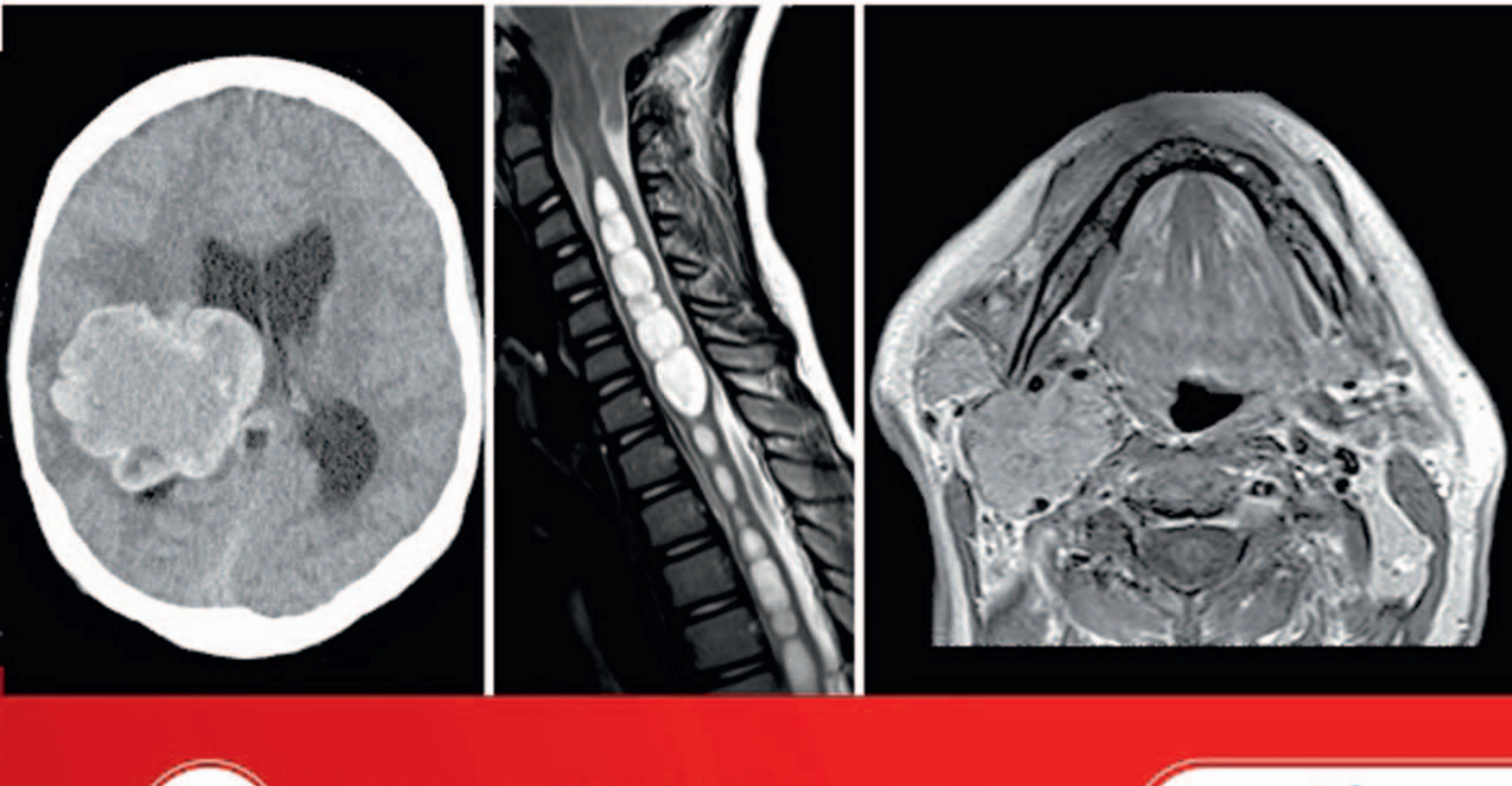
ROHINI NADGIR | DAVID YOUSEM

NEURORADIOLOGY



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THE REQUISITES

Neuroradiology

FOURTH EDITION

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To my husband, Kevin, for always helping me see the forest through the trees and my children, Soniya and Dhilan, for showing me that once you become a parent, everything else (outside of parenthood!) becomes much easier.

To my mother, late father, and brothers, for their unending love and support.

To my mentors and trainees past, present, and future, for always keeping me on my toes.

Rohini Nadgir

To my wife Kelly, and my family, friends, and colleagues who sustain me.

To all of the "muses" that have passed through my life.

To Bob Grossman, the best mentor and co-author of all time.

To every person who has walked up to me and said, "Your book(s) helped me get through (a) my neuroradiology rotation, (b) my general radiology boards, (c) my subspecialty certification test, or (d) my MOC recertification test." When I hear that, it makes me contemplate the next edition(s). Thank you for those words of inspiration.

David M. Yousem

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Foreword

Since the publication of the first edition of *Neuroradiology: The Requisites* in the early 1990s, this book has been one of the most widely read on the subject. Now in its fourth edition, *Neuroradiology: The Requisites* again encompasses its enormous topic in a way that is efficient for the reader while still providing the breadth and depth of material necessary for clinical practice and to meet the expectations for certification by the American Board of Radiology. Drs. Nadgir and Yousem are to be congratulated for this outstanding new addition to the *Requisites in Radiology* series.

After a discussion of cranial anatomy, the rest of *Neuroradiology: The Requisites* is organized by diseases and locations. This organization follows the pattern of the prior editions and based on experience with these prior editions should allow the reader to hone in on a topic of interest very quickly. In addition to the many excellent images used to illustrate key findings, another important strength of this book is the liberal use of drawings, tables, and boxes. Anatomical drawings help orient the reader to radiological features. Tables are used to economically summarize differential diagnoses among other topics, and boxes are used to list and reinforce important characteristics of diseases and conditions.

A challenge held in common in producing each new edition of *Neuroradiology: The Requisites* is the need to address the many new developments that have occurred since publication of the previous edition. These developments include both advances in technology and advances in our understanding of disease. Drs. Nadgir and Yousem have done a masterful job in accomplishing this with many new illustrations and systematically updated material in the text. Methods that were just becoming clinically feasible at the time of the last edition have found important roles in practice. Higher field magnetic resonance imaging has continued to be adopted more widely, and multidetector computed tomography is almost universally available in the United States. To pick just one example, these technologies have helped refine our approaches to the diagnosis and management of stroke.

It is our hope that anyone in radiology, neurology, or neurosurgery with an interest in imaging of the brain or the head and neck will find *Neuroradiology: The Requisites* useful. For residents in radiology, this book will make a challenging subject manageable. In a 1-month rotation, it should be possible to read the entire book. If this is done systematically during each subsequent rotation, the material will be well in hand when the time comes to take the board exams. Fellows in neuroradiology and radiology practitioners will find *Neuroradiology: The Requisites* a useful source for reference and review. Likewise, neurologists and neurosurgeons should find this book useful in better understanding the imaging studies obtained on their patients and the results of those studies.

The original hypothesis behind the *Requisites in Radiology* series was that many textbooks, in trying to be comprehensive, actually make it difficult for the reader to parse out what is truly important to daily practice. One of the guiding principles for the series' authors, captured well by Drs. Nadgir and Yousem, is to only put in the book what you teach to your own residents and fellows. There should be no need to put in obscure things that even the author needs to look up from another source. In this regard, *The Requisites* are not intended to be exhaustive but to provide basic conceptual, factual, and interpretative material required for clinical practice. By eliminating extraneous material using this approach, the reader can focus on what is actually most important in the practice of neuroradiology. Another pitfall in textbooks undergoing revision is to simply "graft on" material without pruning out-of-date material sufficiently. Here again Drs. Nadgir and Yousem have risen to the challenge and done a great job.

I have every confidence that the fourth edition of *Neuroradiology: The Requisites* will join the first three editions as well received and widely read books. I again congratulate Drs. Nadgir and Yousem on their outstanding new contribution. Their book reflects not only their expertise but their willingness to undertake the time and effort to share that expertise with students and seasoned practitioners alike.

James H. Thrall, MD
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Preface

When David Yousem initially invited me to work with him to put together the fourth edition of *Neuroradiology: The Requisites,* I was glad the conversation was over the phone so that he couldn't see my bug-eyed expression. After all, this was the book that had guided me throughout my training and had shaped and defined my career thus far. The shoes of the renowned Drs. Yousem and Grossman were enormous to fill, to say the least, and the task of fitting all that's essential to neuroradiology into one place would certainly not be easy. Nevertheless, as a person who derives much of her job satisfaction in molding successful trainees, I was excited about the prospect of making a greater impact on a larger audience.

Fast forward a couple of years, and I'm proud to say this text is just what the doctor (resident-in-training, that is) ordered. We've refreshed and trimmed it down to a digestible 17 chapters of what's most relevant to the neuroimaging trainee and the daily practitioner while preserving the previous editions' buoyant approach to "learning should be fun."

I am so fortunate to be immersed in a circle of inspiration and support from my colleagues, family, and friends in the making of this book. I owe thanks to Dr. Laurie Loevner for years ago taking me under her wing and introducing to me the beauty (and complexity) of neuroimaging. Drs. Osamu Sakai and Glenn Barest have been my personal mentors and close friends since my days in training, exemplifying the best in compassionate patient care and intellectual pursuits. No less importantly, on the home front I would be remiss not to thank my family for their unconditional love, in particular my mother, the kindest person I know, and my brothers, for somehow finding humor in everything. I am grateful to my wonderful husband, Kevin, and spirited children, Soniya and Dhilan, who always help keep things in perspective. Certainly this book would not have been possible without my right-hand woman and nanny to my children, Kayla, who has always been there for me, especially when the going got tough.

Many thanks to Aylin Tekes-Brady for taking on the daunting task of providing a thorough yet concise review of congenital disorders of the brain and spine. And last but certainly not least, I'd like to express my gratitude to Dave for this tremendous opportunity and for having faith in me to step it up and make a difference.

Rohini Nadgir, MD

Neuroradiology: The Requisites was first published in 1994 and was 544 pages in length with 833 illustrations. Bob Grossman was the "brains" behind this neuroradiology textbook and my mentor, guru, division chief, and close friend. Bob insisted that the book have a "style"; it would be the "story" of neuroradiology that a resident could read cover to cover. Its "plotline" would mirror Ben Felson's *Principles of Chest Roentgenology* (the source of the original "Aunt Minnie") with its educational sense of humor.

Over the course of the next two editions, Bob would move quickly to Chairman of Radiology and then Dean of the NYU Medical School. *Neuroradiology: The Requisites* would mature into a larger and larger book, cater to neuroradiology fellows and then academic faculty, and become much more serious. I remained behind, carrying the torch, trying to be a teacher extraordinaire.

With the fourth edition, Bob Grossman no longer graces the title page, but his impact and literally his words (and even some of his old jokes) still populate the tome. I can still hear his cackle from the origin of the longstanding jokes. But, in an effort to return to its roots, we have endeavored to recapture the "essentials only" nature of the first edition.

My colleague and the first author of the fourth edition, Rohini Nadgir, is my former fellow and now a faculty member with me at Johns Hopkins. As Bob did with me, I have ceded the reins of this child of ours to a delightful and outstanding educator. She has delicately massaged the old messages and modernized the text. She has guided the book expertly to this, its 22nd year of adulthood. I look forward to becoming the "silent partner" with Ro, as Bob did with me on the third edition. Thank you to Bob and Rohini and also to Aylin Tekes-Brady, another bright star in the pediatric neuroradiology sphere who gave the congenital lesion chapter its makeover.

We think we hit that sweet spot of enough material to cover the topic thoroughly without overwhelming the reader. Our goal, as it was year one, was to write a book that residents could read in 2 to 4 weeks during their first or second neuroradiology rotation. At the same time, it would be a refresher for all radiologists who read these cases as part of their daily practice.

Thanks to Robin Carter, Rhoda Howell, and Amy Meros on the Elsevier team who assisted in every way and encouraged, rather than pushed.

Enjoy. Live, love, learn, and leave a legacy.

David M. Yousem, MD, MBA

Contents

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Chapter 1

Cranial Anatomy

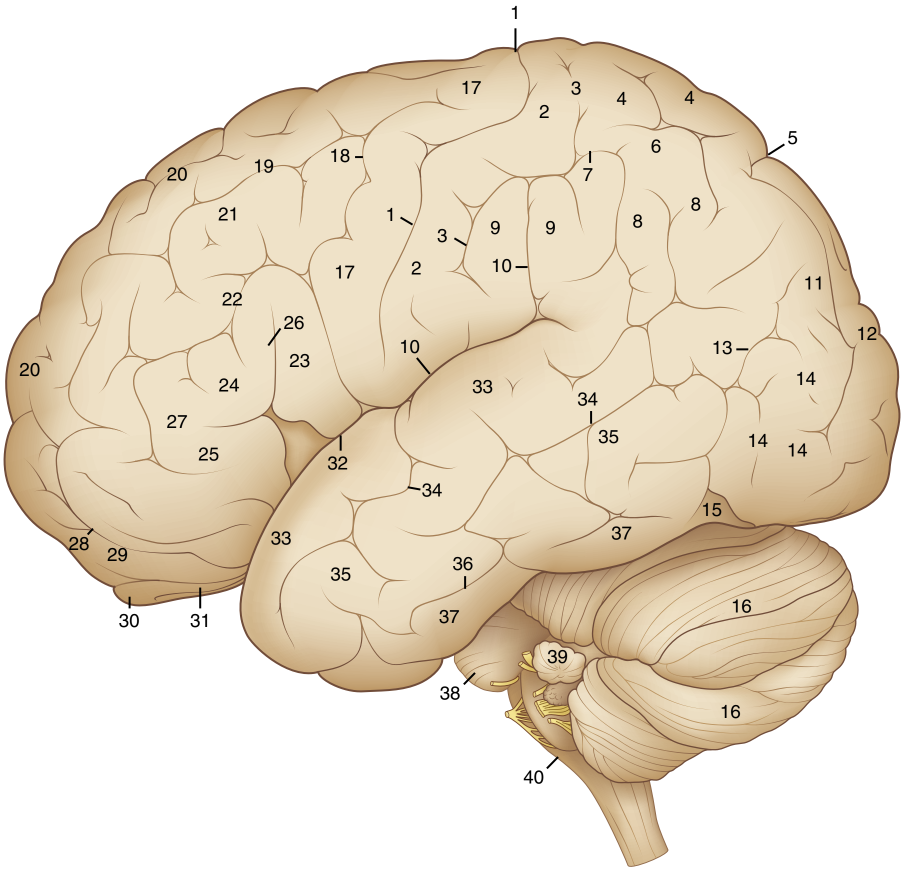
The anatomy and function of the brain is fascinating and complex, and we are still only scratching the surface in terms of our understanding of these structures. Nevertheless, a basic understanding of structure and function is critical in providing meaningful and accurate reporting of the pathology in the brain. Although we will discuss the development of the brain in Chapter 8, we will address the pertinent aspects of normal adult anatomy as it pertains to imaging interpretation in this chapter. Ready? Set? Here we go!

TOPOGRAPHIC ANATOMY

Cerebral Hemispheres

There are four lobes in each cerebral hemisphere: the frontal, parietal, occipital, and temporal lobes. The frontal lobe is separated from the parietal lobe by the central (Rolandic) sulcus, the parietal lobe is separated from the occipital lobe by the parietooccipital sulcus, and the temporal lobe is separated from the frontal and parietal lobes by the sylvian (lateral) fissure (Fig. 1-1).

The main named areas of the frontal lobe are the precentral gyrus (the primary motor strip of the cerebral cortex) and the three frontal gyri anterior to the motor strip: the superior, middle, and inferior frontal gyri. In front of the motor cortex is, quite naturally, the premotor cortex (Brodmann area 6). The dorsolateral prefrontal cortex (DLPFC or DL-PFC) is a critical area frequently referred to by the functional magnetic resonance imaging (fMRI) gurus who ascribe a great deal of cognition/memory/planning to it. It lies in the middle frontal gyrus of humans. It includes Brodmann area 9 and 46 and lies anterolateral to the premotor cortex. The frontal operculum (superior to the sylvian fissure and in the frontal lobe) contains portions of the Broca motor speech area. On the medial surface of the frontal lobe is the cingulate gyrus just superior to and bounding the corpus callosum, and the gyrus rectus



1 Central sulcus
2 Post central gyrus
3 Post central sulcus
4 Superior parietal lobule
5 Parieto-occipital sulcus
6 Inferior parietal lobule
7 Intrapparietal gyrus
8 Angular gyrus
9 Supramarginal gyrus
10 Lateral sulcus (Sylvian fissure), posterior ramus
11 Occipital gyrus
12 Semi lunar sulcus
13 Anterior occipital sulcus
14 Occipital sulcus
15 Pre-occipital incisura
16 Cerebellar hemisphere
17 Precentral gyrus
18 Precentral sulcus
19 Superior frontal sulcus
20 Superior frontal gyrus
21 Middle frontal gyrus
22 Inferior frontal sulcus
23 Opercular part
24 Triangular part
25 Orbital part
inferior frontal gyrus
26 Ascending ramus, lateral sulcus
27 Anterior ramus, lateral sulcus
28 Orbital sulcus
29 Orbital gyrus
30 Olfactory bulb
31 Olfactory tract
32 Lateral sulcus (Sylvian fissure)
33 Superior temporal gyrus
34 Superior temporal sulcus
35 Medial temporal gyrus
36 Inferior temporal sulcus
37 Inferior temporal gyrus
38 Pons
39 Flocculus
40 Medulla

FIGURE 1-1 Surface anatomy of the brain from a lateral view. Gyri are labeled in this figure. (From Nieuwenhuys R, Voogd J, van Huijen C. *The Human Central Nervous System: A Synopsis and Atlas.* Rev 1st ed. Berlin: Springer-Verlag; 1988.)

extending along the medial basal surface of the anterior cranial fossa (Figs. 1-1, 1-2).

The parietal lobe contains the postcentral gyrus (the center for somatic sensation), the supramarginal gyrus just above the temporal lobe, and the angular gyrus near the apex of the temporal lobe. Two superficial gyri of note are the superior and inferior parietal lobules, which are separated by an interparietal sulcus. On its medial side the precuneate gyrus is present in front of the parietooccipital fissure, with the cuneate gyrus posteriorly in the occipital lobe (see Fig. 1-2).

The temporal lobe contains the brain-functioning elements of speech, memory, emotion and hearing. Superior (auditory), medial, and inferior temporal gyri are seen on the superficial aspect of the brain (see Fig. 1-1). The posterior portion of the superior temporal gyrus subserves language comprehension, the so-called Wernicke area. Deep to the sylvian fissure is the insula, or isle of Reil, which is bounded laterally by the opercular regions and subserves taste function. The inferior part of the insula near the sylvian fissure is called the limen of the insula. The inferior and medial surface of the temporal lobe reveals the parahippocampal gyrus with the hippocampus just superior to it (Fig. 1-3). Anteriorly, the almond-shaped amygdala dominates. In the coronal plane, starting at the right collateral sulcus just inferior to the parahippocampus and traveling northward, you would first hit the entorhinal cortex, then turn at the parasubiculum, pass along the subiculum

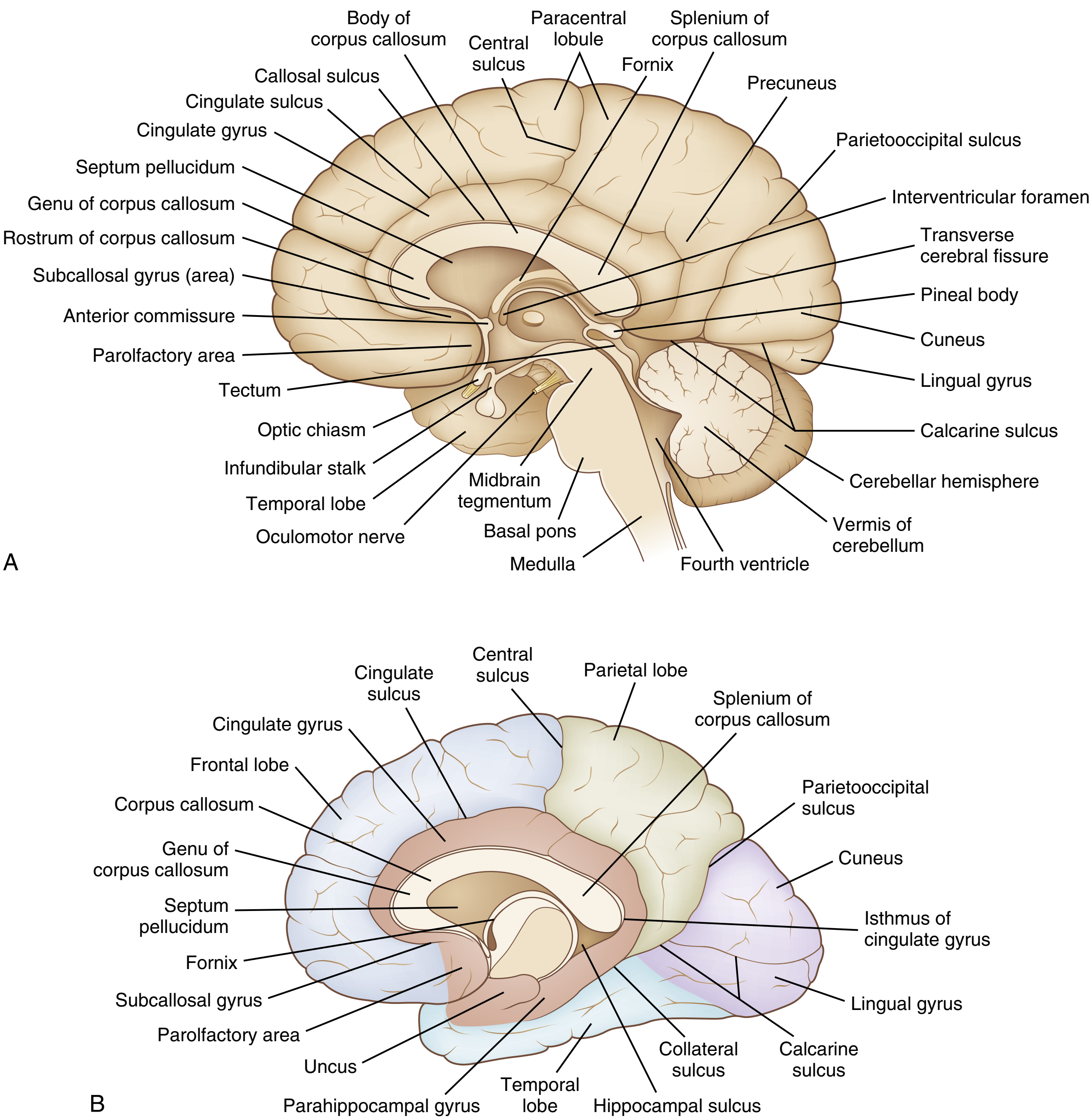


FIGURE 1-2 **A,** Midsagittal view of the brain. **B,** Midsagittal view of the left cerebral hemisphere illustrating the major cortical lobes. Frontal lobe *(blue)*, parietal lobe *(green)*, occipital lobe *(purple)*, temporal lobe *(teal)*, and limbic lobe *(pink)*. (From Burt AM. *Textbook of Neuroanatomy.* Philadelphia: WB Saunders; 1993:159, 160.)

proper, and continue laterally to the presubiculum. All of these represent parahippocampal structures. You would then curl in a spiral into the hippocampus' cornu ammonis and dentate gyrus with the fimbria found superomedially and the alveus on top of the cornu ammonis. Are you dizzy yet? The lateral-most portion of the cornu is particularly sensitive to anoxic injury and is the site where mesial temporal sclerosis occurs.

The occipital lobe is the lobe most commonly associated with visual function. At its apex is the calcarine sulcus, with the cuneate gyrus just above it (posteroinferior to the parietooccipital fissure) and the calcarine gyrus just below it (see Fig. 1-2).

The diencephalon contains the thalamus and hypothalamus. The thalamus has many nuclei, the most important of which (according to your ears and eyes) are the medial and lateral geniculate nuclei associated with auditory and visual functions, respectively. The thalamus is found on either side of the third ventricle and connects across the midline by the massa intermedia. Its other functions include motor relays, limbic outputs, and coordination of movement. Portions of the thalamus also subserve pain, cognition and emotions. The hypothalamus is located at the floor of the third ventricle, above the optic chiasm and suprasellar cistern. The hypothalamus is connected to the posterior pituitary via the infundibulum, or stalk, through which hormonal information to the pituitary gland is transmitted. The hypothalamus is critical to the autonomic functions of the body. Is it getting hot in here?

Brain Stem

Starting superiorly, the brain stem consists of the midbrain, pons, and medulla.

The mesencephalon differentiates into the midbrain. The midbrain is the site of origin of the third and fourth cranial nerves. Additionally, the midbrain contains the red nucleus, substantia nigra, and cerebral aqueduct, or aqueduct of Sylvius (Fig. 1-4). White matter tracts conducting the motor and sensory commands pass through the midbrain. The midbrain is also separated into the tegmentum and tectum, which refer to portions of the midbrain anterior and posterior to the cerebral aqueduct, respectively. The tectum, or roof, consists of the quadrigeminal plate (corpora quadrigemina), which houses the superior and inferior colliculi. The tegmentum contains the fiber tracts, red nuclei, third and fourth cranial nerve nuclei, and periaqueductal gray matter. The substantia nigra is within the anterior border of the tegmentum. Anterior to the tegmentum are the cerebral peduncles, which have somewhat of a "Mickey Mouse ears" configuration. Remember, just as there is only one Mickey, there is only one pair of cerebral peduncles.

The metencephalon develops into the pons and cerebellum. The pons contains the nuclei for cranial nerves V, VI, VII, and VIII (Figs. 1-5, 1-6). Pontine white matter tracts transmit sensory and motor fibers to the face and body. The pons also houses major connections of the reticular activating system for vital functions. One identifies the pons on the sagittal scan by its "pregnant belly."

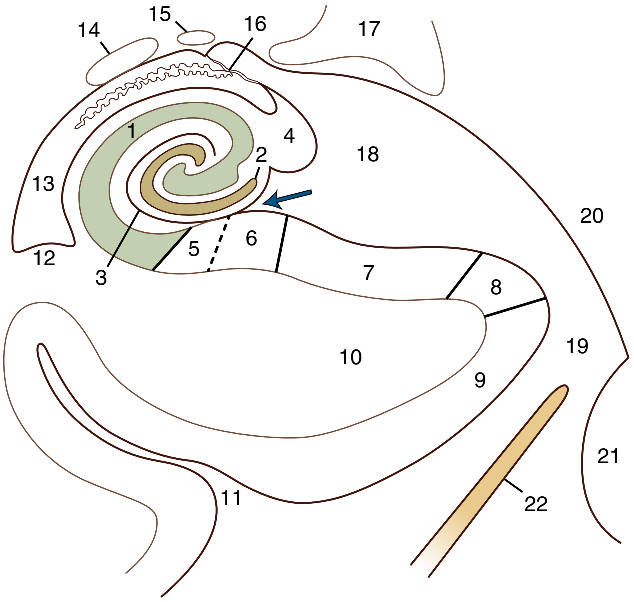


FIGURE 1-3 Hippocampal anatomy, coronal plane. *Arrow* indicates the hippocampal sulcus (superficial part). 1, cornu ammonis (Ammon's horn); 2, gyrus dentatus; 3, hippocampal sulcus (deep or vestigial part); 4, fimbria; 5, prosubiculum; 6, subiculum proper; 7, presubiculum; 8, parasubiculum; 9, entorhinal area; 10, parahippocampal gyrus; 11, collateral sulcus; 12, collateral eminence; 13, temporal (inferior) horn of the lateral ventricle; 14, tail of the caudate nucleus; 15, stria terminalis; 16, choroid fissure and choroid plexuses; 17, lateral geniculate body; 18, lateral part of the transverse fissure (wing of ambient cistern); 19, ambient cistern; 20, mesencephalon; 21, pons; 22, tentorium cerebelli. (Modified after Williams, 1995. From Duvernoy HM. *The Human Hippocampus.* New York: Springer-Verlag; 1998:18. Used with permission.)

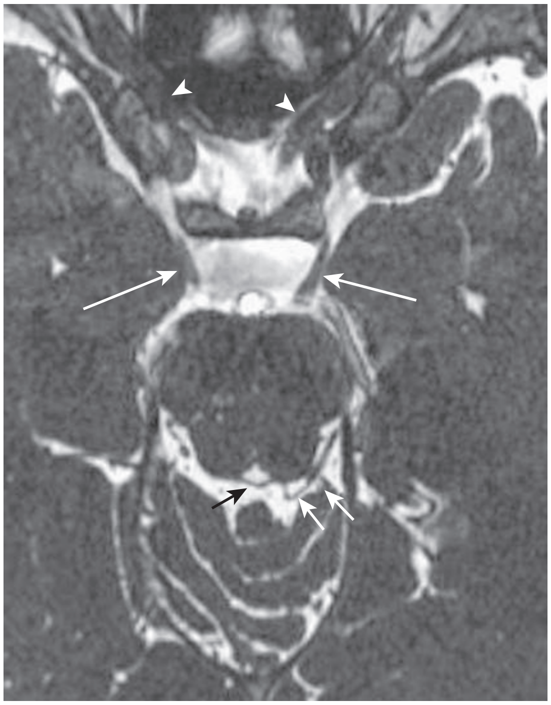


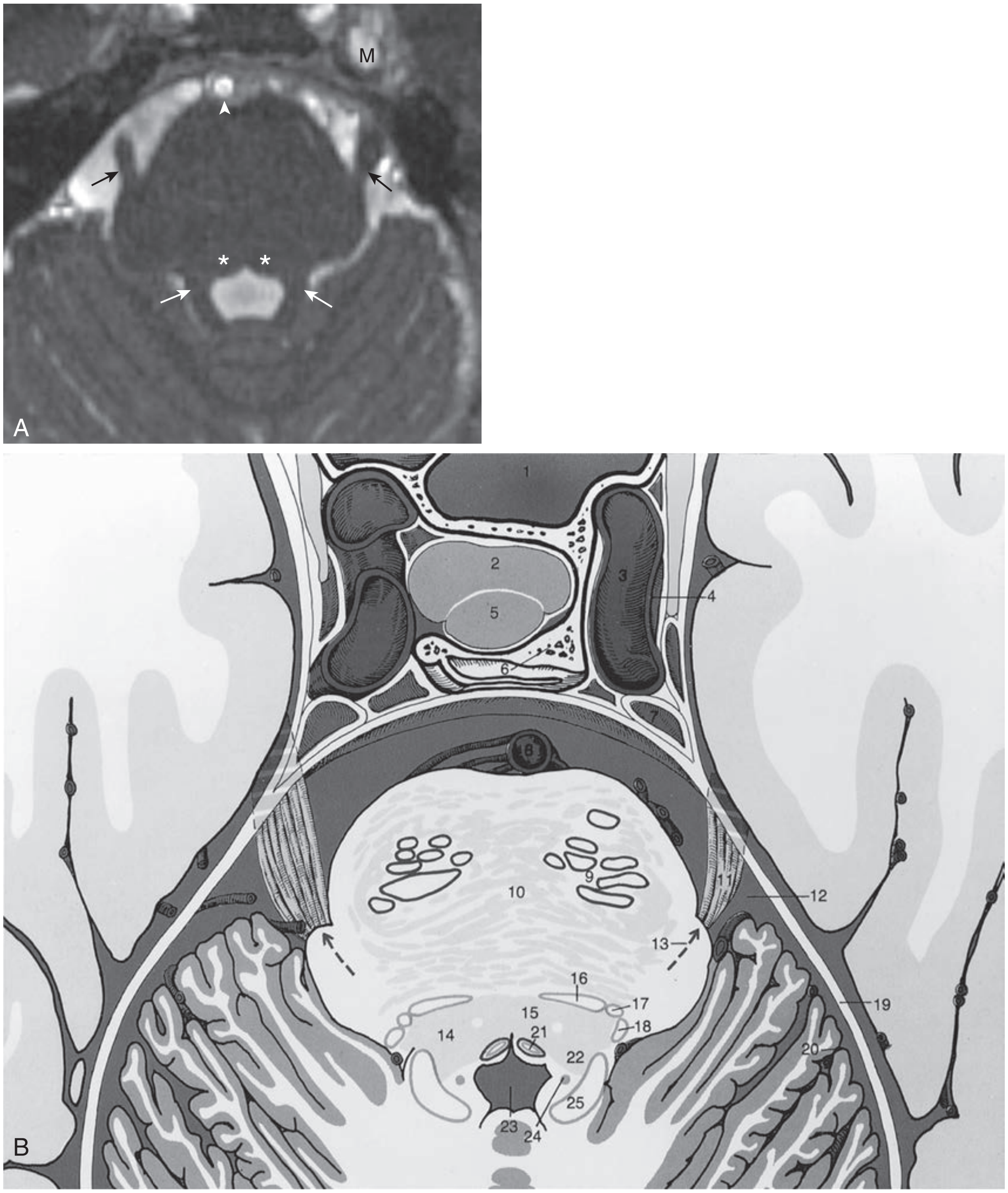
FIGURE 1-4 Midbrain anatomy. This constructive interference steady state (CISS) image shows both oculomotor nerves in their cisternal portions, leading to the cavernous sinus *(long white arrows),* the left trochlear nerve *(double arrows)* emanating from the posterior midbrain and coursing the ambient cistern, and the right trochlear nerve decussating posteriorly in the midline *(small black arrow).* The optic nerves can be seen in the optic canals bilaterally *(arrowheads).*

The myelencephalon becomes the medulla. The medulla contains the nuclei for cranial nerves IX, X, XI, and XII. Again, the sensory and motor tracts to and from the face and brain are transmitted through the medulla. Other named portions of the medulla include the pyramids, an anterior paramedian collection of fibers transmitting motor function, and the olivary nucleus in the mid-medulla (Fig. 1-7).

Cerebellum

The cerebellum is located in the infratentorial compartment posterior to the brain stem. The anatomy of the cerebellum is complex, with many named areas. For simplicity's sake, most people separate the cerebellum into the superior and inferior vermis and reserve the term cerebellar hemispheres for the rest of the lateral and central portions of the cerebellum.

For those interested in details, the superior vermis has a central lobule and lingula visible anteriorly, and the inferior vermis has a nodulus, uvula, pyramid, and tuber on its inferior surface (Fig. 1-8). The superior surface provides a view of the culmen, declive, and folium of the superior vermis. Superolaterally, there is a bump called the flocculus, which may extend toward the cerebellopontine angle cistern. This is a potential "pseudotumor," often misidentified as a vestibular schwannoma. The tonsils are located inferolaterally



1 Sphenoid sinus
2 Adenohypophysis
3 Internal carotid artery
4 Cavernous sinus
5 Neurohypophysis
6 Dorsum sellae
7 Superior petrosal sinus
8 Basilar artery
9 Corticospinal tract
10 Nuclei pontis
11 Trigeminal nerve
12 Cerebellopontine (angle) cistern
13 Trigeminal nerve (within the slice)
14 Reticular formation (PPRF)
15 Paramedian pontine reticular formation
16 Medial lemniscus
17 Spinothalamic tract
18 Lateral lemniscus
19 Tentorium cerebelli
20 Primary fissure
21 Medial longitudinal fasciculus
22 Locus ceruleus
23 Fourth ventricle
24 Mesencephalic nucleus trigeminal nerve
25 Superior cerebellar peduncle

FIGURE 1-5 Pontine anatomy. **A,** Axial T2 constructive interference steady state (CISS) image shows cranial nerve V exiting the pons *(black arrows).* Note the superior cerebellar peduncles *(white arrows),* the Meckel cave on the left (M), medial longitudinal fasciculus *(asterisks),* and basilar artery *(white arrowhead).* **B,** Pontine anatomy at the level of the superior cerebellar peduncle shows several descending and ascending tracts.

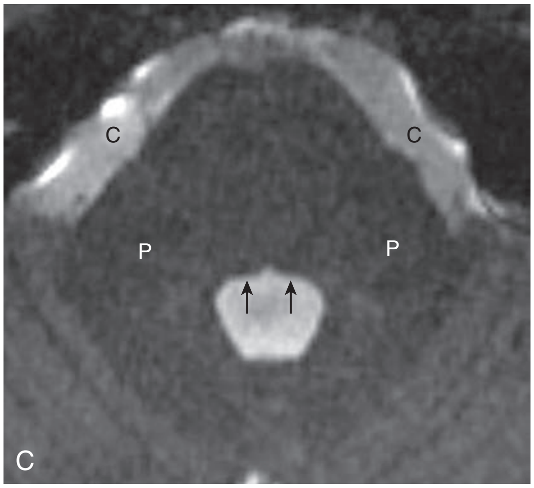
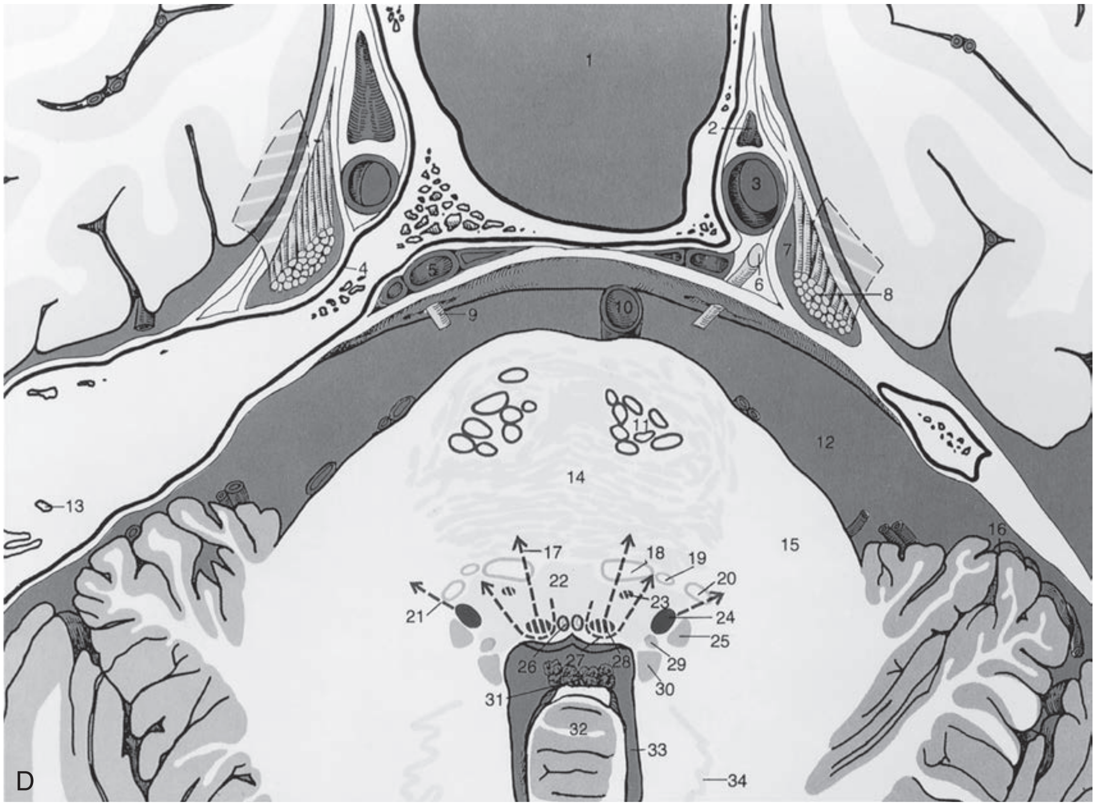


FIGURE 1-5, cont'd C, Facial colliculi *(arrows)* are clearly seen on this axial T2 CISS image. The middle cerebellar peduncle (P) is the dominant structure leading to the cerebellum. Also shown is the cerebellopontine angle cistern (C). **D,** At the facial colliculus one finds numerous cranial nerve nuclei and traversing lemnisci. (**B** and **D** from Kretschmann H-J, Weinrich W. *Cranial Neuroimaging and Clinical Neuroanatomy: Magnetic Resonance Imaging and Computed Tomography.* Rev 2nd ed. New York: Thieme; 1993:139, 137, respectively.)



1 Sphenoid sinus
2 Cavernous sinus
3 Internal carotid artery
4 Trigeminal impression
5 Inferior petrosal sinus
6 Abducens nerve
7 Opening of trigeminal cistern
8 Triangular part of trigeminal nerve
9 Abducens nerve near opening of dura mater
10 Basilar artery
11 Corticospinal tract
12 Cerebellopontine (angle) cistern
13 Anterior semicircular canal
14 Nuclei pontis
15 Middle cerebellar peduncle
16 Primary fissure
17 Abducens nerve (within the slice)
18 Medial lemniscus
19 Spinothalamic tract
20 Lateral lemniscus
21 Portio minor of trigeminal nerve (within the slice)
22 Reticular formation
23 Facial nucleus (in the caudal part of the slice)
24 Motor nucleus of trigeminal nerve
25 Main sensory (pontine) necleus of trigeminal nerve
26 Medial longitudinal fasciculus
27 Facial colliculus
28 Abducens nucleus (within the slice)
29 Mesencephalic nucleus of trigeminal nerve
30 Superior vestibular nucleus
31 Choroid plexus in fourth ventricle
32 Nodule of vermis
33 Posterior recess of fourth ventricle
34 Dentate nucleus

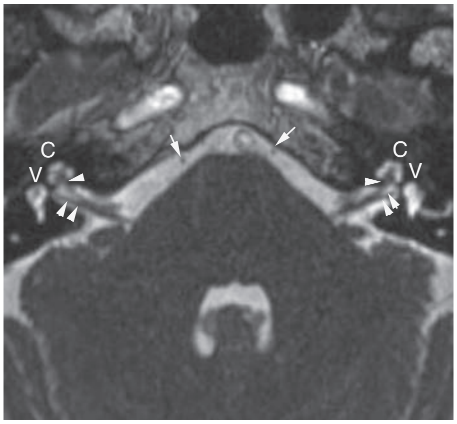
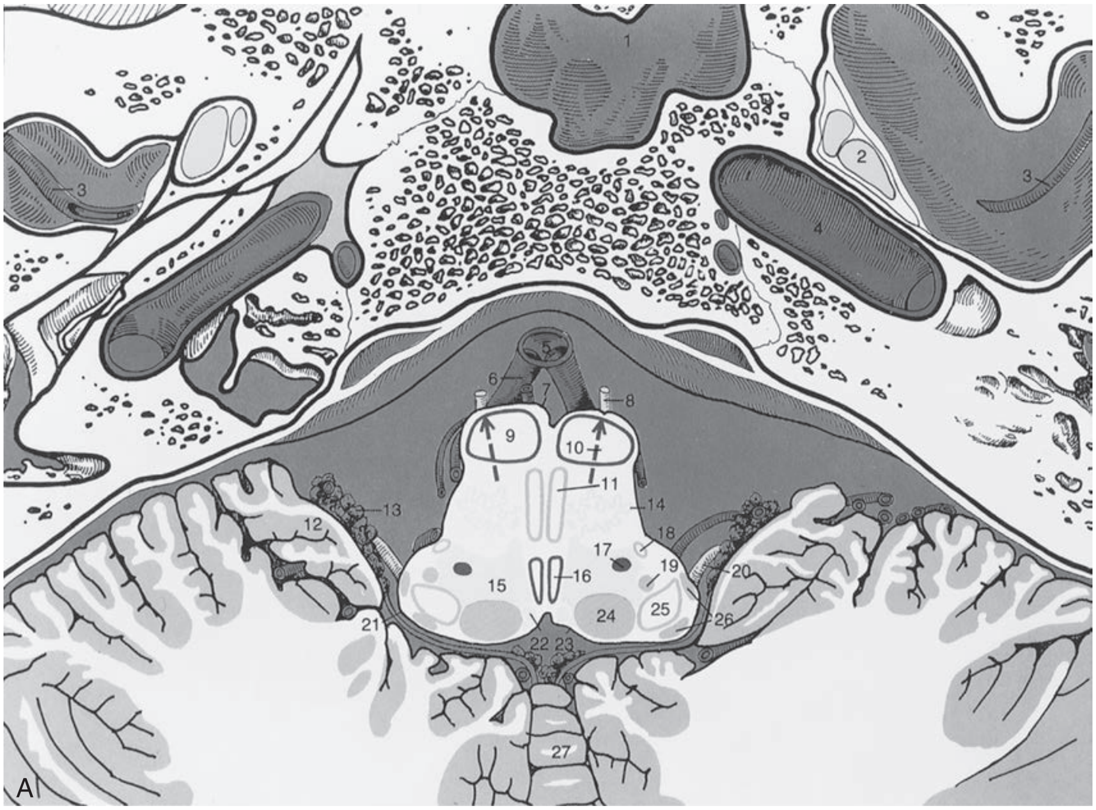


FIGURE 1-6 Lower pontine anatomy. This constructive interference steady state (CISS) image shows the abducens nerve denoted by the *white arrows,* whereas the cochlear (more anterior) and inferior vestibular nerves (more posterior) are seen bilaterally in the cerebellopontine angle cistern (*single and double white arrowheads,* respectively). The fluid-filled cochlea (C) and vestibule (V) are hyperintense on T2.



1 Sphenoid sinus
2 Mandibular nerve
3 Middle meningeal artery
4 Internal carotid artery
5 Basilar artery
6 Vertebral artery
7 Pyramid
8 Abducens nerve
9 Corticospinal tract
10 Abducens nerve (within the slice)
11 Medial lemniscus
12 Flocculus
13 Choroid plexus
14 Inferior olivary nucleus
15 Reticular formation
16 Medial longitudinal fasciculus
17 Nucleus ambiguus
18 Spinothalamic tract
19 Pars oralis of spinal nucleus of trigemi nerve
20 Vestibular nerve
21 Lateral aperture (of Luschka)
22 Hypoglossal nucleus
23 Floor of rhomboid fossa and fourth ventricle
24 Vestibular nuclei
25 Inferior cerebellar peduncle
26 Dorsal and ventral cochlear nuclei
27 Uvula of vermis

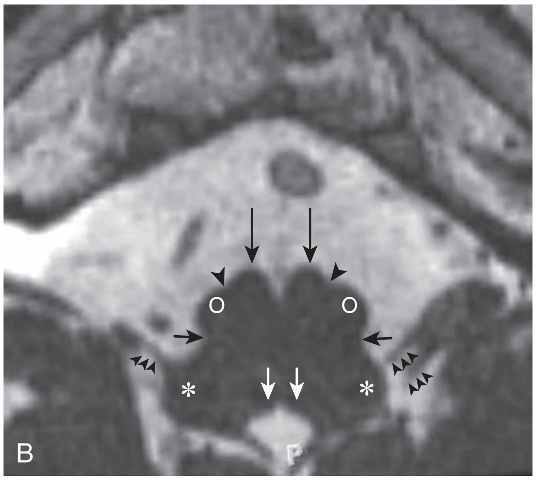
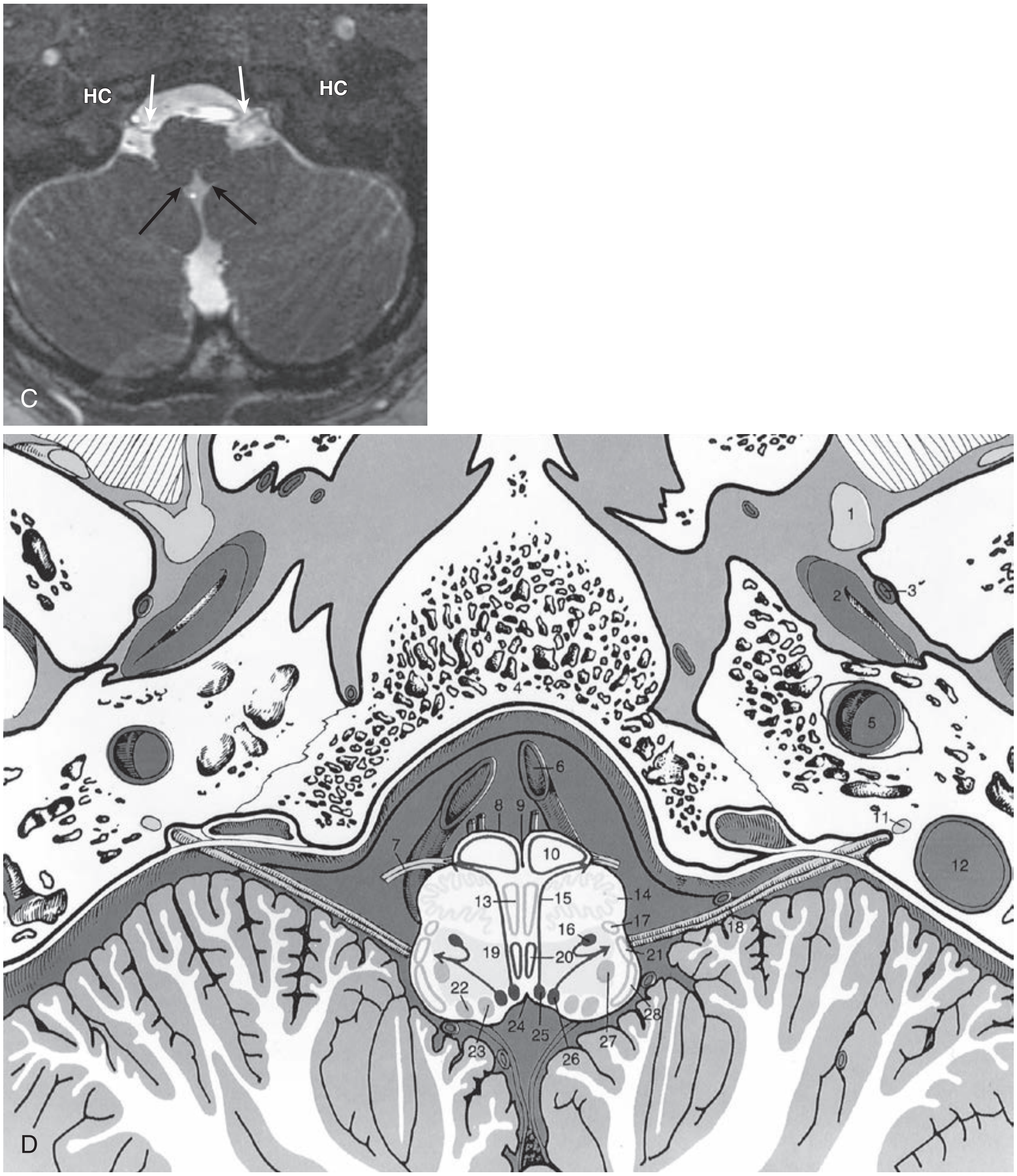


FIGURE 1-7 Medulla anatomy. **A,** This schematic reveals the junction of the vertebral arteries to the basilar artery. The roots of the abducens nerve arise at the border between the medulla oblongata and pons. The upper part of the inferior olivary nucleus is positioned in the medulla oblongata. **B,** Axial T2 constructive interference steady state (CISS) shows the preolivary sulcus *(short black arrows),* the olivary sulcus *(single arrowheads),* pyramidal tract *(large black arrows)* and the inferior cerebellar peduncle *(asterisks),* hypoglossal nuclei *(white arrows),* and nerve complex (cranial nerves IX and X; *small triple arrowheads*). The olive (o) can be seen anteriorly.



1 Mandibular nerve
2 Auditory (pharyngotympanic) tube
3 Middle meningeal artery
4 Clivus
5 Internal carotid artery
6 Vertebral artery
7 Hypoglossal nerve
8 Pyramid
9 Anterior median fissure
10 Corticospinal tract
11 Glossopharyngeal nerve
12 Bulb of internal jugular vein
13 Medial lemniscus
14 Inferior olivary nucleus
15 Hypoglossal nerve (within the slice)
16 Nucleus ambiguus
17 Spinothalamic tract
18 Vagus nerve
19 Reticular formation
20 Medial longitudinal fasciculus
21 Anterior spinocerebellar tract
22 Cuneate nucleus
23 Solitary nucleus
24 Median sulcus
25 Hypoglossal nucleus
26 Dorsal nucleus of vagus nerve
27 Pars interpolaris of spinal nucleus of trigeminal nerve
28 Inferior cerebellar peduncle

FIGURE 1-7, cont'd C, *White arrows* point out hypoglossal nerves coursing to hypoglossal canals (HC). On either side of the midline posterior cleft are the gracile nuclei *(black arrows).* Lateral to them will be the cuneate nuclei. **D,** This schematic shows the numerous nuclei and tracts that are present at the level of the medulla.

Continued

and are the structures that herniate downward through the foramen magnum in Chiari malformations.

Gray matter masses in the cerebellum include the fastigial, globose, emboliform, and dentate nuclei; the dentate nuclei are seen well on T1-weighted images (T1WI), whereas the fastigial, globose, and emboliform nuclei cannot be discerned. The dentate nuclei are situated laterally in the white matter of the cerebellum, and can be seen on computed tomography (CT) because they may calcify in later life.

Three major white matter tracts connect the cerebellum to the brain stem bilaterally (Fig. 1-9). The superior cerebellar peduncle (brachium conjunctivum) connects midbrain structures to the cerebellum, the middle cerebellar peduncle (brachium pontis) connects the pons to the cerebellum, and the inferior cerebellar peduncle (restiform body) connects the medulla to the cerebellum.

The flocculonodular lobe, fastigial nucleus, and uvula of the inferior vermis receive input from vestibular nerves and are thought to be involved primarily with maintaining equilibrium. Lesions of this part of the cerebellum, the archicerebellum, cause wide-based gait and dysequilibrium.

The superior vermis, most of the inferior vermis, and globose and emboliform nuclei receive spinocerebellar sensory information. Muscle tone information, postural tone,

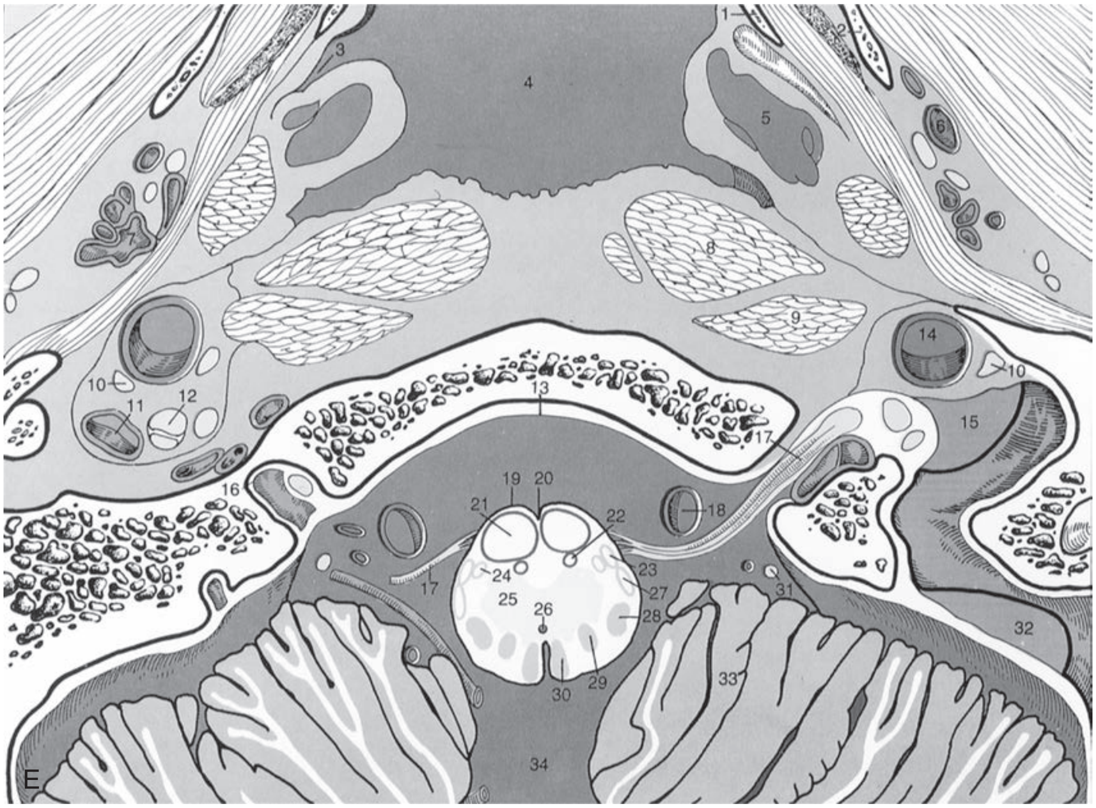


FIGURE 1-7, cont'd E, The caudal portion of the medulla oblongata, the rootlets of the hypoglossal nerves, and the hypoglossal canal are included. (**A, D,** and **E** from Kretschmann H-J, Weinrich W. *Cranial Neuroimaging and Clinical Neuroanatomy: Magnetic Resonance Imaging and Computed Tomography.* Rev 2nd ed. New York: Thieme; 1993:133, 131, 127, respectively.)

and coordination of locomotion appear to be influenced by these sites and by their effect on brain stem fibers, the red nuclei, and vestibular nuclei. The hemispheric portions of the cerebellum receive information from the pons and help to control coordination of voluntary movements. Abnormalities within the cerebellar hemispheres result in dysmetria, dysdiadochokinesis (say THAT five times fast!), intention tremors, nystagmus, and ataxia.

Corpus Callosum

The corpus callosum is the large midline white matter tract that spans the two cerebral hemispheres. Its named parts include the rostrum (its tapered anteroinferior portion just above the anterior commissure), the genu (the anterior sweep), the body or trunk (the superiormost aspect), and the splenium (the posteriormost aspect; see Fig. 1-2). Often there may be focal narrowing within the posterior body, the so called "isthmus," which is a normal anatomic variation and should not be confused with focal pathology.

Other white matter tracts that must tread carefully as they cross the midline include the anterior commissure, located at the inferior aspect of the corpus callosum just above the lamina terminalis, and the posterior commissure, just anterior to the pineal gland near the habenula. The anterior commissure transmits tracts from the amygdala and temporal lobe to the contralateral side. The habenula and hippocampal commissures cross-connect the two hemispheres and thalami.

Deep Gray Nuclei

The basal ganglia are known by a number of names in the neuroanatomic literature. These gray matter structures lie between the insula and midline. The globus pallidus is the medial gray matter structure identified just lateral to the genu of the internal capsule (Fig. 1-10). Lateral to it lies the putamen. The caudate nucleus head indents the frontal horns of the lateral ventricle and is anterior to the globus pallidus; however, the body of the caudate courses over the globus pallidus, paralleling the lateral ventricle and ending in a tail of tissue near the amygdala.

Additional terms used referring to the various portions of the basal ganglia include the striatum (caudate and

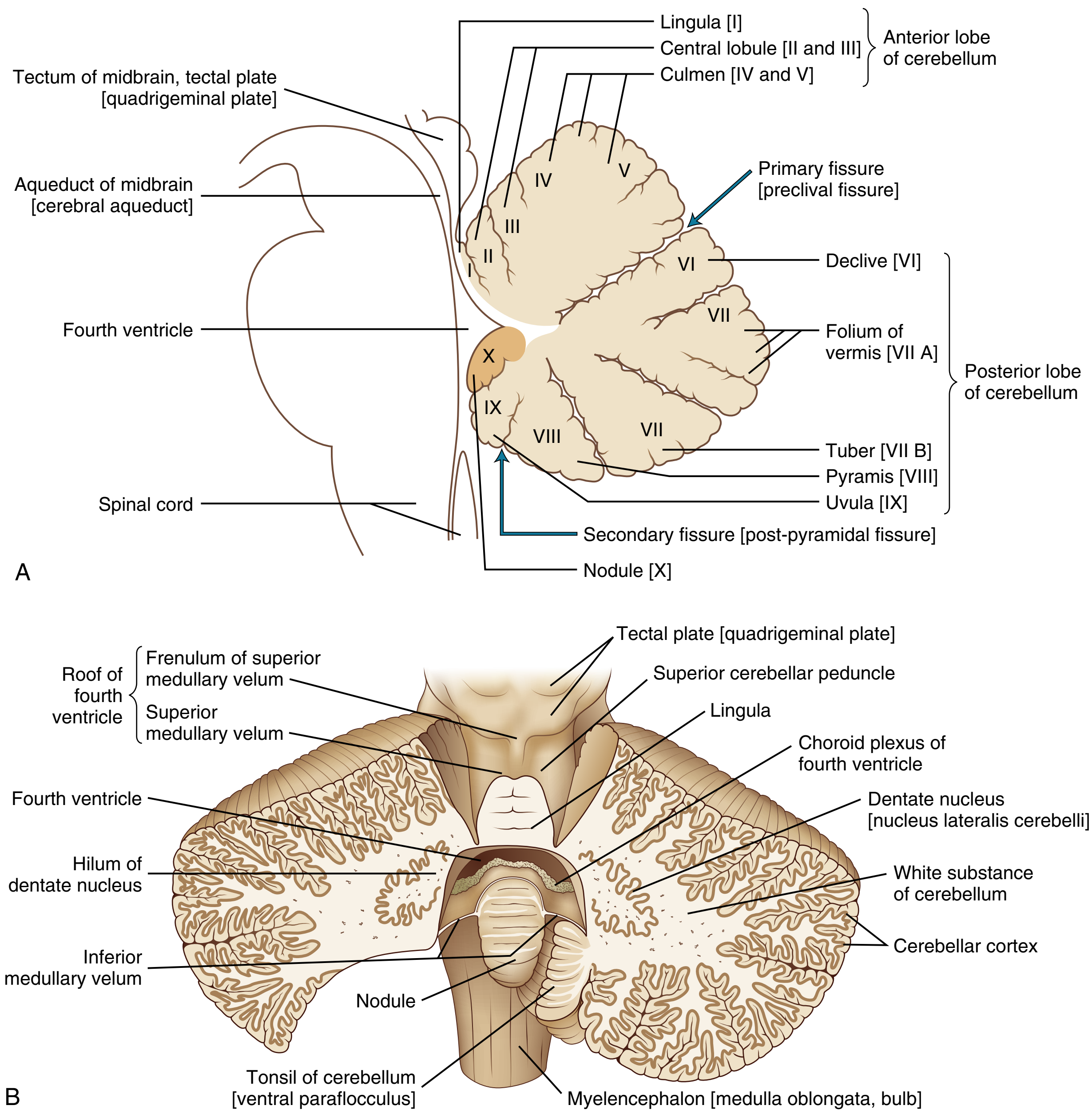


FIGURE 1-8 Cerebellar anatomy. **A,** The parts of the cerebellar vermis. Diagram of a median section. **B,** Coronal diagram of the cerebellar lobes and their lobules. (From Putz R, Pabst R, eds. *Sobotta Atlas of Human Anatomy.* 13th ed. Philadelphia: Lippincott Williams & Wilkins; 1996:292, 293.)

putamen) and the lentiform or lenticular nuclei (the globus pallidus and putamen).

The basal ganglia receive fibers from the sensorimotor cortex, thalamus, and substantia nigra, as well as from each other. Efferents go to the same locations and to the hypothalamus. The main function of the basal ganglia appears to be coordination of smooth movement.

The other deep gray matter structures of interest in the supratentorial space are the thalami, which sit on either side of the third ventricle. The thalamus is subdivided into many different nuclei by white matter striae. The medial and lateral geniculate nuclei, located along the posterior aspect of the thalamus, serve as relay stations for visual and auditory function. The pulvinar is the posterior expansion of the thalamus. Behind the pulvinar are the wings of the ambient cistern. The massa intermedia connects the thalami across the third ventricle.

In the infratentorial space, the dentate nucleus, the largest deep gray matter structure, has connections to the red nuclei and to the thalami.

Ventricular System, Cerebrospinal Fluid, and Cerebrospinal Fluid Spaces

The normal volume of cerebrospinal fluid (CSF) in the entire central nervous system (CNS) is approximately 150 mL, with 75 mL distributed around the spinal cord, 25 mL within the ventricular system, and 50 mL

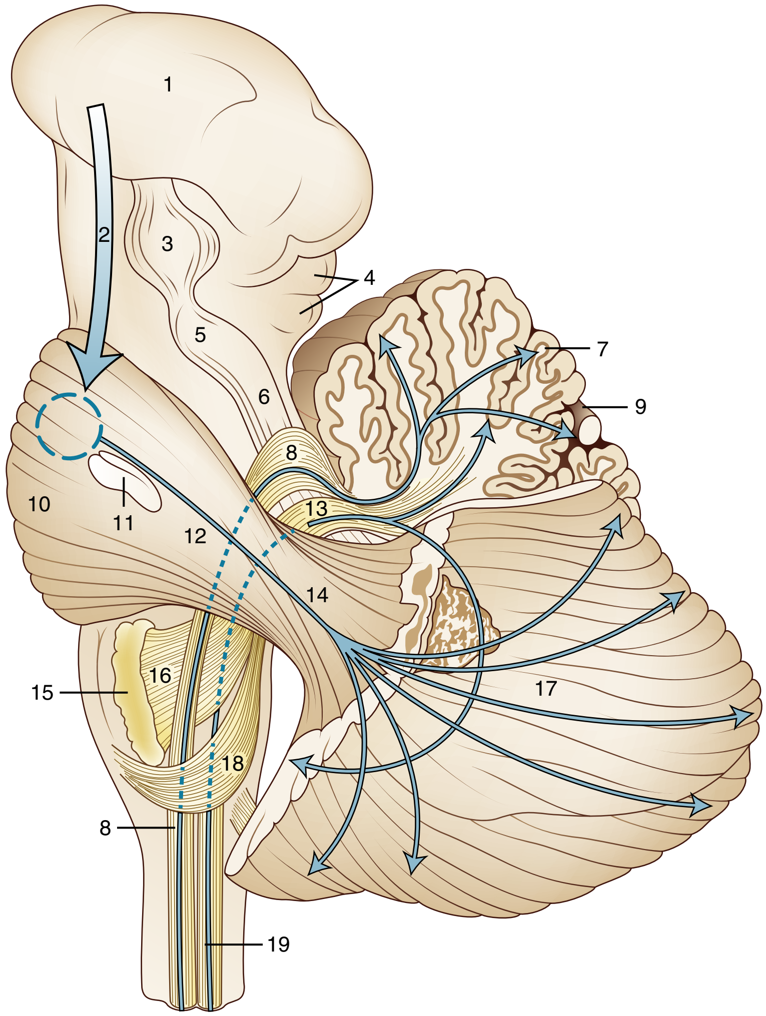


FIGURE 1-9 The afferent systems of the cerebellum (lateral view). The left half of the anterior lobe of the cerebellum was removed. The archeocerebellum was separated and removed caudally from the middle cerebellar peduncle. (From Kretschmann H-J, Weinrich W. *Cranial Neuroimaging and Clinical Neuroanatomy: Magnetic Resonance Imaging and Computed Tomography.* Rev 2nd ed. New York: Thieme; 1993:326.)

surrounding the cortical sulci and in the cisterns at the base of the brain. In elderly persons, the intracranial CSF volume increases from 75 mL to a mean of approximately 150 mL in women and 190 mL in men. The normal production of CSF has been estimated to be approximately 450 mL/day, thereby replenishing the amount of CSF two to three times a day. Each ventricle's choroid plexus contributes to CSF production, whereas the reabsorption of CSF occurs at the level of the arachnoid villi into the intravascular system from the extracellular fluid.

The flow of CSF runs from the lateral ventricles via the foramina of Monro, to the third ventricle, out the cerebral aqueduct of Sylvius, and into the fourth ventricle, finally exiting through foramina of Luschka (bilaterally) and Magendie (in the midline; Fig. 1-11). CSF then flows into the cisterns of the brain and the cervical subarachnoid space and then down the intrathecal spinal compartments. The CSF ultimately percolates back up over the convexities of the hemispheres, where it is resorbed by the arachnoid villi into the intravascular space.

There are several named cisterns around the brain stem and midline structures (Fig. 1-12). Contents of these spaces can be compromised depending on the pathology at play, and critical structures coursing through these spaces may be affected and be the source of the patient's presenting complaint. Therefore, awareness of these cisterns and contents is critical in descriptions of different herniation syndromes and other pathologies that can be identified on imaging (Table 1-1).

Meninges and Associated Potential Spaces

The brain is covered in three protective layers of tissue, the meninges (or mater), which consist of pia, arachnoid, and dura. The dura (or pachymeninges) consists of the thickest and toughest layer and is adherent to the inner table of the skull extending to sutural margins. Pathologic conditions may occur in the space between the inner table and the dura, in the so-called epidural space, and result in mass effect on the underlying brain parenchyma. Epidural compartments are separated by sutures and pathologies typically do not cross the sutures when confined to the epidural space. Deep to the dura but superficial to the arachnoid mater is another potential space called the subdural space. When space-occupying pathologies are

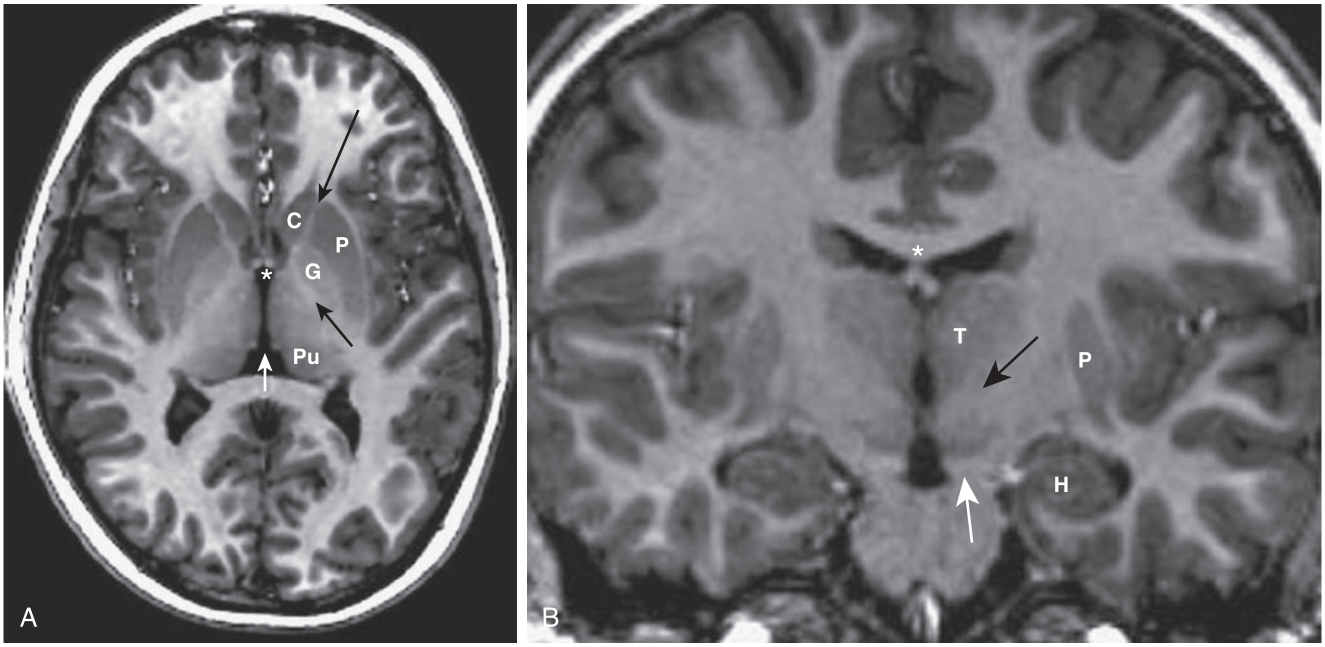


FIGURE 1-10 Deep gray matter anatomy. **A,** Axial T1-weighted image (T1WI) shows the caudate (C), putamen (P), and globus pallidus (G), as well as the anterior limb *(long black arrow)* and posterior limb *(short black arrow)* of the internal capsule. White matter tracts pass between the basal ganglia. The thalamus and periaqueductal gray matter line the third ventricle. The tiny dots of the fornix anteriorly (just ventral to *asterisk*) and the posterior commissure posteriorly *(white arrow),* as well as pulvinar thalamic gray natter (Pu), are also evident. **B,** On this coronal T1WI, the subthalamic nucleus *(black arrow)* and substantia nigra *(white arrow)* can be seen under the thalami (T). The hippocampus (H) is present further laterally. The thalami are joined in the midline at the massa intermedia, and one can also see the forniceal columns (just below *asterisk*) projecting above the thalami.

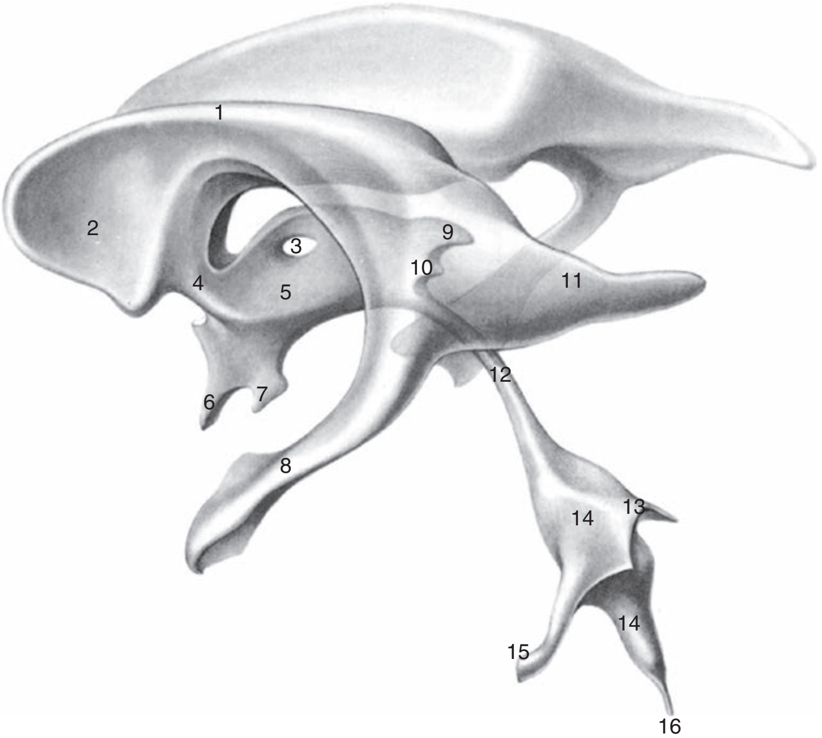


FIGURE 1-11 Ventricular system of the brain. Three-dimensional diagram of the ventricular system of the brain is labeled. (From Nieuwenhuys R, Voogd J, van Huijen C. *The Human Central Nervous System: A Synopsis and Atlas.* Rev 3rd ed. Berlin: Springer-Verlag; 1988.)

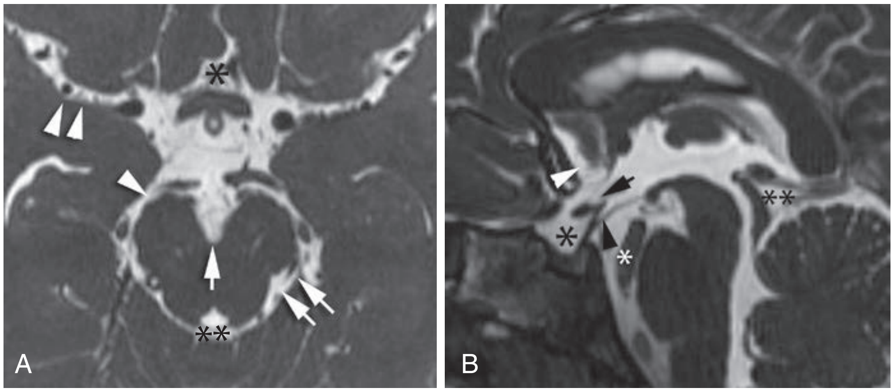


FIGURE 1-12 Cisterns of the brain. **A,** Axial constructive interference steady state (CISS) image shows the interpeduncular cistern *(single arrow),* ambient cistern *(single arrowhead),* perimesencephalic cistern *(double arrows),* sylvian fissure *(double arrowheads),* and quadrigeminal plate cistern *(double asterisk).* The cistern of the lamina terminalis is indicated by *single asterisk*. **B,** Sagittal CISS image shows the cistern of the lamina terminalis *(arrowhead),* suprasellar cistern *(single black asterisk),* and quadrigeminal plate cistern *(double black asterisk).* The basilar artery *(white asterisk)* is seen coursing the prepontine cistern. The chiasmatic recess *(black arrow)* and infundibular recess *(black arrowhead)* are also indicated. Note the crowding of structures at the foramen magnum in this patient with borderline Chiari I malformation.

TABLE 1-1 Cisterns of the Brain

Name	Location	Structures Traversing Cistern
Cisterna magna	Posteroinferior to fourth ventricle	None important
Circum-medullary cistern	Around medulla	Posterior inferior cerebellar artery
Superior cerebellar cistern	Above cerebellum	Basal vein of Rosenthal, vein of Galen
Prepontine cistern	Anterior to pons	Basilar artery, cranial nerves V and VI
Cerebellopontine angle cistern	Between pons and porus acusticus	Anterior inferior cerebellar artery, cranial nerves VII and VIII
Interpeduncular cistern	Between cerebral peduncles	Cranial nerve III
Ambient (crural) cistern	Around midbrain	Cranial nerve IV
Quadrigeminal plate cistern	Behind midbrain	None important
Suprasellar cistern	Above pituitary	Optic chiasm, cranial nerves III, IV, carotid arteries, pituitary stalk
Retropulvinar cistern (wings of ambient cistern)	Behind thalamus	Posterolateral choroidal artery
Cistern of lamina terminalis	Anterior to lamina terminalis, anterior commissure	ACA
Cistern of velum interpositum	Above 3rd ventricle	Internal cerebral vein, vein of Galen
Cistern of the ACA	Above corpus callosum	ACA

ACA, Anterior cerebral artery.

present here, cortical vessels that normally traverse the subarachnoid space just deep to the dura become compressed towards the surface of the brain, and the underlying brain parenchyma can also be compressed. Subarachnoid disease processes occur at the surface of the brain, deep to the arachnoid layer but superficial to the pia, and therefore assume a curvilinear configuration, extending along the surface of the sulci and gyri. Subpial processes do occur, however, the pia and arachnoid cannot always be readily distinguished on imaging; the pia and arachnoid layers are collectively referred to as the leptomeninges.

Physiologic Calcifications

The pineal gland calcifies with age. A small percentage (2% of children less than 8 years old and 10% of adolescents) of children show calcification of the pineal gland. By 30 years of age, most people have calcified pineal glands. Anterior to the pineal gland, one often sees the habenular commissure as a calcified curvilinear structure.

The choroid plexus is calcified in about 5% of children by age 15, and most adults by age 40. Such calcifications may be seen in the lateral, third and fourth ventricles, as well as the foramina of Luschka, Magendie, and choroid fissures.

The dura of the falx and/or tentorium is virtually never calcified in children and should be viewed as suspicious for basal cell nevus syndrome in that setting. However, in adults, foci of calcification and even ossification of the dura and falx are not uncommon. The dura shows higher rates of calcification in patients who have had shunts placed or have been irradiated.

Basal ganglia calcification is also rarely observed in individuals less than 30 years of age and should provoke

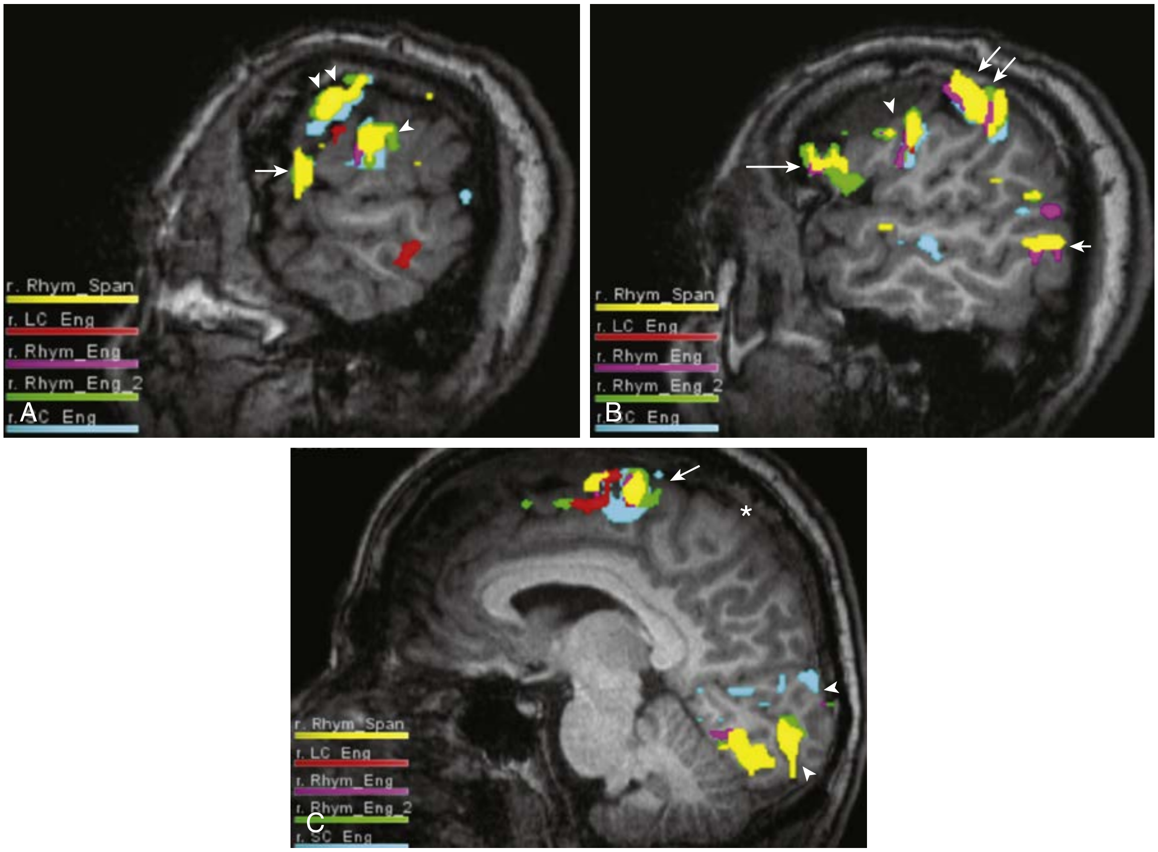


FIGURE 1-13 Functional magnetic resonance imaging (fMRI) with language task. **A,** fMRI blood-oxygen-level dependent (BOLD) activations overlayed onto anatomic T1-weighted images in sagittal plane. The left side of the brain is shown. Convergent activation is seen in the Broca region *(arrow).* The Broca region typically corresponds to the pars opercularis/pars triangularis of the inferior frontal gyrus (Brodmann area 44 and 45), and in right handed patients is typically lateralized to the left cerebral hemisphere. Even without overt movement, language related motor areas can show concurrent activation, as is seen in the area of convergent activation in the subcentral gyrus *(single arrowhead),* which represents the tongue/facial motor regions. The third convergent area of activation is seen in the ventral premotor cortex, also commonly activated during language tasks *(double arrowheads).* **B,** Convergent activation is seen in the left inferior frontal gyrus along the pars triangularis and pars opercularis corresponding to Brodmann area 44 and 45, compatible with Broca activation *(large single arrow).* Activation is also seen in the left ventral premotor cortex *(arrowhead),* as well as language related motor and sensory areas at the banks of the precentral and postcentral gyri *(double arrows).* Posterior temporal lobe convergent activation represents Wernicke activation *(small single arrow).* There are also smaller foci of language-related convergent activation seen just cranial to this in the supramarginal gyrus. **C,** Convergent activation is seen in the pre-supplemental motor area *(arrow),* which is activated during language tasks. This is anterior to the supplementary motor area, which is in turn anterior to the precentral gyrus. The central sulcus *(asterisk)* is seen as the sulcus immediately anterior to the marginal segment of the cingulate sulcus. Visual areas also demonstrate activation *(arrowheads)* as most of the language tasks used for this patient employed visual language task paradigms. (Courtesy Haris Sair, M.D.)

a search for metabolic disorders or a past history of perinatal infections if seen in youngsters. (See the online Appendix at ExpertConsult.com for causes of basal ganglia calcification.) Over the age of 30, however, basal ganglia calcifications are very common to the point that these do not necessarily need to be mentioned in routine reporting unless true pathology is suspected. Such benign basal ganglia mineralization is typically bilateral, although in some cases it may be more conspicuous on one side compared with the other. Care must be made not to confuse these physiologic calcifications, which are hyperdense on CT, with hemorrhage, which is also hyperdense on CT.

FUNCTIONAL ANATOMY

Understanding the functional anatomy requires a little bit of the cartographer in each of us (or a GPS-enabled smartphone). After having assimilated the destinations and points of departure, one should talk about the entire routes of neuronal travel. For functional anatomy, we can now use fMRI to identify the sites of cortical activation (the points of departure and destinations; Fig. 1-13) and diffusion tensor imaging to perform white matter tracking as the highways between gray matter destinations (Fig. 1-14). The directionality of these white matter tracts can also be inferred now.