deficits that progress over a period greater than 2 months. Symptoms improve with treatment (intravenous immunoglobulin [IVIg], plasmapheresis, and glucocorticoids) over the course of months to years.
9. **a.** Trimethoprim/sulfamethoxazole is considered the drug of choice for patients with nocardiosis. While the lungs are the most commonly affected site, nocardiosis can also affect the skin, CNS, or lead to a disseminated

infection, as in this patient. Nocardiosis is more common in patients with certain risk factors, which this patient does have, such as immunocompromise due to a kidney transplant.

10. **b.** Fever, headache, vomiting, and a stiff neck with positive Kernig's and Brudzinski's signs indicate meningitis. Given the appearance of gram-negative coccobacilli in CSF, the most likely pathogen is *H. influenzae*. Transient or permanent sensorineural hearing loss may occur as early as 48 hours after the onset of infection because of spread of infection from the meninges to the cochlea via the cochlear aqueduct.

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# 18 Interdisciplinary Care

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## 18.1 Neurology

### 18.1.1 Dementia

#### Basics of Dementia

Dementia is defined by the Diagnostic and Statistical Manual of Mental Disorders, fifth edition (DSM-5) as evidence of significant cognitive decline from a previous level of performance in one or more of the following cognitive domains<sup>1</sup>:

- Learning and memory
- Language
- Executive function
- Complex attention
- Perceptual motor skills
- Social cognition

These deficits must not be better explained by another mental disorder such as depression, which can present as “pseudodementia.”

It is important to distinguish dementia from simple delirium. Delirium is defined as an *acutely* disturbed state of mind that is characterized by restlessness, illusions, and incoherence of thought and speech. Electroencephalography (EEG) in delirium will typically show diffuse slowing, while EEG in dementia may be normal.

#### Basic Guidelines for Biopsy (CJD)

So-called *rapidly progressive dementias* may require brain biopsy for diagnosis. The most concerning are prion diseases such as Creutzfeldt–Jakob disease (CJD), variant CJD (vCJD), kuru, fatal familial insomnia, and Gerstmann–Sträussler–Scheinker disease.<sup>2</sup>

Biopsy guidelines are as follows:

- The biopsy should be large enough (at least 1 cm<sup>3</sup>).
- It should be taken from an affected area.
- It should include gray and white matter.
- All tools should be sterilized properly afterward.

### 18.1.2 Headache

#### Basics

Headache can be divided into two classifications: primary and secondary. Primary headaches include migraine and tension headaches, while secondary headaches are caused by systemic illness, intracranial pathology, trauma, surgery, and lumbar puncture.

#### Headaches Requiring Investigation

Headaches that are new, sudden in onset, severe, different from patient's usual headache, or headaches associated with an abnormal neurologic examination require further investigation with computed tomography (CT) or magnetic resonance imaging (MRI).

### Migraine

#### Common Migraine

Migraine is defined as an episodic headache lasting several hours, typically unilateral and associated with either nausea, vomiting, photophobia, or phonophobia.<sup>3</sup>

## Classic Migraine

Classic migraine is a common migraine plus an aura. Typically, migrainous auras consist of “positive” phenomena like flashing lights, kaleidoscope vision, and paresthesias which help to differentiate them from stroke-like symptoms.<sup>3</sup>

## Cluster

### Basics

These headaches, lasting typically 30 to 90 minutes, are characterized by severe, recurrent unilateral attacks of pain, usually around the V1 location with associated ipsilateral autonomic symptoms including conjunctival injection, nasal congestion, rhinorrhea, lacrimation, or facial flushing.<sup>4,5</sup>

### Treatment

- 100% O<sub>2</sub>
- Sumatriptan subcutaneous (SQ)
- Steroids
- Refractory cases may be considered for the following:
  - Percutaneous radiofrequency sphenopalatine ganglion blockade
  - Hypothalamic deep brain stimulation
- May be treated prophylactically with verapamil

## Post Puncture Headache

### Basics

Also known as “spinal headache.” May occur after any procedure where the dura is punctured and may also occur idiopathically with spontaneous intracranial hypotension.<sup>4</sup>

### Features

Headache is positional and worsens significantly when patient sits up or stands

up from a reclined position and is relieved or resolved when patient is recumbent.

## Pathophysiology

Cerebrospinal fluid (CSF) leak from unhealed dural openings can lead to persistent intracranial hypotension.

## Neuroimaging

MRI may show diffuse pachymeningeal enhancement and T2 hyperintensity.

## Treatment

- Lay flat for 24 hours
- Hydration, both oral (PO) and intravenous (IV)
- Tight abdominal binder
- Caffeine, PO or IV
- High-dose steroids
- Blood patch if above fails

## 18.1.3 Parkinsonism

### Classic Parkinson's Disease

Parkinson's disease (PD) is the second most common neurodegenerative disorder after Alzheimer's disease. It affects 1% of the population older than 60 years, but it has several mimics which can make diagnosis difficult even for the experienced neurologist.

It is characterized by the following constellation of symptoms:

- Bradykinesia
- Rigidity
- Resting tremor
- Postural instability and gait impairments

Symptoms are due to a loss of dopaminergic neurons, mainly in the substantia nigra pars compacta. These neurons normally project to the caudate and putamen and modulate corticostriatal transmission, which is essential for normal movement.



The cause of degeneration is unknown, but there is buildup of  $\alpha$ -synuclein protein in these cells which can be seen microscopically.<sup>6</sup>

## Other Types of Parkinson's Disease Plus

Other types of parkinsonism, often referred to as "Parkinson's disease plus (PD+)" can be seen. These disorders include progressive supranuclear palsy (PSP), multiple system atrophy (MSA), corticobasal degeneration (CBD), and dementia with Lewy bodies (DLB). All forms involve bradykinesia and rigidity but frequently have early-onset of memory loss and disturbances in mentation. Parkinsonism can also be drug induced from antidopaminergic medications like antipsychotics and antiemetics. It can also be vascular, normal pressure hydrocephalus (NPH), or stroke-related. There are rare familial forms of parkinsonism as well.<sup>7</sup>

## Surgical Treatment

Surgical options include placement of a deep brain stimulator (DBS) to unilateral or bilateral subthalamic nucleus (STN), or to the globus pallidus internus (GPi). GPi DBS may have fewer neuropsychiatric side effects.



Surgery has been shown to be superior to the best medical therapy for dyskinesia, but patient selection is very important.<sup>8</sup>

### 18.1.4 Essential Tremor

Thalamic DBS, targeting the ventral intermediate nucleus (VIM) markedly reduces the severity of essential tremor, even in those refractory to medication.<sup>9</sup>

## 18.1.5 Multiple Sclerosis

### Basics

Multiple sclerosis (MS) is a central nervous system (CNS) demyelinating disease affecting the brain, spinal cord, and cranial nerves. There is no peripheral nervous system (PNS) involvement.

### Epidemiology

MS affects approximately 450,000 patients in the United States and 2.3 million worldwide. It is three times as common in women, and the usual age of onset is in young adulthood, but it does not have a major impact on life expectancy. The lifetime financial burden of MS is estimated at well over \$1.2 million per person.<sup>10</sup>

### Clinical

With the most common variant, relapsing-remitting MS, patients experience short periods of acute inflammation and new disability in between longer periods of disease inactivity. Inflammation can occur anywhere in the CNS, but demyelinating plaques most commonly occur in the optic nerves, periventricular white matter, corpus callosum, juxtacortical U-fibers, and cerebellar peduncles.

A relapse consists of neurologic disturbance at least 24 hours in duration in the absence of fever or infection. Separate attacks should be divided by at least 30 days without symptoms.<sup>10,11</sup>

### Diagnostic Criteria

The most current criteria are the 2010 revised McDonald Diagnostic Criteria. Diagnosis requires elimination of more likely diagnoses. In order to diagnose MS, the lesions *must* be disseminated in time and space. Clinical evidence alone will

suffice if there have been two or more separate attacks consistent with MS.

Dissemination in space consists of at least one T2 lesion in at least two out of four areas of the CNS:

- Periventricular
- Juxtacortical
- Infratentorial
- Spinal cord

Dissemination in time consists of a new T2 and/or gadolinium-enhancing lesion on repeat MRI or the presence of asymptomatic gadolinium-enhancing and nonenhancing lesions at any time.

Active demyelinating lesions will enhance with gadolinium, while old inactive lesions will be hyperintense on T2 and FLAIR without enhancement. The reason for enhancement is breakdown of the blood-brain barrier (BBB).<sup>10</sup> CSF analysis can support the diagnosis. Positive CSF findings including oligoclonal immunoglobulin G (IgG) bands or elevated IgG index should be checked in all suspected MS cases if the diagnosis is not straightforward.

### 18.1.6 Motor Neuron Diseases

#### Amyotrophic Lateral Sclerosis

##### Epidemiology

In the United States, nearly 5,000 people per year are diagnosed with amyotrophic lateral sclerosis (ALS). Mean age of onset is 56 years. Male to female ratio is about 1.6:1. Patients typically die of respiratory failure and typically pass away around 3 years after diagnosis.<sup>12</sup>

##### Pathology

The most common genetic cause is a mutation of *C9orf72* which causes a GGGGCC

nucleotide repeat and accounts for up to 40% of familial cases. Mutations in the *SOD1* gene account for 20% of familial ALS. Both upper and lower motor neurons are affected, including the giant Betz cells in the motor cortex, however, most sclerosis occurs in the lower motor neurons of the anterior horns.<sup>12</sup>

##### Clinical and Diagnosis

The El Escorial criteria were published in 1994 to outline the diagnosis of ALS. ALS is a clinical diagnosis that is characterized by predominantly lower motor neuron dysfunction including atrophy, fasciculations, and weakness. Upper motor neuron degeneration signs are also required to make the clinical diagnosis. Symptoms typically begin in one extremity and spread to other regions. The body is divided into four regions: bulbar, cervical, thoracic, and lumbosacral and the certainty of the diagnosis increases with the number of regions involved. A small portion of patients have “bulbar” onset with weakness of the swallowing muscles and dysarthria which carries a worse prognosis.<sup>12</sup>

##### Treatment and Prognosis

In adjunct with supportive care, riluzole, a drug which blocks the release of neuronal glutamate, and edaravone, a drug with an unknown mechanism of action but acts as a free radical scavenger, are the only currently Food and Drug Administration (FDA)-approved treatments for ALS. They have been shown to slow the decline of ALS.

##### Spinal Muscular Atrophy

Spinal muscular atrophy (SMA) is an autosomal recessive disease caused by loss of the *SMN1* gene on chromosome 5q13.2. The carrier frequency in the United States is

1/50. There is now an FDA-approved intrathecal therapy, nusinersen, which is an antisense oligonucleotide that has demonstrated significant improvement in survival and motor milestone attainment.<sup>12</sup>

## Spinal Bulbar Muscular Atrophy

Spinal bulbar muscular atrophy, or Kennedy's disease, is an X-linked recessive genetic muscular atrophy caused by a CAG trinucleotide repeat in the androgen receptor gene on the X chromosome. Facial and oral fasciculations are the usual presenting symptoms followed by proximal muscle group atrophy in weakness.<sup>12</sup>

### 18.1.7 Guillain-Barre

#### Clinical

Also known as acute inflammatory demyelinating polyneuropathy (AIDP), Guillain-Barre syndrome (GBS) is typically preceded by either a respiratory or gastrointestinal illness. It is thought to be triggered by a "molecular mimicry" response, with the immune system erroneously attacking host myelin and axons. Neurologic symptoms develop rapidly over several days typically with an ascending symmetrical paralysis. Low back pain is very common at the onset of GBS and may be the presenting symptom.<sup>13</sup>

#### Diagnostic Features

- Progressive, relatively symmetric motor weakness
- Areflexia
- Autonomic dysfunction: tachycardia, labile blood pressure
- CSF: albuminocytologic dissociation (increased protein without pleocytosis)
- Demyelination begins at the nerve roots

## Treatment

Either IV immunoglobulin (IVIg) 400 mg/kg daily for 5 days or 1,000 mg/kg for 2 days or plasma exchange every other day for 10 days.

### 18.1.8 Myelitis

Transverse myelitis is a spinal cord disorder defined by any cause of inflammatory myelopathy, idiopathic or secondary to other neurologic or systemic conditions.

#### Etiology

Etiologies can be inflammatory, vascular, or compressive. Differential diagnosis includes MS, neuromyelitis optica, Sjögren syndrome, lupus-associated transverse myelitis, antiphospholipid antibody syndrome, copper deficiency, B<sub>12</sub> deficiency, tertiary syphilis, sarcoidosis, and multiple separate viral/bacterial illnesses, or even vaccinations.

#### Clinical Presentation

There is no clinical sign that can differentiate transverse myelitis from emergent compressive myelopathy, so all patients presenting with an acute myelopathy should be evaluated and treated emergently. Patients will present with sensory loss, back pain, weakness below the level of the lesion, ataxia, and bladder and bowel dysfunction. These symptoms can progress over hours, days or weeks. Reflexes can be diminished early on but eventually become hyperreflexic. A sensory level and urinary retention are highly suggestive of spinal cord disorder.<sup>14</sup>

#### Work-up

Imaging of the entire spinal cord should be strongly considered as even small cervical lesions can cause isolated lower extremity symptoms. MRI with and without contrast

is the diagnostic modality of choice. CSF analysis in transverse myelitis will typically show a pleocytosis and elevated IgG.

## Treatment

1 g/d of IV methylprednisolone. In severe cases where steroids are not effective, consider IV Ig 400 mg/kg/d for 5 days or plasma exchange every other day for five treatments.<sup>14</sup>

### 18.1.9 Neurosarcoidosis

Sarcoidosis is a disorder characterized by granulomatous inflammation of unidentified etiology able to affect all organ systems. The CNS is involved in fewer than 5% of cases although there are cases of pure CNS sarcoidosis without systemic involvement.<sup>15</sup>

## Pathology

Definitive diagnosis requires histological proof of noncaseating granulomatous inflammation. This is a macrophage infiltration with epithelioid, nonnecrotic differentiation, multinucleated giant cells, with occasional lymphocytic or monocytic infiltration.<sup>16</sup>

## Clinical Findings

For neurosarcoidosis, the most common presentation is that of a chronic meningitis, with headache, meningeal signs, and encephalopathy. Cranial nerve palsies, such as Bell's palsy or ophthalmoplegia, are commonly seen as well, although any cranial nerve may be affected. The next most common presentation is myelopathy, followed by conus medullaris or cauda equina syndrome. These patients may also present with an asymmetric mononeuropathy multiplex picture.

## Laboratory

CSF shows a pleocytosis with a predominance of lymphocytes. Protein is commonly elevated, greater than 100. CSF glucose is low to normal. CSF angiotensin-converting enzyme (ACE) levels carry a high false-positive rate and low sensitivity and are usually not useful.

## Imaging

MRI of the entire neuraxis should be obtained with gadolinium. Common findings are T2 hyperintensity with gadolinium enhancement. Special attention should be paid to leptomeningeal enhancement and focal dural enhancement. There may also be enlargement of the pituitary stalk and focal parenchymal brain lesions. Different patterns of enhancement may be seen, such as uniform and mass-like, or irregular and linear. MRI of the spinal cord may show an interesting pattern of central canal and dorsal cord enhancement in a three-pronged "trident-head" shape. Chest X-ray or CT should be obtained to look for granulomatous inflammation and hilar lymphadenopathy.<sup>16</sup>

## Biopsy

As mentioned before, definitive diagnosis of neurosarcoidosis requires tissue examination and the diagnosis guides treatment. Transbronchial lung biopsy may be the most straightforward approach if the lungs are involved, and skin biopsy is an option if there are dermal nodules. However, if primary neurosarcoidosis without systemic involvement is suspected, then CNS biopsy should be pursued.

## Treatment

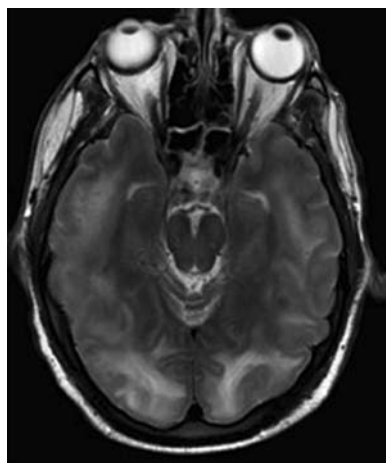
The mainstay of treatment is steroids coupled with steroid-sparing immunosuppressants.

Methotrexate, mycophenolate, tacrolimus, azathioprine, cyclophosphamide, and several others have been tried anecdotally. An objective measurement of improvement should be chosen beforehand, may it be imaging enhancement, neurologic deficit, or CSF pleocytosis.<sup>15,16</sup>

## 18.1.10 Posterior Reversible Encephalopathy Syndrome

### Clinical Features

Patients present with the signs or symptoms of a hypertensive encephalopathy, which include, but are not limited to, headache, nausea, vomiting, confusion, seizures, and visual changes with associated T2 hyperintense lesion in the white matter of the occipital white matter (► Fig. 18.1).<sup>17,18</sup>



**Fig. 18.1** Posterior reversible encephalopathy syndrome on MRI fluid attenuation inversion recovery sequence.

## Imaging

MRI will show T2 hyperintensities in the white matter with little mass effect while CT scans looking at the same areas show reduced density in the corresponding areas. The changes on imaging are often located most prominently in the posterior part of the hemispheres.

## Treatment

Treatments of posterior reversible encephalopathy syndrome (PRES) are limited with the most important being controlling the blood pressure, decreasing the peak blood pressure by about 20% or targeting a pressure of 150/100 is relatively safe.<sup>18</sup>

## 18.1.11 Vasculitis

### Introduction

Vasculitis refers to inflammation of the blood vessels and includes a variety of disorders in which the blood vessel wall inflammation leads to end-organ ischemic and inflammatory damage. They can be idiopathic, associated with immune complex deposition, chronic infections, or connective tissue diseases. Most have multisystem involvement, however, primary angiitis of the CNS and nonsystemic vasculitic neuropathy are pure CNS vasculitides. The vasculitides that may affect the CNS are as follows: polyarteritis nodosa, hypersensitivity vasculitis, giant cell arteritis (GCA), Takayasu's arteritis, granulomatosis with polyangiitis, lymphomatoid granulomatosis, isolated angiitis of the CNS, and Behçet's disease.<sup>19,20</sup>

## Giant Cell Arteritis

### Epidemiology

Giant cell arteritis (GCA), also known as temporal arteritis, is a chronic granulomatous

arteritis, which primarily affects the extracranial carotid arteries and may also affect other arteries and when there is involvement of the internal carotid artery, ischemic strokes can occur. GCA is seen in older patients, generally, older than 50 years. Up to 50% of patients have concomitant polymyalgia rheumatica.

### Clinical

GCA typically presents with temporal headache, aching in proximal muscles, low-grade fever, weight loss, malaise, fatigue, and jaw claudication. Superficial temporal arteries can be tender to palpation with diminished pulsations present upon palpation. Visual loss can be transient, then progress to permanent visual loss via ischemic optic neuropathy.<sup>20,21</sup>

### Evaluation and Biopsy

Erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) are often highly elevated; ESR is typically greater than 50 mm/h. Angiography can show stenotic lesions with associated inflammatory changes. Temporal artery biopsy is the gold standard for diagnosis of GCA and should be done on the side of involvement.<sup>20</sup>

### Treatment

Prednisone 60 to 80 mg should be started. Treatment can be deescalated when ESR lowers.<sup>20</sup>

## Other Vasculitides

### Polyarteritis Nodosa

Polyarteritis nodosa (PNA) affects small- and medium-sized arteries with a predilection for branch points. It is a necrotizing vasculitis which eventually leads to thrombosis of the

affected arteries. Presenting symptoms include headache, seizures, subarachnoid hemorrhage, retinal hemorrhages, and stroke. Treatment involves disease-modifying treatments such as cyclophosphamide rather than chronic steroids.<sup>20</sup>

### Wegener's Granulomatosis

This affects the upper and lower respiratory tracts and the kidney. Myeloperoxidase (MPO)/perinuclear antineutrophil cytoplasmic antibodies (p-ANCA) are frequently present. Neurologic involvement includes focal cranial neuropathies, mononeuritis multiplex, and sensorimotor polyneuropathy. Treatment includes immunosuppressive agents like cyclophosphamide.<sup>20</sup>

### Behçet's Disease

Classic presentation is a triad of oral ulcers, genital ulcers, and uveitis. Pathophysiology involves perivascular lymphocytic infiltration of the veins, venules, capillaries with occasional arterial involvement. Neurologic presentations include meningoencephalitis with headaches, encephalitis form with gradually evolving multifocal signs, strokes, and headache with papilledema caused by dural venous sinus thrombosis. Steroids can be used to treat the ocular and brain symptoms, but often do not affect the skin or genital lesions.<sup>20,21</sup>

### Primary CNS Vasculitis

Primary angiitis of the CNS often presents as a small-vessel vasculitis affecting leptomeningeal and parenchymal blood vessels. It presents as a subacute encephalopathy without systemic symptoms. Once suspected, brain biopsy is necessary to confirm diagnosis.<sup>20,21</sup>

### 18.1.12 Fibromuscular Dysplasia

#### Etiology and Aneurysms

Fibromuscular dysplasia (FMD) is a non-atherosclerotic, noninflammatory, multifocal arterial disease which can involve any or all the three layers of the arterial wall and is classically associated with hyperplasia of the smooth muscle layer in the tunica media. It can lead to a propensity for focal irregularity of the blood vessels, stenosis, aneurysms, and increased risk for dissections and subsequent downstream organ dysfunction.<sup>21</sup>

#### Presentation

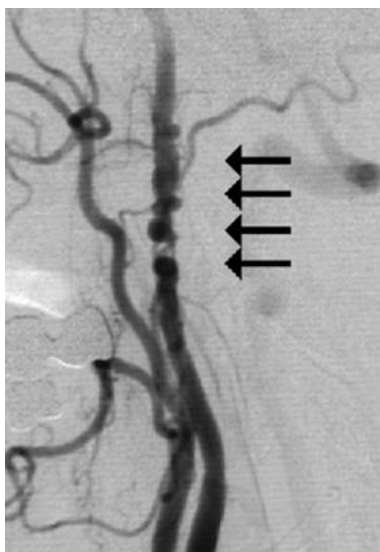
Many of these lesions are asymptomatic, however, they can lead to stenosis, thrombus formation, and dissections which can present as ischemic strokes or even uncontrolled hypertension if the renal arteries are affected. These patients may also have headaches, pulsatile tinnitus, cervical bruits, migraines, and may develop Horner's syndrome if the cervical vasculature is affected.

#### Diagnosis

Diagnosis is made by CT angiography (CTA), MR angiography (MRA), or standard angiography. Classically, it can be visualized as the "string of beads" appearance (► Fig. 18.2).

#### Treatment

The mainstay of therapy consists of reducing other vascular risk factors and treatment with antiplatelet therapy such as aspirin. Calcium channel blockers are commonly used for hypertension and to



**Fig. 18.2** String of beads sign on angiography (arrows).

prevent vasoconstriction. Those patients with hypertension should have evaluation of their renal arteries to rule out stenotic lesions.<sup>21</sup>

### 18.1.13 CADASIL

Cerebral autosomal dominant arteriopathy with subcortical infarcts and leukoencephalopathy (CADASIL) is an autosomal dominant disorder, which leads to a variety of neurologic phenomenon including ischemic subcortical strokes, migraine with aura, depression, and dementia. CADASIL is due to a mutation in *NOTCH3* gene which is important for vascular smooth muscle development. Molecular genetic testing is now the gold standard of diagnosis.<sup>22</sup>

The following are some high-yield paraneoplastic syndromes and their associated antibodies and malignancies<sup>19</sup>:

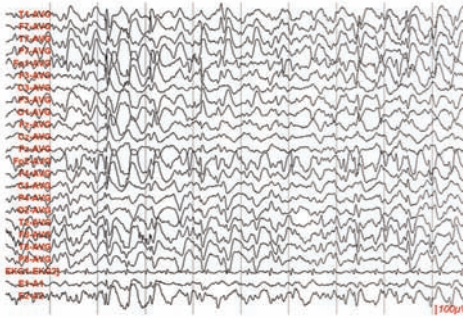
- **Anti-Ma1 antibody:** Limbic and/or

- **West syndrome (infantile spasms):**





**Fig. 18.4** Centrotemporal spikes in rolandic epilepsy.



**Fig. 18.5** Spike and slow waves seen in Lennox-Gastaut.

## 18.2 Neuroanesthesia

### 18.2.1 Modifiable Parameters

Parameters relevant to Neurosurgery that can be modulated by the Anesthesiologist include blood pressure which helps to determine a patient's cerebral perfusion pressure (CPP), jugular venous pressure, arterial carbon dioxide tension, arterial oxygen tension, hematocrit, temperature, blood glucose level, CSF output, level of the patient's head, intravascular volume, and body position. Many of the above-mentioned parameters can affect the intracranial pressure (ICP), CPP, and mean arterial pressure (MAP). All of which together affect your patients' cerebral blood flow (CBF) as well as their cerebral metabolic rate of oxygen consumption (CMRO<sub>2</sub>).<sup>24,25</sup>

### 18.2.2 Drugs

#### Inhalational Agents

These agents, except for nitrous oxide (N<sub>2</sub>O), suppress neuronal activity and thus reduce cerebral metabolism. These agents do cause some degree of vasodilation which can increase cerebral blood volume and thus increase ICP.

N<sub>2</sub>O is a potent vasodilator and can markedly increase CBF, with minimal increases in cerebral metabolism.

N<sub>2</sub>O may convert a pneumocephalus to a tension pneumocephalus as it is much more soluble than nitrogen, so it is more likely to precipitate out of solution.

N<sub>2</sub>O can also cause an acute B<sub>12</sub> deficiency by directly deactivating the B<sub>12</sub> molecule.

Halogenated agents include isoflurane (Forane), desflurane (Suprane), and sevoflurane (Ultane). All of these agents suppress EEG activity and have been theorized to provide some degree of cerebral protection.<sup>24</sup>

## Intravenous Agents

These agents are often used for induction of anesthesia as well as often being used for conscious sedation and include propofol, barbiturates, etomidate, and ketamine.

Propofol has a short half-life allowing for repeated neurologic examinations in those under sedation. There is a dose-dependent drop in MAP and thus ICP. The adverse effects are often monitored by following triglyceride levels and watching for metabolic acidosis.



Large continuous dosing can cause propofol infusion syndrome consisting of metabolic acidosis, cardiac failure, rhabdomyolysis, renal failure, and other abnormalities including eventual death.

Barbiturates can produce significant decreases in cerebral metabolism and suppress EEG activity all the way to burst suppression or electrographic silence. Most are used orally as antiepileptic drugs or used intravenously to treat status epilepticus. All forms may cause dose-dependent hypotension. The most commonly used IV agent is sodium thiopental (Pentothal) as it has a rapid onset and shortest half-life.

Etomidate (Amidate) is an anesthetic with amnestic but no analgesic properties. It has also been known to impair renal function and may produce adrenal insufficiency. It is a very hemodynamically stable agent to use for induction, often the drug of choice

for induction with patients who have increased ICP.

Ketamine produces a dissociated anesthesia with very little effects on cardiac output or respiratory function. In the past, its use was avoided in those with increased ICP, as it was thought to cause some mild increase in heart rate and blood pressure leading to increased ICP. However, this is not proven and in those with hypotension you may argue for its use. Patients should be monitored for paradoxical agitated delirium with prominent hallucinations and agitation.<sup>24,25</sup>

## Narcotics

These agents can all slow the EEG but will not produce electrographic silence. They all cause dose-dependent respiratory depression and thus can cause hypercarbia leading to cerebral vasodilation and increased ICP in nonventilated patients.

Nonsynthetic agents, including morphine, may produce hypotension, vasodilation, and its excretion is impaired in those with renal insufficiency. Meperidine (Demerol), which has neuroexcitatory metabolites, can cause hyperactivity as well as seizures.

Synthetic narcotics, including fentanyl, sufentanil (which can cause increases in ICP), alfentanil (which can also raise ICP), and remifentanyl, can be used in awake craniotomies. These agents, unlike the nonsynthetic agents, do not lead to histamine release. This means that they cause less hypotension and thus less effects on patient's CPP.

## Miscellaneous Drugs

Benzodiazepines produce anticonvulsant action and produce amnesia. Those commonly used for anesthesia or sedation include lorazepam or, the now more popular, midazolam.

Lidocaine suppresses the laryngeal reflexes and can help blunt ICP elevations especially during intubation. It is used by some as pretreatment for those being intubated who have known elevated ICP. Fentanyl is more commonly used in this situation.

Esmolol can also be used to blunt the sympathetic response to intubation, although in emergent situations where blood pressure may be in flux, the use of a  $\beta$ -blocking agent may be problematic, limiting its use.

Dexmedetomidine (Precedex) is central  $\alpha_2$ -adrenergic agonist which has multiple uses including sedation, control of postoperative hypertension, agitated delirium, withdrawal symptoms, and sedation during awake craniotomy.<sup>24,25</sup>

corresponding cortical areas and in the interconnecting subcortical areas. These pathways cannot all be directly measured. However, their representative areas can be detected with specific electrode placement and by using computers to average inputs forming waveforms. The latencies and amplitudes can be measured and followed to help with diagnostic reasons as well as for monitoring during neurosurgical interventions.

Anesthetics can have effects on the evoked potentials, which are being monitored during neurosurgery. All volatile agents produce dose-dependent reduction in somatosensory-evoked potentials (SSEP).

## Paralytics for Intubation

To facilitate endotracheal intubation, paralytics are used in conjunction with induction agents. Succinylcholine is the drug of choice of rapid sequence intubation in those acutely neurologically ill patients with elevated ICP due to its rapid onset and short duration of action.

There are cases where other agents such as rocuronium should be used. These include those with or at risk for hyperkalemia, those with disuse atrophy, or those with neuromuscular junction disorders, such as myasthenia gravis, in which the depolarization neuromuscular blocking effect of succinylcholine can be prolonged.<sup>24,25</sup>

Generally using the minimal effective dose is required, staying away from barbiturates and volatile agents. Using continuous infusions versus intermittent boluses will minimize anesthetic effects on evoked potential monitoring.<sup>24</sup>

## 18.2.4 Malignant Hyperthermia

### Presentation

This is a hypermetabolic state in which one observes rapidly rising body temperature, and extreme muscle rigidity. It is often associated with the use of volatile inhalation anesthetics (e.g., halothane) or succinylcholine.<sup>24</sup>

### Treatment

Discontinuation of the offending anesthetic agent and treatment with dantrolene sodium (Dantrium) at a dose of 2.5 mg/kg IV, infuse until symptoms improve up to 10 mg/kg.

## 18.2.3 Evoked Potentials

Stimulation of sensing organs or peripheral nerves leads to responses in their

## Prevention

Patients at risk include those with a family history of malignant hyperthermia, heavy musculature, muscular dystrophies (particularly Duchenne's type), or scoliosis. For those at risk, avoid use of succinylcholine and use non-halogenated anesthetics.<sup>24</sup>

## 18.3 Neuro-Ophthalmology

### 18.3.1 Nystagmus

Nystagmus refers to either a spontaneous or induced oscillation of the eyes that begins with a slow phase and may or may not have a quick corrective saccadic correction. The direction of the nystagmus is named for the direction of the quick phase. Horizontal or upbeating gaze-provoked nystagmus has a large differential diagnosis, including medications like antiepileptic drugs (AEDs). Vertical nystagmus which is not gaze-evoked, especially if down ward beating, is very concerning for brainstem pathology.<sup>26,27</sup>

### 18.3.2 Papilledema

Papilledema refers to optic nerve swelling secondary to increased intracerebral pressure believed to cause axoplasmic stasis, and most of the time is bilateral. Causes include direct compression from tumors, vascular disease such as anterior ischemic optic neuropathy or vasculitis, Foster Kennedy syndrome, and demyelinating disorders. Over time, it will lead to optic nerve damage and can cause permanent loss of visual acuity.<sup>28</sup>

### 18.3.3 Visual Fields Introduction

Visual field testing is an important bedside testing maneuver and, with more

formal testing, can help with diagnostics, following disease progression, and determining driving safety. Normal visual fields are about 50 degrees above and below the horizontal meridian, 35 degrees nasally, and 90 degrees temporally. About 15 degrees nasally from the fovea lies the optic disc, at that point on the retina there are no photoreceptors. This creates the physiologic blind spot lying about 15 degrees temporally and slightly inferior from the point of central fixation.<sup>29</sup>

### Visual Field Deficits

These can be tested for by bedside confrontation testing which should be performed on each eye individually. Formal testing can be performed using tangent screens, Goldmann's perimetry or Humphrey's visual field (automated perimetry) examinations.

Visual field deficits are often described regarding location and extent of the lesion. For lesions affecting just one eye, they are often referred to as scotomas. Complete visual loss is referred to as anopia. The rest of the lesions are referred to by their location (right, left, inferior, superior) and size (hemi-, quadrant-). ► Fig. 18.6 shows common lesions and their associated areas of damage.<sup>29</sup>

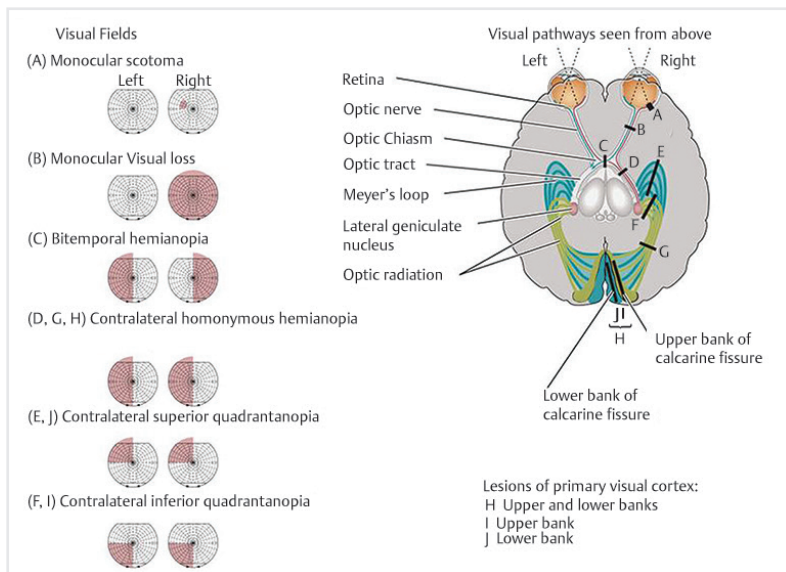
### 18.3.4 Pupillary Diameter

#### Pupillodilator and Tract

The pupillodilator muscle is a set of muscle fibers which act on the iris and when contracted, the pupil dilates.<sup>27</sup>

#### Pupilloconstrictor and Tract

The pupilloconstrictor muscle consists of muscle fibers that narrow the pupil when they contract.<sup>27</sup>



**Fig. 18.6** Effects of lesions in the primary visual pathways. (Reproduced with permission from Blumenfeld H, *Neuroanatomy through Clinical Cases*, 2nd edition, Oxford University Press, USA, 2010.)

## Afferent Pupillary Defect (Marcus Gunn Pupil)

This phenomenon is seen when the direct and consensual pupil response to light when stimulating the affected eye are decreased or absent, while the direct and consensual pupil response when stimulating the unaffected eye to light is normal.<sup>30</sup>

## Light-Near Dissociation and Argyll Robertson Pupil

With light-near dissociation, the pupils do not constrict as strongly to light as compared to constriction seen with testing of accommodation. When referring to this finding in relation to neurosyphilis, it is known as the Argyll Robertson pupil.

However, it is associated with other etiologies such as dorsal midbrain syndrome, vascular disease (such as diabetes or alcohol leading to cranial nerve [CN] III dysfunction), and in those with Adie's pupil.<sup>30</sup>

## Anisocoria

Anisocoria refers to unequal pupil sizes usually more than 1 mm.<sup>30</sup> A physiological anisocoria less than 1 mm in difference can be seen in roughly 20% of the population.

## Adie's Pupil

Adie's myotonic pupil, or a tonic pupil, is due to a lesion of postganglionic parasympathetic fibers and the true etiology is often unknown. If the patient has

associated decreased reflexes, it is then referred to as Holmes–Adie syndrome, which is more commonly seen in young women.

Slit-lamp examination will reveal that some parts of the iris are contracting while others are not. If the pupillary abnormality has been present for several weeks, there has been enough time for hypersensitivity of the acetylcholine receptors on the iris to develop and if dilute pilocarpine is applied (0.125%), about two drops, the dilated eye will exhibit miosis.<sup>30</sup>

**Pharmacologic Pupil** Although mydriatic agents are used commonly to perform a dilated eye examination, there are times when patients may be exposed to mydriatic agents and are unaware of this, leading to their presentation to a clinician for pupillary abnormalities. This should normalize with time.<sup>30</sup>

## Cranial Nerve III Compression

Cranial nerve III compression can initially manifest with pupillary dilation as the parasympathetic fibers travel in the periphery of the nerve where they are vulnerable to mechanical compression. Etiologies include aneurysm expansion, tumor compression, and uncal herniation.<sup>30</sup>

## Horner's Syndrome

Horner's syndrome is a triad of miosis, ptosis, and anhydrosis. This set of symptoms occurs when there is disruption of the sympathetic innervation to the face and eye. Miosis occurs due to denervation of the pupillodilator muscle. Ptosis occurs due to denervation of Müller's muscle. This only leads to a minor ptosis which is not complete. Anhydrosis is secondary to denervation of the sweat glands. Differential diagnosis includes lateral medulla infarction, Pancoast's tumor, and carotid dissection.<sup>27</sup>

## 18.3.5 Extraocular Muscles

### Introduction

The extraocular muscles are made up of six striated muscles that are under the control of three cranial nerves which direct eye movement. The cranial nerves that have direct control over the extraocular muscles are CN III (oculomotor), CN IV (trochlear), and CN VI (abducens).<sup>31</sup>

### Intranuclear Ophthalmoplegia

Lesions to the medial longitudinal fasciculus (MLF) will produce a syndrome known as intranuclear ophthalmoplegia. This syndrome consists of poor adduction ipsilateral to the lesion as the MLF conveys information between the contralateral abducens nucleus and the ipsilateral oculomotor nucleus. At times, patients may have nystagmoid beating of the abducting eye. Common causes include MS, other demyelinating lesions, and cerebrovascular accidents.<sup>32</sup>

## CN III (Oculomotor) Palsy

### Complete Oculomotor Palsy

The classic complete CN III palsy is that of the “down and out” eye, which consists of ocular depression and abduction. There is associated mydriasis due to loss of parasympathetic innervation and severe ptosis due to loss of the levator palpebrae superioris.<sup>33</sup>

### Non-Pupil-Sparing Oculomotor Palsy

When the pupil is not spared, the pathology usually involves extrinsic compression of the third cranial nerve as the parasympathetic fibers travel along the periphery of the nerve.

Common etiologies include tumors, vascular lesions such as aneurysm, uncus herniation, and cavernous sinus lesions.

## Pupil-Sparing Oculomotor Palsy

In these patients, there will be weakness of the motor component of the third cranial nerve, however, the pupillary function will remain intact. This is believed to occur usually due to vascular compromise of the small vessels feeding the nerve itself. Common etiologies include diabetic mononeuropathy, atherosclerosis, and vasculitis.

## CN IV (Trochlear) Palsy

The trochlear nerve is unique in that it is the only cranial nerve to exit from the dorsal aspect of the brainstem and that it is the only completely crossed cranial nerve. Patients with a trochlear nerve palsy may present with diplopia and often have some compensation which is achieved by tilting their head opposite of the affected eye. Common etiologies of CN IV palsy are trauma, congenital palsies (with decompensation later in life), and small-vessel disease. However, most of the time the etiology is idiopathic.<sup>33</sup>

## CN VI (Abducens) Palsy

Patients with lesions affecting CN VI will experience horizontal diplopia at distance due to loss of function of a lateral rectus muscle. Common etiologies for an abducens palsy include changes in ICP, diabetic mononeuropathy, vasculitis, and cavernous sinus lesions.<sup>33</sup>

## Orbital Pseudotumor

Orbital pseudotumor is an inflammatory orbital disease in which patients have idiopathic inflammation of the extraocular muscles, their tendinous insertions, and

the other orbital contents. This is not due to changes in ICP. In most cases, this is a unilateral phenomenon and responds to steroids.<sup>34,35</sup>

## Tolosa–Hunt Syndrome

Tolosa–Hunt syndrome presents as unilateral orbit pain with accompanied oculomotor paresis. These findings are like those found with structural or anatomic lesions, and MRI may reveal a focal enhancing mass. Tolosa–Hunt is secondary to granulomatous inflammation of the cavernous sinus and may extend to the superior orbital fissure and orbit itself. Of note, this may be the presenting sign/symptom of neurosarcoidosis. This syndrome responds well to corticosteroid treatment.<sup>35</sup>

## Raeder's Syndrome

Raeder's syndrome is also known more precisely as paratrigeminal oculosympathetic syndrome consisting of unilateral pain in the distribution of the trigeminal nerves ophthalmic division along with at least a partial Horner's syndrome with unilateral ptosis and miosis. This constellation of syndrome can be associated with a carotid artery dissection.<sup>36</sup>

## Gradenigo's Syndrome

Gradenigo's syndrome consists of a triad of periorbital unilateral pain, diplopia, and persistent otorrhea. The periorbital facial pain comes from involvement of CN V and diplopia due to CN VI dysfunction. This used to be associated with bacterial otitis media with apex petrositis (inflammation of the petrous portion of the temporal bone). In the post-antibiotic era, the triad seen in Gradenigo's syndrome secondary to otitis media has become rare and the triad is now more often associated with

cholesteatomas, other tumors/cancers, or even chronic osteomyelitis of the petrous bone.<sup>37</sup>

### 18.3.6 Miscellaneous Signs

#### Corneomandibular Reflex

The corneomandibular reflex, sometimes referred to as the Wartenberg reflex, consists of contralateral deviation of the jaw following tactile stimulation of the cornea. It is believed to be due to severe supranuclear eye movement center dysfunction of the rostral brainstem. It is a rare sign, however, when present indicates upper brainstem area dysfunction and can help with localization in the comatose patient.<sup>38</sup>

#### Duane's Syndrome

Duane's syndrome is a congenital disorder in which patients can have a variety of extraocular motor abnormalities. Duane's syndrome has three different types: type 1 consists of an inability to abduct the affected eye; type 2 consists of an inability to adduct the affected eye; and type 3 consists of an inability to both abduct and adduct the affected eye. These patients will have normal alignment upon primary gaze and due to suppression, despite obvious extraocular motion abnormalities, will not complain of double vision. Patients with type 1 Duane's syndrome will classically have narrowing of the palpebral fissure as well as globe retraction that occurs when the eye is moved into adduction.<sup>39</sup>

#### Hippus

Hippus is a normal phenomenon that is most commonly seen when testing the pupillary light reflex in patients. Hippus describes small spontaneous oscillation of the pupil. Simply wait until the

hippus abates prior to measuring pupillary size.<sup>40</sup>

#### Ocular Bobbing

Ocular bobbing is a physical examination sign that consists of rapid conjugate downward eye deviation followed by a slow return of the eyes to the primary position. This finding is usually accompanied by bilateral horizontal gaze palsy and indicates a destructive pontine lesion usually involving the bilateral paramedian pontine reticular formations, which are the supranuclear control centers of horizontal gaze. This is different from ocular dipping consisting of a slow downward deviation and fast return to primary position, which is a rather nonspecific finding lacking localization value.<sup>41</sup>

#### Opsoclonus

Opsoclonus (saccadomania) consists of back to back conjugate saccades without an intersaccadic interval and is multidirectional with horizontal, vertical, and torsional components. This is always abnormal and common causes include viral encephalitis, paraneoplastic syndromes, drug intoxication (such as lithium), and classically in the opsoclonus-myoclonus syndrome seen in children with a neuroblastoma.<sup>41</sup>

#### Oscillopsia

Oscillopsia is the term used to describe the illusion of environmental motion or blurred vision. This is usually seen in patients with abnormal spontaneous eye movements like an acquired nystagmus. Patients with congenital forms of nystagmus often do not report oscillopsia, even if their spontaneous eye movements are readily visible on examination.<sup>41</sup>



## 18.4 Neurotology

### 18.4.1 Vertigo

#### Differential Diagnosis

When medical practitioners are seeing a patient complaining of dizziness, the initial differential is quite daunting, ranging from vascular, inflammatory, infectious, neoplastic, degenerative, drug mediated, congenital, autoimmune, traumatic, endocrine, or metabolic disturbances. Examination techniques, such as the Dix–Hallpike maneuver (► Fig. 18.7), are useful in examining the vertiginous patient. If nystagmus is present, examination and documentation of the nystagmoid eye movement in a variety of directions of gaze can help direct further management and work-up.<sup>42</sup>

### Vestibular Neurectomy

#### Surgical Considerations

Two conditions in general are treated with vestibular neurectomy, Ménière's disease and partial vestibular injury (viral or traumatic). The vestibular nerve itself is the superior half of CN VIII and can be slightly grayer in color than the cochlear division. It is important to divide the vestibular portion from the cochlear portion to maintain a patient's ability to hear. As the facial nerve lies near, it is often desirable to have electromyographic (EMG) monitoring of

the facial nerve during surgery to avoid any indirect damage.<sup>43</sup>

#### Surgical Approaches

Surgical approaches for vestibular neurectomy include a retrolabyrinthine, retrosigmoid, and middle fossa approaches.<sup>43</sup>

### 18.4.2 Ménière's Disease

#### Clinical

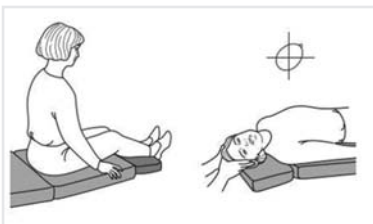
Ménière's disease is described clinically as recurrent attacks of vertigo (typically lasting 20 minutes up to hours), unilateral hearing loss, ear fullness, and tinnitus. The diagnostic criteria for definite Ménière's disease include two or more episodes of vertigo, documentation of low- to medium-frequency hearing loss, fluctuating aural symptoms, and that other causes have been ruled out or are less likely. It is likely due to a process known as endolymph hydrops in which transient fluctuation occur where perilymph enters the endolymph space leading to swelling and organ dysfunction.<sup>44</sup>

#### Epidemiology

The prevalence of Ménière's disease is about 1 in 150,000 people and affects both men and women in similar numbers, with the peak incidence between 40 and 60 years.<sup>44</sup>

#### Differential

Other causes of vertigo include compressive tumors, anatomical deformities (like a Chiari malformation), benign paroxysmal peripheral vertigo, transient ischemic attacks, strokes, or acute vestibular inflammation (labyrinthitis or vestibular neuritis). Once these have been ruled out, the main differential left is that of vestibular migraine, which is not associated with hearing loss.<sup>44,45</sup>



**Fig. 18.7** Dix-Hallpike maneuver.

## Diagnostic Studies

Imaging with MRI to rule out underlying mass. Audiography should be pursued, to see if there is associated, and often transient, low- or medium-frequency sensorineural hearing loss. Further testing by specialists with videonystagmography can be completed as well and vestibular-evoked potentials are an option as well.<sup>44</sup>

## Treatment

### Nonsurgical

During acute attacks, a patient's vertiginous symptoms can be managed with a variety of vestibular suppressing medications which include, but not limited to, antihistamines (like meclizine), phenothiazines, benzodiazepines, antiemetics (like metoclopramide or ondansetron), and topical anticholinergics (like scopolamine). Prevention of further attacks is managed with a low-sodium diet (1,500 mg/d) and often the addition of thiazide diuretics. Betahistine, a potent H<sub>3</sub> receptor antagonist, may have a role in long-term management. There are no high-quality randomized clinical trials regarding the long-term treatments described above.<sup>44,45</sup>

### Surgical

For patient who are unable to manage with medical therapies or diet changes alone, surgical treatment is the next step. There are a variety of treatment options ranging from intratympanic corticosteroid injections, use of gentamycin, and even endolymphatic shunt procedures. For patients who do not respond, vestibular neurectomy or labyrinthectomy can be attempted. Labyrinthectomy should only be pursued if the patient is already deaf in the affected ear.<sup>44</sup>

## 18.4.3 Facial Nerve Palsy

### Localization

Facial nerve palsy is divided into two different types of lesions depending on the location of the lesion. The differentiation between the two comes down to the lesion involving the CN VII nucleus or peripheral nerve itself, leading to a lower motor neuron lesion and those proximal to the nucleus, leading to upper motor neuron type lesions. In general, upper motor neuron lesions spare the forehead causing only mild orbicularis oculi weakness, whereas lower motor lesions affect the entire half of the face.<sup>46,47</sup>

### Etiology

The differential diagnosis is quite broad for a facial nerve palsy and a good way to break up the differential is sources of dysfunction leading to central or peripheral palsy. The differential for central CN VII palsy includes, but is not limited to, strokes, tumors, demyelination, and CNS infection (including abscess). The differential for peripheral CN VII palsy includes Bell's palsy, demyelination, stroke, neoplasms (both intra- and extracranial), trauma, congenital, iatrogenic, meningitis (which could be bacterial/fungal/viral/noninfectious), inflammatory disorders, infiltrative diseases, myopathies, and neuromuscular junction disorders.<sup>46</sup>

### Bell's Palsy

Bell's palsy is a subtype of an idiopathic facial nerve palsy with an acute (< 72 hours) onset of unilateral peripheral facial nerve weakness for which no specific etiology is uncovered. In the case, where a specific etiology is discovered, infectious or otherwise, this no longer becomes a Bell's

palsy but rather a CN VII palsy. There is usually spontaneous recovery over the course of months.<sup>46</sup>

## Management

If the facial palsy is caused by an identified underlying issue, then that should be addressed itself, whether this is treatment of an infection, removal of an enlarging tumor, or treatment of an autoimmune or demyelinating disorder. In the case of Bell's palsy, the American Academy of Neurology (AAN) has recommendations with regard to both steroids and antiviral treatments.<sup>48</sup>

## Herpes Zoster Oticus

Herpes zoster oticus is often referred to by its eponym, Ramsay Hunt's syndrome. This syndrome is characterized by a peripheral facial palsy with associated erythema and/or vesicular eruptions in the external auditory canal, tympanic membrane, or oropharynx. This disorder is secondary to either primary or secondary activation of a herpes zoster infection affecting the facial nerve via the geniculate ganglion. If disseminated or associated with zoster meningitis, it may affect other cranial nerves as well. This disorder is more aggressively treated with an antiviral regimen depending on the extent of the infection. If there is possible ocular involvement (eruptions on the tip of the nose via the nasociliary nerve), ophthalmologic specialists should be involved early in the treatment course.<sup>49</sup>

## Surgical Treatment

Surgical decompression specifically for facial palsy is addressed by the clinical practice guidelines by the American Academy of Otolaryngology Head and Neck

Surgery Foundation. In their most recent update, they did not find evidence to provide any recommendations for surgical decompressive treatments. This does not apply to those with brainstem compressive tumors or invasive parotid tumors leading to facial nerve palsy. In these cases, depending on the tumor type and patient characteristics, decisions must be made on an individual basis. Another group of patients who benefit from surgery are those with traumatic causes of facial palsy and those with a vascular loop causing hemifacial spasm.<sup>46,50</sup>

### 18.4.4 Conductive and Sensorineural Hearing Loss

Hearing loss is one of the most common sensory deficits in older adults. Hearing loss is divided into two categories: conductive and sensorineural. Conductive hearing loss occurs when sound is prevented from reaching the inner ear, which implies dysfunction ranging from simple occlusion of the external ear canal, a middle ear effusion, ossicular chain malfunction, and other mechanically disruptive processes. Sensorineural hearing loss signifies malfunction of the cochlea or disruption of the auditory nerve.<sup>51</sup>

Hearing aids can always lead to some improvement in conductive hearing loss. Sensorineural hearing loss on the other hand must be managed with either hearing aids or with cochlear implants in those with profound hearing loss. Cochlear implants directly stimulate the auditory nerve and bypass the cochlea all together. The cochlear implant has an internal implant which inserts directly into the cochlea next to the auditory nerve and an external portion, which is a sound processor usually attached at ear level. In general, postlingual adults and congenitally deaf children are great candidates for cochlear implants.<sup>52</sup>

## Pearls



- Signs that a headache needs further evaluation can be remembered by the F's: "First, fast, focal, febrile, fluctuates (changes with position)."
- Post lumbar puncture headache frequency can be reduced by using an atraumatic, blunt-tipped needle.
- Parkinson's disease almost never presents with dementia or personality change. If this occurs early in the disease, it is probably one of the "Parkinson's Plus" diseases.
- Deep brain stimulation can be considered early for life-limiting essential tremor.

## 18.5 Top Hits

### 18.5.1 Questions

- Diagnosis of which dementia may require a biopsy?
  - Alzheimer's
  - Parkinson's
  - Dementia with Lewy Bodies
  - Creutzfeldt-Jakob disease
  - Vascular dementia
- Deep brain stimulation of which structure may be beneficial in Parkinson's Disease?
  - Hypothalamus
  - VPL
  - GPI
  - Putamen
  - Caudate
- Riluzole, a drug which is used to treat ALS, has which mechanism of action?
  - Acetylcholinesterase inhibitor
  - Phosphodiesterase inhibitor
  - Inhibits release of neuronal glutamate
  - Antihistaminergic effects at the H-2 receptor
  - Dopamine blocker at D-2 receptor
- Which test is required for definitive diagnosis of neurosarcoidosis?
  - MRI of the brain and spinal cord demonstrating characteristic lesions
  - Biopsy of affected tissue showing granulomatous inflammation
  - Elevated serum and CSF ACE levels
  - Clinical picture consistent with the diagnosis including multiple cranial nerve palsies
- Which vasculitis classically presents with oral ulcers, genital ulcers and uveitis, but can also present with headaches, meningoencephalitis and multiple cranial nerve palsies?
  - Behçet's Disease
  - Wegner's Granulomatosis
  - Polyarteritis Nodosa
  - Primary CNS Angiitis
  - Giant Cell Arteritis
- A patient undergoes general anesthesia for their first time and then develops lead-pipe rigidity and fever of 105 degrees Fahrenheit. What is the treatment of choice?
  - Acetaminophen
  - Dantrolene
  - Diazepam
  - Phenytoin
  - Succinylcholine
- A patient presents with double vision and examination shows inability to adduct the right eye on left gaze. This is known as:
  - CN VI Palsy
  - Intranuclear Ophthalmoplegia (INO)
  - CN IV Palsy
  - CN III Palsy
  - Horner's Syndrome
- Which non-ophthalmologic sign can represent ocular involvement, and therefore risk of blindness, of herpes zoster (shingles) infection?

- a) Vesicular eruptions in the external auditory canal
- b) Ptosis
- c) Jaw claudication
- d) Vesicular eruptions on the tip of the nose

## 18.5.2 Answers

1. **d.** Creutzfeld-Jakob Disease, or CJD, is a prion disease which presents as a rapidly progressive dementia. Another clinical feature is myoclonic jerks. There is no specific biomarker or clinical sign for CJD and biopsy may be required to make the diagnosis.
2. **c.** In addition to the STN, GPI is a target for DBS in Parkinson's disease. GPI as a target has become more prominent because it has been associated with less psychiatric side effects.
3. **c.** Riluzole inhibits the release of neuronal glutamate.
4. **b.** While MRI, ACE level, and clinical picture are important, the gold standard of sarcoidosis diagnosis is tissue biopsy.
5. **a.** Wegener's granulomatosis presents variably with rhinitis, epistaxis, scleritis, glomerulonephritis, pulmonary nodules, arthritis and/or sensory neuropathy. Polyarteritis nodosa (PAN) is associated with mononeuritis multiplex, stroke, pericarditis, arthritis, fevers, fatigue and weakness. Primary CNS angiitis is typically chronic to subacute and is associated with headaches, cognitive impairment, stroke, transient ischemic attack, and cranial neuropathies without signs of systemic vasculitis. Giant cell arteritis presents in patients over 50 with new, usually temporal, headaches, abrupt onset of visual disturbances, jaw claudication, and high ESR/CRP and is often associated with polymyalgia rheumatica.
6. **b.** The patient is showing signs of malignant hyperthermia related to anesthesia. Dantrolene is the treatment of choice. Dantrolene acts rapidly on skeletal muscle to inhibit the release of calcium ions from the sarcoplasmic reticulum.
7. **b.** Inability to adduct the eye, or medial rectus muscle palsy, is known as an intranuclear ophthalmoplegia, or INO. It is named for the side that cannot adduct and is caused by a disconnect between the ipsilateral oculomotor (CN III) nucleus and the contralateral abducens (CN VI) nucleus. These nuclei are connected by the medial longitudinal fasciculus, or MLF, and lesions here cause an INO.
8. **d.** Eruptions on the tip of the nose indicate involvement of the ophthalmic division of the trigeminal nerve, the nasociliary nerve, and is known as Hutchinson's sign. This nerve innervates the ciliary body, iris, cornea and conjunctiva. Its terminal branch, the anterior ethmoidal branch, innervates the tip of the nose.

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# 19 Socioeconomics in Neurosurgery

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## 19.1 Training

### 19.1.1 Overview

In order to practice specialty medicine in the United States, you must complete medical school, pass the United States Medical Licensing Examination (USMLE) Parts I, II, and III, complete an approved residency program, obtain a state license to practice, and be credentialed to work at a hospital. Each of these steps has federal, state, and local regulatory control.

salaries of teaching physicians, fees, and overhead expenses. The amount depends on the percentage of Medicare patients treated at a teaching hospital and the number of residents in AC-GME-accredited programs that practice at that hospital.

- **IGME:** It covers costs not directly related to resident training such as costs related to treating more complex cases. The amount varies based on the hospital's ratio of residents to beds.

### 19.1.2 Residency



Residency program regulation falls primarily under the auspices of the Accreditation Council for Graduate Medical Education (ACGME) with individual programs gaining approval for meeting essential training requirements through an RRC.

A special board association drives the standards that a specific RRC follow; for neurosurgery it is the American Board of Neurological Surgery (ABNS).

### 19.1.3 Licensing

In order to practice medicine in a state, a physician must obtain a medical license. A licensure is a legal approval from the state government and cannot be transferred to another state. (Note: at the time of publication, efforts are underway to establish license reciprocity between states.) Each state has specific requirements that must be fulfilled before their approval such as graduation from medical school, passage of all parts of the USMLE, and completion of 1 or 2 years of residency training. There may be additional prerequisites that vary from state to state. Renewal may be required at specified intervals.

## Funding

The largest single program that provides support for graduate medical education (GME) is Medicare. These funds are divided into direct graduate medical education (DGME) funding and indirect graduate medical education (IGME) funding.

- **DGME:** It covers a portion of the costs of training residents—stipends, benefits,

### 19.1.4 Certification

Certification is provided by a nongovernment, national professional organization such as the ABNS and verifies competence in that field. In neurosurgery, one must pass the written examination which is taken during residency and an oral examination,



taken several years after completion of an accredited residency program. The Maintenance of Certification (MOC) program promotes learning throughout a physician's life and self-assessment to ensure that neurosurgeons are maintaining and continually improving their knowledge and practice.

### 19.1.5 Credentialing

Credentialing is a local hospital or hospital system process. Each such application will be unique but will generally require the following:

- Completion of a demographic and professional qualification application.
- Attestation to the practitioner's health (including tuberculosis [TB] testing).
- Attestation regarding disciplinary issues (malpractice, licensure, hospital privileges, etc.).
- Request for general privileges.
- Request for specialized privileges.
- Peer recommendations.

Hospital bylaws govern the frequency of recredentialing and the status of credentialed physicians (provisional, full, consultative, etc.). Practice at multiple hospitals will require separate credentialing.

## 19.2 Patient Care

Neurosurgeons are committed to providing the right care, to the right patient at the right time.

In addition, neurosurgeons acknowledge the unique challenges that many of our patients face in this arena due to special nature of neurosurgical disorders including intense anxiety related to pain and diagnoses, possible cognitive impairment, and

the emergency nature of many of these problems.

### 19.2.1 Patient Safety

Health care is built on a *culture of safety* that involves health care professionals, organizations, and patients.

Patient safety has been defined as “the prevention of harm to patients” by the Institute of Medicine. Practices to improve patient safety have been established including surgical simulators for resident training, team time-outs, surgical checklists, perioperative antibiotic use, maximal sterile barriers with invasive procedures, and antibiotic-impregnated catheters. Organized neurosurgery has actively embraced the priority of patient safety through system-based approaches, educational initiatives, and support for a vibrant patient safety committee.

### 19.2.2 Communication

Communication is the foundation for providing good patient care and succeeding as a physician. It is an integral part of day-to-day medicine and can affect diagnostic accuracy, compliance with medical treatment plans, patient satisfaction, patient safety, team satisfaction, and malpractice risk. A clinician's ability to explain, listen, and empathize is essential. While some individuals may be “natural communicators,” communication is a skill that must be learned and improved upon to enhance the experience for patients and the health care teams. Given its importance, many new tools and programs have been developed to foster communication such as sign-outs, checklists, changing workflow, and utilizing technology.

## 19.2.3 Informed Consent

Informed consent is the “process of communication between a patient and physician that results in the patient’s authorization or agreement to undergo a specific medical intervention.”

Patients must be given enough information to be fully informed before deciding to undergo a major treatment, and this informed consent must be documented in writing. As neurosurgeons, this is a part of our daily lives. Consequences of a poor informed consent process may result in increased chance of a medical error, malpractice, and violation of professional and ethical obligation to clinicians to respect the rights of your patients. The ethical principles guiding the purpose of informed consent are protection, autonomy, prevention of abusive conduct, trust, self-ownership, nondomination, and personal integrity.

The process of informed consent is much more than the written document. A signed consent in no way serves as a substitute for the substantial communication that must occur between the physician and patient. Exceptions to informed consent are lack of decision-making capacity and emergency circumstances where the patient’s wishes are unknown. The person obtaining consent must be capable of performing the procedure himself or herself or have received specialist training in advising patient about procedure. Clear documentation of the informed consent process should be a priority for every neurosurgeon. Many medical organizations have established criteria for the informed consent process including the American Medical Association and the American College of Surgeons. Neurosurgeons are encouraged to read these guiding principles and

also to learn the specific requirements in your state and hospital.

## 19.3 Medical Economics

- CMS: Centers for Medicare and Medicaid Services
- RVU: Relative Value Unit
- DRG: Diagnosis-related Group
- CPT: Common Procedural Terminology
- ICD-10: International Classification of Disease
- AANS: American Association Neurological Surgeons
- CNS: Congress of Neurological Surgeons

### 19.3.1 Medicare

This is a federally administered health insurance program designated for people aged 65 or older, certain disabled people, and individuals with end-stage renal disease. It was established in 1965 and is run by the Center for Medicare and Medicaid Services (CMS). The program is funded by federal general revenue, payroll taxes, and beneficiary premiums.

### Components

- **Part A:** Covers inpatient care including inpatient hospital services, skilled nursing facility care, home health, and hospice care. There are limits on the number of days paid for in a facility. These are subject to copayments and deductibles.
- **Part B:** Covers outpatient care including physicians’ services, outpatient hospital services, medical equipment, and other services not covered by Part A.

These are also subject to copayments and deductibles.

- **Part C Medicare Advantage:** Voluntary programs that allow beneficiaries to opt out of traditional Medicare and enroll in private insurance plan that will cover all regular Medicare benefits and possible additional benefits. Medicare then pays the private insurers a fixed amount per beneficiary per month.
- **Part D:** Covers voluntary prescription drug coverage. Beneficiaries sign up through private insurers. It covers 75% of annual prescription costs up to \$2,700 and 95% of costs over \$6,154. Costs between \$2,700 and \$6,154 are not paid and this coverage gap is called the “donut hole.”

### 19.3.2 Medicaid

Medicaid is a government health insurance program administered by each state, which provides coverage for individuals and families with the greatest need, usually based on low income. It was also initiated in 1965. States must cover all citizens in groups whose incomes are less than a certain level set by each state. Included in these groups are children, parents with dependent children, pregnant women, people with severe disabilities, and seniors.

### 19.3.3 Insurance Payments

Health care facilities, individual providers, and insurers receive payment for services provided in an ever-complex way. The traditional direct payment by a patient to a doctor or hospital has largely been replaced by complicated contractual agreements between insurers and providers. In these, the physicians and hospitals or health systems may have independent contracts with insurers.

## Mechanisms of Payments

- **Fee for service:** A set price is paid for a given health care action. This may incentivize providers to perform more procedures and tests to receive more payment.
- **Pay for performance:** Payment based on measures of clinical quality, safety, efficiency, and patient satisfaction.
- **Per diem:** A flat fee is paid for each day the patient is admitted and covers any care that occurs during that day.

Today, most physician services are paid and calculated based on the following:

- **Relative value unit (RVU):** A RVU is calculated for each action a physician performs and is based on the work of the physician, expense to the practice, and cost of malpractice insurance.

In contrast, hospital services are paid and calculated based on a nonparallel system of the following:

- **Diagnosis-related groups (DRGs):** Payment is given for treatment of a patient based on the DRG, which best describes the condition. Treatment of the same illness can result in a wide variety of payments, depending on which DRG the patient falls into. These were originally developed as a classification scheme to relate the types of patients a hospital treats to the costs occurred by that hospital.

Both of these are dependent on the two additional systems of coding:

- **CPT (Common Procedural Terminology):** A set of codes that match a specific treatment or encounter. These include office visits and consultations (inpatient and outpatient) as well as surgery and procedures.
- **ICD-10 (International Classification of Disease):** A worldwide set of numbers that correspond specifically to diagnoses

and etiologies that bring the patients to health care providers.

Increasingly, hospitals and physicians may also be subject to the following:

- **Bundled payments:** One lump sum is paid per diagnosis for the entirety of the patient's care. This includes laboratory tests to nursing assistance, to posthospitalization rehab.
- **Capitation:** A flat rate is paid per patient, regardless of the severity of the disease, complications, or length of hospitalization.

### 19.3.4 Advocacy

In a time of everchanging health care, it remains vital to defend and protect the abilities of neurosurgeons to practice medicine freely and advance the specialty for the patients they serve. Organized neurosurgery via the American Association Neurological Surgeons (AANS) and the Congress of Neurological Surgeons (CNS), through its Washington Committee and Washington office, work tirelessly to improve our nation's health care delivery through a fundamental influence in health care policy development (see section 20.6). Although the AANS and CNS Legislative and Regulatory Agenda may change from year to year based on current trends and up-to-date neurosurgeon surveys, what remains constant is the ongoing support of high-quality patient care and access to timely advancements in our specialty, continuance of quality resident's training and education, meaningful medical liability reform, fair payment, and streamlining meaningful quality improvement. Neurosurgery leaders continue to remain at the forefront in shaping health policy debate while maintaining a high-quality neurosurgery workforce and ensuring a health care system that offers better value for today and the future.

## 19.4 Personal Finance

Despite our near constant exposure to death, illness, and incapacitation, less than 66% of physicians have completed the essential legal documents related to this inevitable process. These include the following:

- **Living will:** Written, legal document spelling out what medical treatments you would or would not want to be used to keep you alive.
  - Includes pain management, organ donation, resuscitation, mechanical ventilation, tube feeding, etc.
- **Health care proxy:** Type of advance directive in which you name a person to make medical decisions for you in the event you are unable to express your preferences.
  - Also called health care surrogate, durable medical power of attorney, health care agent, patient advocate.
- **Living will and testament:** Provides the legal basis of transferring your estate to others (including a spouse, family, charity, offspring) as well as establishing the basis of care for any surviving minors.
  - There is no standard form and does not require an attorney though they can be invaluable in helping to guide you through critical decisions. It does require two witnesses, a date and time.
  - It is strongly recommended that your Will be reviewed every 5 years as your finances and family situations are constantly changing.
- **Durable power of attorney:** This essential document provides another individual to make legal and financial decisions on your behalf should you be temporarily or permanently unable to do so.

In addition to the legal documents, there are other financial issues that every physician should consider:

1. **Life insurance:** Contract between an insurer (insurance company) and policyholder.
  - Policy holder/owner: Pays the premium payments to the insurance company.
  - Insured person: Person whose life the policy is based on.
  - Insurer: Responsible for paying out claims in the case of a death of the insured person.
  - Beneficiary: Person who receives the claim after the death of the insured.
2. **Disability insurance:** Form of insurance that offers income protection to individuals who become disabled or are unable to work for a period of time (terms vary between policies).
  - Short term: Generally 3 to 6 months.
    - Waiting period of 0 to 14 days after becoming sick/disabled—some require use of certain number of sick days/vacation time.
    - Usually covers 40 to 60% of employee's weekly gross income.
  - Long term: Begins after 3 to 6 months.
    - Usually covers 50 to 60% of weekly income.
3. **Retirement:** Most physicians (except a small number working in the military or government service) will not receive any type of pension upon cessation of work as a doctor. Therefore, each individual must provide for themselves the necessary funds for years of retirement, which are everexpanding given the extension of life expectancy. Financial models clearly support the following concepts:
  - Starting early is key (some may even have the option to establish funds during training).
  - Maximize all available options, particularly any programs where institutions offer matching funds.
  - Saving money is far easier when the money never becomes accessible

(i.e., when it is directly placed into retirement rather than requiring postpayment investment).

- A well-selected financial advisor can be invaluable but does not replace your own need for diligence and determination based on your individual needs and values.

## 19.5 Job Satisfaction

Most neurosurgeons have already worked many hard years before establishing an independent practice. This likely has required significant sacrifice personally and for your loved ones. Thus, it becomes even more important as you embark on this next stage of your life as a neurosurgeon to work to achieve career satisfaction as well as a solid work-life balance.



Job satisfaction and career growth must be an active process in which you are constantly evaluating your goals and achievements, being your own worst critic and also being realistic and knowing there is no “perfect job.”

Having a mentor can prove invaluable in this process. For this, it is also important to understand the following points:

- Understand the leading trends in health care delivery.
- Perceive the goals, challenges, and preferences of those around you.
- Recognize that you don't work in a vacuum.

It is equally important to stop and “smell the roses.” In this, you must constantly strive to establish and maintain priorities beyond your career that encompass family, health, fun, and sleep. These will ultimately make you a better physician and allow you to be a better provider for your patients.

## 20 Advice from the Masters

Michael D White, Michael P D'Angelo, Ahmed Kashkoush, Edward A Monaco III

### 20.1 Introduction

This chapter is intended to be used as a comprehensive guide for medical students and residents who are interested or training in the field of neurosurgery. Though there is a large amount of information and resources in this chapter, it is recommended to take this chapter in sections, only focusing on sections that pertain to the level of medical education you are currently at. First year medical students may want to focus on the *Peer-Reviewed Journals* and *National Conferences* sections. However, as you go through medical training and your interests begin to take hold, you may want to focus more on the subspecialty subchapters, as we provide valuable resources in a myriad of neurosurgical subspecialties. For the *Peer-Reviewed Journals* section, each journal is rated by its impact factor (based on the 2016 Thomson Reuters™ Journal Citations Reports®), a measure of how many times the average paper is cited each year. The following resources were compiled from recommendations of top neurosurgeons throughout the country and from multiple programs.

### 20.2 Additional Reading

Reading about neurosurgery should be a daily habit and will provide you with a solid foundation of knowledge that will help guide you throughout your training.

#### 20.2.1 General

##### **Essential Neurosurgery**

*Andrew H. Kaye*

This resource is written for medical students and junior residents and is a great

overview of the field of neurosurgery. The book includes information on diagnosis and management of common central nervous system disorders as well as the pathologic basis for disease.

##### **Landmark Papers in Neurosurgery**

*Reuben D. Johnson and Alexander L. Green*

This collection of influential studies in the field of neurosurgery is essential for any neurosurgical trainee. With the increased emphasis on evidence-based medicine, the key findings from landmark studies within the field will help guide clinical decision making.

##### **Handbook of Neurosurgery**

*Mark S. Greenberg*

An invaluable resource for all neurosurgeons that covers anatomy, physiology, differential diagnosis, and principles of clinical management useful for quick referencing.

##### **Neurosurgery Knowledge Update**

*Harbaugh, Saffrey, Couldwell, Berger.*

Large textbook that covers a broad range of the important topics in neurosurgery.

##### **Neuroanatomy through Clinical Cases**

*Hal Blumenfeld*

An interactive approach to the teaching of neuroanatomy, using over 100 actual clinical cases and high-quality radiologic images.

##### **So, You Want To Be a Neurosurgeon? Second Edition**

*Muraszko, Benzil, Todor*

This “brochure,” originally written in 1999 by Dr. Muraszko and Dr. Benzil, was updated in 2009 by Dr. Roxanne Todor. It is

a short read and a fantastic guide for those wishing to pursue neurosurgery.

### Principles of Neurological Surgery

#### *Principles of Neurological Surgery*

This is a comprehensive overview of neurosurgery topics. Covers every aspect of neurosurgery, including pre-op/post-op, neuroradiology, spine surgery, oncology, pediatrics, etc.

## 20.2.2 Operative

### Schmidek & Sweet Operative Neurosurgical Techniques

#### *Alfredo Quinones-Hinojosa*

A great resource for neurosurgical procedures including operative indications, techniques, and complications. There are also accompanying videos for each procedure for visual learners.

### Youmans Neurological Surgery

#### *H. Richard Winn*

Thorough guide to operative neurosurgery that covers the latest neurosurgical procedures. This resource is also accompanied by almost 100 online videos of procedures.

### Neurosurgical Instrument Guide

#### *Christopher S. Eddleman*

Valuable overview of operative principles and instrument sets. Great reference for visual identification of surgical instruments used in neurological surgery and their uses.

### Operative Dictations: Neurosurgery

#### *Chaim B. Colen*

This reference is useful to gain proficiency in verbal dictation. With the current emphasis on medical documentation, this is an essential text for any neurosurgical trainee.

## 20.2.3 Subspecialties

### Critical Care

#### **Marino's The ICU Book**

##### *Paul L. Marino*

A comprehensive critical care resource, which includes both medical and surgical aspects of critical care. This book is not specific to neurosurgery, but the principles Marino discusses are imperative for any incoming resident to understand.

### The NeuroICU Book

#### *Kiwon Lee*

This book provides evidence-based approaches to neurological critical care and has the latest studies that guide management.

## Endovascular

### Diagnostic Cerebral Angiography

#### *Anne G. Osborn*

This book is one of the best references for cerebral angiography. It is organized into three sections covering techniques, anatomy, and pathological entities..

## Neuroradiology

### Neuroradiology: The Requisites

#### *Rohini Nadgir and David M. Yousem*

Contains everything you need to know about the conceptual, technical, and interpretive core knowledge required for imaging the brain, spine, and head and neck.

## Pain

### Textbook of Pain

#### *Wall and Melzack*

The newest edition (6th) provides the most up-to-date and comprehensive information

regarding genetics, neurophysiology, psychology, and assessment of pain.

## Peripheral Nerve

### Examination of Peripheral Nerve Injuries

*Stephen M. Russell*

This is an anatomically based guide to diagnosing peripheral nerve injuries. There are excellent illustrations that aid in understanding the complex anatomy and its variations.

### Aids to the Examination of the Peripheral Nervous System

*Michael O'Brien*

This atlas is the standard photographic guide to examination of patients with peripheral nerve lesions.

## Pediatrics

### Principles and Practice of Pediatric Neurosurgery

*Albright, Pollack, and Adelson*

Extremely thorough book outlining the management techniques of clinical pediatric neurosurgery.

### Handbook of Pediatric Neurosurgery

*Jallo, Kothbauer, Recinos*

This book covers the full breadth of pediatric neurosurgery and covers congenital, developmental, and acquired disorders. It is an excellent pocket reference to carry with you on the wards.

## Skull Base

### Skull Base Surgery

*Paul Gardner and Carl Snyderman*

Offers step-by-step expert instruction on over 45 procedures, covering both open and minimally invasive approaches to the skull base.

## Spine

### Handbook of Spine Surgery

*Baaj, Mummaneni, Uribe, Vaccaro, and Greenberg*

Much like the other handbook by Greenberg, this is a great pocket reference for spine.

## Stereotactic Radiosurgery

### Intracranial Stereotactic Radiosurgery

*L. D. Lunsford and Jason P. Sheehan*

A comprehensive resource that discusses a multitude of intracranial disorders this technology can treat as well as indications, techniques, and complications for treating each disorder.

### Modern Stereotactic Neurosurgery

*L. D. Lunsford*

As a pioneer of stereotactic radiosurgery, Dr. Lunsford explains the basic techniques and neurosurgical treatment of disease with stereotactic radiosurgery.

### Spine Radiosurgery

*Peter C. Gerszten and Samuel Ryu*

This book focuses on radiosurgical treatment of spinal pathology. Discusses most recent advances in devices, techniques, and treatment planning for spinal radiosurgery.

## Vascular

### Vascular Neurosurgery

*R. Loch Macdonald*

Part of the Neurosurgical Operative Atlas, this book offers extreme detail regarding the surgical management of neurovascular diseases.

### Seven Aneurysms

### Seven AVMs



### Seven Bypasses

Michael T. Lawton

These are essential references for vascular neurosurgery and are written clearly with phenomenal illustrations.

## 20.2.4 Online

### Neurosurgical Survival Guide

This is a mobile app which provides easily accessible, high-yield information regarding neurosurgical care.

### HeadNeckBrainSpine.com

This is a website devoted to neuroradiology, providing case reports, modules, and flash cards, all designed to familiarize the student with neuroradiology anatomy.

### NeurosurgicalAtlas.com

This is a website that provides reading material, surgery videos, and grand rounds videos covering all facets of neurosurgery.

### The Rhoton Collection

This is a collection of neuroanatomy teaching materials which includes slides, video lectures, and an interactive atlas. Access is free for AANS members.

### The Surgeon's Armamentarium

This is a website for CNS members which provides access to a variety of neurosurgical resources including video libraries, case reports, and anatomy atlases.

### NeuroVascularCases.com

This is a website designed to help students become more familiar with neurovascular disease through case reports and angiography diagrams.

## 20.2.5 Memoirs

### When the Air Hits Your Brain

Frank Vertosick Jr.

Dr. Vertosick tells tales of the triumphs and tragedies throughout his training and practice of neurosurgery. This book offers an appreciation for the great privilege and responsibility that comes with a career in neurosurgery.

### Another Day in the Frontal Lobe

Katrina Firlik

Dr. Firlik gives a very candid and, at times, humorous glimpses into her experiences as a neurosurgeon. Her writing style is engaging and makes for a very entertaining and insightful read.

### Gifted Hand

Ben Carson and Cecil B. Murphy

This is an autobiography in which Dr. Carson reflects on his experiences as a neurosurgeon. He wrote this book with a wide audience in mind and may lack medical details that some medical students or residents desire. However, it is an insightful and easy read.

### When Breath Becomes Air

Paul Kalanithi

An intimate autobiography from Dr. Kalanithi that he wrote after he discovered he had terminal cancer. This is a powerful book that provokes reflection into one's own meaning of life and defining one's identity.

### Do No Harm

Henry Marsh

In this New York Times best seller, Dr. Marsh gives intimate insight into the life of a neurosurgeon. He gives a surprisingly honest and frank perspective on the field.

### Being Mortal

Atul Gawande

In this book, Dr. Gawande explores death and dying, where doctors often forget the overall well-being of patients in their attempt to do

everything medically to prolong their life. An interesting read about aging and the medical field's approach to end of life care.

## 20.3 Conferences

National conferences attract neurosurgeons from all over the country and are a great way to meet faculty and residents from different programs. Conferences also provide an opportunity to present and discuss your research with others in the field of neurosurgery.

### 20.3.1 General

#### **American Academy of Neurology (AAN)**

The AAN annual conference is the largest gathering of neurologists and neuroscientists in the world. There is also a travel scholarship for students to attend the conference.

#### **American Association of Neurological Surgeons (AANS)**

This conference is free for medical students. You can also become a member of the AANS, which has many benefits and is free to join as a medical student. The AANS also has medical student and resident positions on the Young Neurosurgeons Committee that you can apply for and become a representative for the AANS.

#### **Congress of Neurological Surgeons (CNS)**

Great networking opportunity for both medical students and residents. Like the AANS, you can also apply for membership in the CNS, which is also free for medical students.

#### **Council of State Neurosurgical Societies (CSNS)**

This is a biannual meeting that focuses on discussion and proposals of action regarding socioeconomic issues within neurosurgery.

#### **Society for Neuroscience**

This meeting is not a dedicated neurosurgery conference and may be expensive for nonmembers.

### 20.3.2 Subspecialties

#### **Endovascular**

##### **Society of NeuroInterventional Surgery**

This conference is great for those interested in endovascular neurosurgery.

#### **Neuroradiology**

##### **American Society of Neuroradiology (ASNR)**

Annual conference for general neuroradiology. The conference is not specific to neurosurgery.

##### **American Society of Spine Radiology (ASSR)**

This annual conference is specific for imaging related to spinal disorders.

##### **American Society of Head and Neck Radiology (ASHNR)**

This is neuroradiology-specific conference related to head and neck imaging that attracts physicians from a multitude of specialties, and not just neurosurgery.

#### **Pain**

##### **Cancer Pain Research Consortium**

Expensive and not advertised for medical students, only providers. It is also not a dedicated neurosurgery conference.

##### **AANS/CNS Joint Section on Pain**

Conference meets every other year and is again, a niche field. This is a dedicated neurosurgery conference, making networking an option.

## Pediatrics

### **AANS/CNS Joint Section on Pediatric Neurosurgery**

This joint AANS and CNS conference is devoted specifically to pediatric neurosurgery and is one of the primary pediatric neurosurgery conferences.

### **International Society for Pediatric Neurosurgery**

Meeting is held in new places all across the world and attracts the biggest names in pediatric neurosurgery.

## Peripheral Nerve

### **Peripheral Nerve Society**

Annual conference showcasing international research across specialties in peripheral neuropathy.

### **American Society for Peripheral Nerve**

Annual conference pertaining to peripheral nerves that is intended for surgeons, researchers, and healthcare professionals in the field.

## Skull Base

### **North American Skull Base Society**

This annual meeting brings together health care professionals across a multitude of specialties to discuss the most recent recommendations for management of skull base pathology.

## Spine

### **Cervical Spine Research Society (CSRS)**

Expensive for nonmembers though a great conference for those interested in spine.

### **Lumbar Spine Research Society (LSRS)**

This is an annual meeting that concentrates on advancements in lumbar spinal

surgery. The goal of the LSRS conference is purely for scientific research presentations and debate.

### **North American Spine Society (NASS)**

Largest spine meeting in the country. Expensive without a membership, though an excellent meeting for those interested in spine.

### **Society of Lateral Access Surgery (SOLAS)**

An annual conference with a focus on lateral access spinal surgery.

### **Society for Minimally Invasive Spine Surgery**

Somewhat pricey conference that is geared more toward providers rather than medical students.

### **Spine Summit**

Annual meeting with a focus on disorders of the spine and peripheral nerves. A relatively inexpensive conference (\$50 for medical students and residents) without a membership requirement.

## Stereotactic and Functional

### **North American Neuromodulation Society (NANS)**

Not free for medical students and can cost several hundred dollars to register. Young scientist travel awards are available for \$1,000. You can also gain membership in the NANS; however, it costs \$50 for medical students and residents.

### **American Society for Stereotactic and Functional Neurosurgery (ASSFN)**

A very niche field that would only appeal to those interested in functional neurosurgery. Conference meets every other year. Membership in the ASSFN provides reduced fees to their biennial meeting and a subscription to the journal *Stereotactic and Functional Neurosurgery*.

## Tumor

### AANS/CNS Joint Section on Tumors

A specialty conference with a focus on central nervous system tumors.

### AANS/CNS Tumor Section Satellite Symposium

Held in conjunction with the CNS meeting and covers various topics in the field of neuro-oncology and management of CNS tumors.

## Vascular

### Microsurgical Approaches to Aneurysms and Skull Base Disease

Geared toward medical providers, not medical students. Another relatively inexpensive conference (\$100 registration fee for residents and physicians).

### AANS/CNS Joint Cerebrovascular Section

This is a joint conference between AANS and CNS related to cerebrovascular disorders and neurointerventional treatments.

## 20.4 Grants and Awards

Available grants can not only help fund your research, but will also demonstrate on residency applications that you are capable of designing a research project whose quality merits outside funding. Additionally, receiving research awards is an opportunity to demonstrate your aptitude in conducting research to your peers and residency directors.

### 20.4.1 General

#### CSNS/CNS Medical Student Summer Fellowship in Socioeconomic Research (MSSF-SER)

This is an 8- to 10-week fellowship for medical students who are interested in conducting socioeconomic research in the field of neurosurgery. A stipend of \$2,500 is given to accepted applicants.

### Howard Hughes Medical Institute (HHMI) Medical Research Fellows Program

Year-off fellowship for medical students to fund basic science research. Increase your chances of acceptance by getting involved in a laboratory early during medical school and by producing preliminary results to include in the application. Also helps to seek out National Institutes of Health (NIH)-funded scientists, HHMI investigators, or Nobel Laureates to sponsor year off.

### Galbraith Award

Awarded to the best abstract submitted by a resident at the annual CNS meeting.

#### NREF Medical Student Summer Research Fellowship

Offers 25 grants \$2,500 grants to first or second year medical students who wish to spend the summer conducting neurosurgery research under an AANS neurosurgeon mentor. Needs two letters of recommendation from neurosurgeons, so plan for this early.

### Presuss Award

Awarded to the best basic science abstract by a resident at each AANS and CNS annual meeting.

### Technology Development Grant

Offers a \$2,500 to \$10,000 grant for medical students or residents with a technology-based project that can be completed within a year.

## 20.4.2 Subspecialties

### Pediatrics

#### Shulman Award

Presented to the best paper presented by a resident at the joint CNS/Pediatric Neurologic Surgery meeting.

## Spine

### Charlie Kuntz Scholar Award

Awards are given to the top 30 neurosurgical residents or fellows who author outstanding abstracts in clinical or laboratory research of spinal disorders. The award consists of \$500 for award recipients with the opportunity to be awarded an additional \$1,000 for those who submit a complete manuscript with their abstract. Award winners are announced at the annual Spine Summit.

### Journalistic and Academic Neurosurgical Excellence (JANE) Award

Awarded annually at the Spine Summit to the senior resident or fellow with the top manuscript as well as showing commitment to advancing the field through research and publications over the past 12 months. Award winners receive a prize of \$1,500 and the opportunity to give an oral presentation during the conference.

### Kline Award

The recipient of the Kline award is provided up to \$10,000 of funding for basic science or clinical research pertaining to peripheral nerves. Current residents are eligible for the award but will need a faculty sponsor for the project.

### Mayfield Clinical Science Award

Awarded to residents or fellows with outstanding manuscripts in clinical or laboratory research in the field of spinal and peripheral nerve disorders. Two award winners, one in clinical and one in laboratory research, will be announced at the annual AANS/CNS section of spinal and peripheral nerve conference and awarded a \$1,000 honorarium and up to \$2,000 to cover cost of attending the conference.

### Synthes Award

Awarded to the best abstract by a resident related to spinal cord or spinal column injury at the annual CNS and AANS meetings.

## Tumor

### Ronald L. Bittner Award

Awarded to the best abstract related to brain tumor research at the AANS annual meeting by a resident or junior faculty.

### Farber Award

Presented at the annual CNS conference to the best abstract related to neuro-oncology.

### National Brain Tumor Foundation Translational Research Grant Award

A \$15,000 grant awarded to the best translational research proposal related to brain tumors.

## Vascular

### Brain Aneurysm Foundation (BAF) Research Grant

This is the largest private fund for brain aneurysm research and awarded \$310,000 to 11 recipients in 2016. Grants are mainly awarded to basic science projects that will help improve outcomes of patients with aneurysms; however, clinical and translational research projects can also get funded.

### Robert J. Dempsey, MD, Cerebrovascular Research Award

This fellowship supports a basic science or clinical research project by a resident in an approved neurosurgical residency program.

### Kate Carney Cerebrovascular Research Fellowship Grant

A relatively new award that provides funds to pursue cerebrovascular research; however, the exact award amount has not been confirmed.

## 20.5 Journals

After conducting a research project, you will want to share your findings with the scientific community by

having the results published in a peer-reviewed journal. Your research productivity will be measured by your “h-index” which is measured by how many citations your top publications receive. For example, an h-index of 5 indicates that the author has five publications that were each cited at least five times in other papers. Below is an expansive list of possible journals in which to submit scientific papers (►Table 20.1, ►Table 20.2).

## 20.6 Leadership

Leadership positions are one last opportunity to round out your resume should you have the time and drive to do so. They will help you become a well-rounded applicant and also show that you have an ability to work with others.

### MISSION Fellows

The Medical Student in Organized Neurosurgery (MISSION) Fellowship is a 2-year fellowship that allows medical students to

**Table 20.1** General journals

| Journal name                                                          | Impact factor |
|-----------------------------------------------------------------------|---------------|
| Journal of Neurology Neurosurgery & Psychiatry                        | 7.35          |
| Neurosurgery                                                          | 4.89          |
| Journal of Neurosurgery                                               | 4.06          |
| Journal of Neurosurgical Anesthesiology                               | 3.24          |
| Neurosurgical Focus                                                   | 3.14          |
| World Neurosurgery                                                    | 2.59          |
| Neurosurgery Clinics of North America                                 | 2.49          |
| Journal of Neurological Sciences                                      | 2.3           |
| Neurosurgical Review                                                  | 2.26          |
| Neural Regeneration Research                                          | 1.77          |
| International Journal of Neuroscience                                 | 1.75          |
| Clinical Neurology and Neurosurgery                                   | 1.74          |
| Operative Neurosurgery                                                | 1.67          |
| Surgical Neurology                                                    | 1.67          |
| Journal of Clinical Neuroscience                                      | 1.56          |
| British Journal of Neurosurgery                                       | 1.24          |
| Journal of Korean Neurosurgical Society                               | 0.86          |
| Turkish Neurosurgery                                                  | 0.78          |
| Journal of Neurological Surgery Part A: Central European Neurosurgery | 0.73          |
| Interdisciplinary Neurosurgery                                        | 0.11          |

| <b>Table 20.2</b> Subspecialty Journals            |                      |
|----------------------------------------------------|----------------------|
| <b>Journal name</b>                                | <b>Impact factor</b> |
| <b>Endovascular</b>                                |                      |
| Journal of Neurointerventional Surgery             | 3.55                 |
| Vascular and Endovascular Surgery                  | 1.09                 |
| <b>Infection</b>                                   |                      |
| Clinical Infectious Diseases                       | 8.22                 |
| The Journal of Infectious Diseases                 | 6.27                 |
| Journal of Neuroinflammation                       | 5.19                 |
| Journal of Neurovirology                           | 3.23                 |
| Neuroinfectious Diseases                           | 0.77                 |
| <b>Neuro-Oncology</b>                              |                      |
| Journal of Neuro-Oncology                          | 2.98                 |
| <b>Neuroradiology</b>                              |                      |
| American Journal of Neuroradiology                 | 3.55                 |
| <b>Stereotactic and Functional</b>                 |                      |
| Neuromodulation                                    | 2.61                 |
| Stereotactic and Functional Neurosurgery           | 1.69                 |
| <b>Pediatrics</b>                                  |                      |
| Journal of Neurosurgery: Pediatrics                | 2.17                 |
| Pediatric Neurology                                | 2.02                 |
| Journal of Child Neurology                         | 1.38                 |
| Child's Nervous System                             | 1.24                 |
| Pediatric Neurosurgery                             | 0.55                 |
| Journal of Pediatric Neurology                     | 0.08                 |
| <b>Skull Base</b>                                  |                      |
| Journal of Neurological Surgery Part B: Skull Base | 1.07                 |
| Otolaryngology: Head and Neck Surgery              | 2.44                 |
| <b>Spine</b>                                       |                      |
| The Spine Journal                                  | 2.96                 |
| Journal of Neurosurgery: Spine                     | 2.7                  |
| European Spine Journal                             | 2.56                 |
| Spine                                              | 2.5                  |
| Clinical Spine Surgery                             | 1.99                 |
| The Journal of Spinal Cord Medicine                | 1.63                 |
| Journal of Craniovertebral Junction and Spine      | 1                    |
| Scoliosis                                          | 0.3                  |

(Continued)

**Table 20.2** (Continued) Subspecialty Journals

| Journal name                                     | Impact factor |
|--------------------------------------------------|---------------|
| <b>Trauma</b>                                    |               |
| Journal of Neurotrauma                           | 5.19          |
| <b>Vascular</b>                                  |               |
| Stroke                                           | 6.03          |
| Journal of Vascular and Interventional Neurology | 2.78          |

serve on subcommittees under the guidance of an AANS Young Neurosurgeon's Committee member. Applicants will also be expected to propose a research topic that addresses a system or practice issue in an area of interest. They will then have the opportunity to present their work at the Young Neurosurgery Committee's annual meeting.

#### **CSNS Socioeconomic Fellowship**

This is a fellowship specific for residents, hosted by Council of State Neurosurgical Societies, that is intended to offer a chance to explore and understand the socioeconomic issues in the neurosurgical world. You should have a firm interest for socioeconomic health care issues, as there are many requirements, all of which can be found on CSNS's website.

#### **Washington Committee Fellowship**

This fellowship is offered to residents who are currently completing or have recently completed the CSNS socioeconomic fellowship. It presents an opportunity for a resident to serve on a committee that advocates for the specialty of neurosurgery and its patients to legislative, regulatory, and other health care stakeholders.

#### **CNS Leadership Fellows**

This is another resident-specific fellowship that allows participants to integrate into the CNS leadership structure by serving on

a specific committee for which they serve 2 years.

#### **Young Neurosurgeons Committee**

This is a resident-specific fellowship that provides representatives to the AANS leadership. It is intended to foster the development of the future leaders in the field and to allow younger voices an opportunity to speak on the direction of neurosurgery.

## **20.7 Board Review**

In order to become board certified in neurologic surgery, residents must first pass the American Board of Neurological Surgery's written and oral examinations. Below we provide a list of the most useful preparatory resources for these examinations.

#### **SANS Written Board Module Bundle**

This is a module-based online review program from CNS, which includes 700 practice questions to prepare for the written boards. It costs \$425 for residents and includes a pretest and posttest assessment—a great way to see what you've learned from the 700 practice questions with instant feedback and references as you answer.



**SANS Boards App**

This is an app for mobile devices from CNS, which includes 200 board review questions with feedback and references. Questions can be taken in test format as well, and can be taken as many times as you want.

**Comprehensive Neurosurgery Board Review**

*Citow, Macdonald, and Refai*

This is a comprehensive review book for the written neurosurgical boards. The book covers concepts in anatomy, physiology, pathology, radiology, neurology, neurosurgery, and critical care. A bullet point format provides clear and concise text, along with illustrations that are representative of those found on the examination.

**Colen Flash-Review: Neurosurgery**

*Chaim B. Colen and Roxanne E. Colen*

Two volumes of flashcards containing high yield information for both board review and clinical applications.

**Neurosurgery Board Review: Questions and Answers for Self-Assessment**

*Alleyne, Woodall, and Citow*

Written in a multiple-choice format, this board review book mirrors the written examination's format and covers the same topics: neurosurgery, clinical neurology, neuroanatomy, neurobiology, neuropathology, neuroradiology, clinical skills/critical care. This resource provides over 1,000 questions with explanations.

**Definitive Neurological Surgery Board Review**

*Moore and Psarros*

With coverage of all topics found on the written board examinations, this review book is a great succinct resource for boards preparation. The book provides illustrations

and hits all the key concepts encountered on the examination.

**Intensive Neurosurgery Board Review: Neurological Surgery Q&A**

*Psarros and Moore*

A companion book to the previously listed resource, this book provides 1,300 practice questions written in the same format as the written board examinations. Each question includes detailed explanations for each answer option. The book finishes with a self-assessment examination designed to simulate the real written board examination.

**Neurosurgery Rounds: Questions and Answers**

*Shaya, Nader, Citow, Farhat, Sabbagh*

The ultimate defense against tough pimping questions. The field of neurosurgery is known for frequent pimping questions, and this resource is invaluable in allowing yourself to stand out.

**Neurosurgery Oral Board Review**

*Citow and Johns*

This book is a summary of all topics covered on the neurosurgery oral examinations. Sections include medical management, surgical techniques, and key insights on how to study for the oral test. Written in a clear and concise manner with illustrations, this book is designed to be a quick and readable preparatory resource.

**Neurosurgery Primary Board Review**

*Ross C. Puffer*

This is a comprehensive question bank aimed towards preparing neurosurgeons for the ABNS written examination. The review book consists of over 600 questions and explanations, with another 900 questions via access to corresponding online material. Great resource for practice questions that mimic the written exam.

## 20.8 The Masters

**Robert M Friedlander, MD, MA**

Chairman and Professor

Walter E Dandy Chair

Head of Cerebrovascular Neurosurgery

Department of Neurosurgery

University of Pittsburgh Medical Center

Pittsburgh, Pennsylvania

### *General advice*

"You want to be passionate. You want that fire in your belly, that sparkle in the eye, and someone who gets excited about doing things. Neurosurgery is a small community so we spend a lot of time with the residents. So you want to have people that you get along with. People who are pleasant, who are good to get along with, who are passionate, and who work. When they're given a project, they finish it. If I give you a project, and you never do it, then I'm not going to give you another project. You want to think if the applicant would be in my chair, what would they be looking for. You don't look for someone who's average at this, average at that, and not passionate."

### *Feasibility of basic science research*

"I had a mentor, Bob Martuza, who was a faculty member with his own laboratory. If you have a mentor, if you see it in someone, you believe that it can be done. However, if you don't see someone who does it, it's difficult to make those two points meet. If someone really, really, really wants to have a laboratory in neurosurgery, you have to spend the time doing it. I was always thinking about research, reading about different fields. However, in residency, I really did 2 years of research and that's key because you have to do a focused amount of work. I don't have a PhD. You have to do a focused amount of work at some point. One of my concerns with all of these enfolding fellowships is that people are not doing research. It doesn't work if you go to

the laboratory 1 day a week or 2 days a week. It's really, really, really hard to develop the material for you to go start a laboratory. It's really important that if you're going to be a neurosurgeon in a basic field, try to do something that makes you special. Whether you're the very first person in the field, if you create a field that'd be great, or work in a field that nobody other than a neurosurgeon can do. For me, I wanted to be the first person to look at caspases in all of these neurologic diseases. When I was in the laboratory, we published it on stroke. That was the first demonstration in the world of functional caspase activity in any neurologic disease. Then we did it in ALS and in Huntington's disease, which eventually led to my first RO1 in my first year out of residency."

### *Excelling in your field*

"Some people think that shadowing is important. Some people do months and months of shadowing. That's a waste of time. Figure out what you like and don't like. Get involved with projects and find out what you want to do in the long term. To me, eventually I figured out neurosurgery. However, I wanted to have a laboratory, so I did research and I was in a laboratory. That's how I spent my time. It's a zero-sum game. There's only 24 hours in a day. You have to figure out what you want to do. You can't do it all. You can't do it all well. There's a certain amount of brain time that you have so you have to figure out where you want to spend it. However, try to make an impact. Whenever I try to do something, I choose what's going to have the highest impact. For instance, I usually don't write review articles. For my publications, as best as I can, I try to aim high. Making high-impact publications is pretty tough. However, you want to aim high. Think of your life in 5-year chunks. You don't have to do a high-impact study every year, but if you can do one every 5 years, that's pretty cool."

If you don't aim for JAMA or New England Journal papers, then you'll never get it. You may not get it, but maybe you'll fall right below. However, if you don't aim for something big, you'll never get something big. So you have to be strategic how you spend your time. As a student, you can't ignore the ABCs like anatomy, physiology, and all that other stuff, but in addition to that, you want to decide what you want to be."

#### *Work-life balance*

"It's important to have a balance with family. I got married right at the end of residency. Whether the ability to work really, really hard without children was an advantage, I don't know, that's not how I planned it. However, when you have children you want to dedicate time to them. I had children during second year of faculty. The first couple of years during faculty I learned to devote myself to the clinic and the laboratory. When the children come, you have to spend time with them, because you want to spend time with them. That really balances my life. To me, my life is work and family."

#### **L Dade Lunsford, MD, FACS**

Lars Leksell Distinguished Professor  
Department of Neurosurgery  
Director, Center for Image Guided  
Neurosurgery  
Director, Neurosurgery Residency  
Program  
Chair, Technology and Innovative Practice  
Committee  
University of Pittsburgh  
Pittsburgh, Pennsylvania

#### *Traits of successful applicants*

"If we look at the composite of people that are successful applicants to neurosurgery and eventually successful practitioners of it, they have a lot of energy, a lot of drive, and they can multitask well. They tend to perform well in terms of their school activities, usually in the upper 20% of their class.

They're hard workers. They tend to perform well on standardized testing, although standardized testing is not a good predictor of subsequent success, either as a resident or later in your career. They are often involved in research activities, much more so now than what was ever seen in the past. They tend to be multidimensional, in the sense that they often have some other particular interests, which is important to neurosurgeons because of the types of problems that we have to deal with. Often, there are fantastic results and beautiful outcomes, and every once in a while disasters and very bad outcomes, so you have to have a personality that is resilient enough. You must be able to deal not only with the great triumphs but also with the great tragedies that occur in your career. Many of them have other skill sets that are important. Almost everybody who is going to be a successful surgeon has some evidence that his or her skill set includes the brain being able to tell the hands to do something. So sometimes that may be a musical instrument, sometimes that may be sports, sometimes in today's world, you're the world's greatest computer whiz. However, there has got to be substantial outside interests to be able to help your mind deal with stress. Training in neurosurgery is among the most difficult and longer career choices. That means that somebody's got to be well-focused, and can be able to look at long-term goals. Neurosurgery is a tremendously rewarding career, but also a tough lifestyle choice. So people need to be prepared for that. You might think that working for 80 hours a week is no big deal as a resident because you're young and healthy, but the reality is that neurosurgery is an 80-hour workweek for the rest of your life. We're the only training program in any discipline that's 7 years in the United States right now. No other surgical discipline is that long. People that go into neurosurgery are a different breed—it's not made for everyone. We want to attract

people that are potential game changers in the field of neurosurgery. These are bright people with energy, who can look down the road and see what needs to be fixed in the field. We're primarily interested in training people who are future trainers and leaders in the field of neurosurgery."

### **Nathan Zwagerman, MD**

Assistant Professor  
Department of Neurosurgery  
Medical College of Wisconsin

#### *Performance during residency*

"From a practical standpoint, the keys to residency are very simple. You must figure out a way to be in two places or more at the same time. You must work extremely hard. You must take pride in caring for your patients and always be willing to go the extra yard for them. You never want to be the last one in and first one out of the hospital. You want to be available, because being available means people are going to ask you to do things. They will build confidence in you and ask you to do more things. During junior residency, the most important thing is to be available and to read. If you're in the hospital and you're reading, people will find things for you to do and that's how you develop as a resident. This job is not 9 to 5. This job, at least for me, has been an all-encompassing part of my life and everything that I do outside of work has been dictated by what happens here at work. The best residents I know don't know how many hours a week they work.

For junior residents, it's always better to be seen not heard. If you can keep your head low and do the job, not stick your neck out, not do anything foolish, and if you can fly under the radar, that will get you a long way. If people notice you as a junior resident, most of time they're noticing you for the bad things, not the good things."

#### *Performance during subinternships*

"Being a rotator is extremely hard, because you're never going to impress anybody. Any rotator coming in thinking that they're going to impress people, I think, already is a step behind. However, what you can do to help yourself is to always be available. Always be seen and be around. Don't say too much, because that's another way you can get yourself in trouble. Don't try to overstep your bounds. Stay within the system. Talk to the other residents to see how you can be most effective. One of the things that can happen is that these rotators get very ambitious. They want to see and present four ICU patients. Our time is very limited and by the time they present four patients, half an hour goes by and although the presentation may be very thorough, it changes the cadence for the entire team. While they do a good job, it takes time and makes things stressful for everybody else. The goal of the rotation for the rotator should be to learn as much as possible from the residents, but also show that the candidate understands the concept of a team and works to fit within the system. Reading about patients is very important, because at some point the student will be asked about anatomy and disease processes, and knowing those things will go a long way.

For me, if a rotator can show that they care about the patient that will go a very long way. One of my things, especially for our patients that are doing well, is that I tell jokes with them every day. One rotator this past year had a joke for a particular patient that we were seeing every day. Those are the sorts of things that set you apart.

One of the cardinal sins of a rotator is showing up the junior residents. If a resident doesn't know the answer to a question and the rotator blurts things out, you're just making things uncomfortable for the junior residents who are already beat down because of the length of time that they have

to work. Being available, reading a lot, and showing that you care about patients will get you farther than anything else.

Technical skills, such as knot tying and stitching, are less essential because people come from different backgrounds. I don't think we've ever taken anyone here because they were a whiz in the OR. I would never knock a person down because they couldn't tie a knot or if they tied a couple of air knots. That's not fair because I don't expect them to know that coming in. I like to see they have an interest in it. I like to see that they practice their knot tying, but frankly I'm not going to evaluate them and say this person's knots aren't square, they're going to be less in the OR. That wouldn't concern me."

**Shelly D Timmons, MD, PhD, FACS, FAANS**

Professor of Neurosurgery  
Vice Chair for Administration  
Director of Neurotrauma

Department of Neurosurgery  
Penn State University Milton S. Hershey  
Medical Center  
Hershey, Pennsylvania

"The best advice I can give to students considering entering this challenging and exciting field is to be certain that you are committed and that this is your passion. Neurosurgery has expanded so dramatically since its inception and only stands to grow further as we develop brain-machine interfaces, advanced methods for modulating neural circuits, sophisticated neurophysiologic monitoring, and safer and more efficient methods of treating the variety of neurologic and musculoskeletal problems we address on a daily basis. It has been an extreme privilege to call this profession my own, and the most rewarding aspect is helping patients and their families through some of their greatest challenges."

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