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1 Taxonomy

Summary

Cavernous malformations are highly variable and seemingly random vascular anomalies that occur in every possible size, shape, and location in the central nervous system. This variability makes it difficult to envision the spectrum of disease caused by these lesions within a simplified framework. The creation of a taxonomy to organize cavernomas by neuroanatomical location and morphology brings order to an otherwise chaotic disease spectrum. The taxonomy defines seven cavernoma types and 35 subtypes and organizes them into a classification system that guides surgical strategy and patient management.

Keywords: brainstem, cavernous malformation, cerebellum, cerebrum, ependymal, hemorrhage, pial, resection, subtype, tenet

1.1 Classifying Surgical Pathology

Cavernomas occur in every imaginable size, shape, and location in the central nervous system, from cerebral convexity to conus medullaris. They range in size from submillimeter specks seen only on gradient echo sequences on magnetic resonance imaging (MRI) to the nearly holohemispheric 13 × 7-cm lesion I removed through a hemicraniotomy in a 12-year-old child. They can be shaped like freshly picked mulberries, intermixed with pockets of liquified or desiccated blood, or encapsulated in a thick rind. Cavernomas are far more variable than aneurysms, which occur regularly at specific branch points around the circle of Willis. Detailed knowledge of even just seven aneurysm types, and mastery of the basic surgical steps for treating them, empowers the neurosurgeon to manage more than three-quarters of all aneurysms seen in clinical practice. In contrast, cavernomas are seemingly random and endless in their distribution and morphology, making it difficult to encompass this spectrum of disease with a simplified framework.

Taxonomy is one method to bring order to an otherwise chaotic spectrum of disease. Taxonomy comes from the Greek word *taxis*, meaning arrangement or order, and *nomos*, meaning method or law, and is defined as the scientific classification of organisms and things. In zoology, for example, the study of animals' structure, physiology, embryology, habits, and habitats enables their classification into genera and species to make sense of the unlimited variety seen in the animal kingdom. The taxonomic binomial nomenclature uniquely defines the more than 1.5 million species of wildlife encountered in nature. Just as taxonomy classifies animals hierarchically into a system that enables biologists to identify animals in the wilderness, this cavernous malformation (CM) taxonomy classifies cavernomas hierarchically into a system that enables neurosurgeons to uniquely define the spectrum of pathology encountered in clinical practice (► Fig. 1.1). In short, taxonomy organizes a broad spectrum of pathology into a discrete number of entities that can be easily recognized to simplify and better understand the disease.

1.2 Informing Surgical Strategy

In addition to simplifying something complex, taxonomy enables scientists to find the information they need about a particular organism or thing. For example, a trip to Bali before starting my neurosurgical residency introduced me to the Komodo dragon. Tourists like me would ferry to the southeastern Indonesian island of Flores to observe these 70- to 90-kg (150- to 200-lb) beasts that grow to nearly 3 m (10 ft) in length and are capable of consuming livestock in several bites. These so-called dragons were first described by Europeans in 1910 as land crocodiles but are members of the monitor lizard family Varanidae (*Varanus komodoensis*), which also includes earless and Gray's monitors. Monitors are known as the most intelligent of lizards, forage for meat and fruits, and possess unidirectional pulmonary airflow. Just as taxonomy leads quickly to an understanding of the Komodo dragon in this example, it can also lead neurosurgeons to information needed to optimally manage patients with a particular CM in the brain.

Taxonomy has its greatest value when the differentiation of things leads to the differentiation of actions. Distinguishing one cavernoma type from another may be unimportant if the treatment for both is the same, but making such a distinction is crucial if their treatments are different. The classification of spinal arteriovenous malformations provides a dramatic example. The dural arteriovenous fistula (type 1) and the perimedullary arteriovenous fistula (type 4) can look similar on spinal angiography with arteriovenous shunting from a radicular artery to draining perimedullary veins. The fistulous site is located at the dural root sleeve in type 1 lesions and more distally at the pial surface in type 4 lesions. Surgical treatment of the former interrupts the fistula by coagulating and dividing the vein as it exits the fistula at the dura. In contrast, surgical treatment of the latter interrupts the fistula by clipping and dividing pathological branches from the anterior spinal artery on the ventral spinal cord. Misinterpretation of a type 4 fistula as a type 1 fistula might lead to the occlusion of an artery of Adamkiewicz as it enters the spinal subarachnoid space, with harmful neurological consequences and residual arteriovenous shunting. Conversely, misinterpretation of a type 1 fistula as a type 4 fistula might lead to the ineffectual remote occlusion of the draining vein from the fistula and residual arteriovenous shunting. In this example, successful treatment of the patient depends on the correct interpretation of the angiogram and classification of the arteriovenous pathology. Taxonomy for CMs has a similar potential to empower the management of this disease because the differentiation of cavernoma types and subtypes leads to different operations involving different craniotomies and surgical approaches. Therefore, a taxonomy for cavernomas has value because it informs surgical strategy.

1.3 Neuroanatomy

Like zoological taxonomy, neurosurgical taxonomy should be rooted scientifically in precise and reproducible facts, and in

Lesion Circulation Location		Approach	Lesion Location	Approach	Intervention Generation Type	Location	Donor	Recipient	Lesion Type	Subtype	
Aneurysm	Anterior	PcaA	Pterional	Frontal	1st	EC-IC	STA OA	MCA ACA PCA/SCA PICA/AICA	Cerebrum	Convexity Medial Basal Sylvian	
		MCA		Temporal		EC-IC interpos.	Cervical carotid	ECA CCA ICA			MCA ICA PCA/SCA
		OphA		Parieto-occipital	Bypass	3rd	Reimplantation	MCA ACA PCA/SCA PICA/VA	MCA ACA PCA/SCA PICA	Thalamus	Anterior Medial Lateral Choroidal Pulvinar Geniculate
		PCoA		Vent./Perivent.			In situ	MCA ACA PCA/SCA PICA/AICA			
		ACoA		Deep	Reanastomosis	MCA ACA PCA/SCA PICA	Pontine	Basilar Peritrigeminal Middle peduncular Inferior peduncular Rhomboid Supraolivary			
	Posterior	Basilar bifurcation	Orbitozygomatic	Brainstem	Anterior	Combination			Scalp	STA OA	MCA ACA PCA/SCA PICA/AICA
					Posterior		Cerv. carot.	ECA CCA ICA			
	PICA	Far lateral	Cerebellar	Cerebellar	Suboccipital Tentorial Vermian Tonsillar Petrosal	Combination	Cerv. carot.	MCA ACA PCA/SCA PICA ICA IMA VA	MCA ACA PCA/SCA PICA/AICA	Cerebellum	Suboccipital Tentorial Petrosal Vermian Tonsillar Deep nuclear

Fig. 1.1 The cavernous malformation taxonomy classifies cavernomas hierarchically into a system that enables neurosurgeons to uniquely define the spectrum of pathologies encountered in clinical practice. This taxonomy organizes a broad spectrum of pathologies into discrete entities that can be easily recognized to simplify and better understand the disease. Similar taxonomies have classified the spectrums of aneurysm and arteriovenous malformation pathologies, as well as the spectrum of bypass techniques. (Reproduced with permission from Barrow Neurological Institute, Phoenix, AZ.)

Table 1.1 Taxonomy of cavernoma types and subtypes

Type	Subtypes
Cerebrum	Convexity, medial, basal, and sylvian
Basal ganglia	Caudate, putaminal, and pallidal
Thalamus	Anterior, medial, lateral, choroidal, pulvinar, and geniculate
Midbrain	Interpeduncular, peduncular, tegmental, quadrigeminal, and periaqueductal
Pontine	Basilar, peritrigeminal, middle peduncular, inferior peduncular, rhomboid, and supraolivary
Medullary	Pyramidal, olivary, trigonal, gracile, and cuneate
Cerebellum	Suboccipital, tentorial, petrosal, vermian, tonsillar, and deep nuclear

the case of cavernomas, that taxonomy should be based on neuroanatomy. The big idea in *Seven Cavernomas: Tenets and Techniques for Resection* is the introduction of a comprehensive taxonomy for all CMs encountered in the brain that is based on neuroanatomy, clearly defined, and applicable at the bedside. Like other taxonomies, the cavernoma taxonomy is a hierarchical system that characterizes a lesion's type and subtype (► Table 1.1). There are seven types according to lesion location in the brain: (1) cerebrum, (2) basal ganglia, (3) thalamus, (4) midbrain, (5) pons, (6) medulla, and (7) cerebellum. Cavernomas in the gyri, sulci, and subcortical white matter of the superficial cerebrum are the most common in clinical practice because this territory comprises 85% of the brain's volume. Deep cerebral cavernomas reside in the basal ganglia and thalami, which together make up the central core of the brain and serve as the brain's information gateway, relaying and modulating signals from the periphery to the cortex. The brainstem occupies only roughly 5% of the brain's overall territory, but brainstem cavernomas account for three of the seven cavernoma types because their central location and depth make surgical strategy nuanced and complex. The seventh type comprises cavernomas in the cerebellum, the so-called little brain. The borders and boundaries of the seven types satisfy our conditions of clarity and applicability for a meaningful taxonomy.

Cavernoma types are defined by general brain regions, and subtypes are defined by the surface within that region where the lesion presents (► Fig. 1.2, ► Fig. 1.3). Surface presentation is a fundamental concept in surgical strategy because it guides approach selection and minimizes brain transgression. Lesions presenting at (superficial) or protruding through (exophytic) the pial or ependymal surfaces are accessed with minimal violation of normal tissue and resected with an inherently lower risk of neurological injury. In contrast, lesions presenting beneath the pial and ependymal surfaces (deep) are accessed only by violation of normal tissue, which raises the risks. Each cavernoma type has multiple pial or ependymal surfaces that define the subtypes. The cerebral hemispheres have four surfaces—convexity, medial, basal, and sylvian surfaces—throughout the frontal, parietal, occipital, and temporal lobes. The brainstem has anterior, anterolateral, lateral, posterolateral, and posterior surfaces, giving five or six subtypes for each type. The cerebellum has six subtypes, of which five are based on surfaces: suboccipital, tentorial, petrosal, vermian, and tonsillar. The thalamus and basal ganglia have limited or no communication with subarachnoid surfaces, and

subtyping for these deep cerebral types is based on buried surfaces and nuclear anatomy. Similarly, the sixth cerebellar subtype is based on the deep anatomy of the dentate, emboliform, globose, and fastigial nuclei rather than surface presentation.

The comprehensive taxonomy for all CMs contains 7 types, 3 to 6 subtypes within each type, and 35 subtypes overall. The neuroanatomy of the 35 subtypes follows in Section II of the book, each defined with prominent surface landmarks that can be identified radiographically and microsurgically. The borders and boundaries of the 35 subtypes also satisfy our conditions of clarity and applicability for a meaningful taxonomy. From the cartographer's perspective, taxonomy partitions the brain into types like countries on the map and into subtypes like states within each country. Collectively, taxonomy systematically classifies every conceivable cavernoma, just as nationality and state or province of residence help classify every citizen's home.

1.4 Neuroradiology

The MRI appearance of cavernomas makes them easy to diagnose. Their popcorn-like morphology, mixed signal intensities, hemosiderin ring, and associated developmental venous anomalies are pathognomonic. Immediately after the diagnosis is established, thoughts turn to the surgical plan. The exquisite anatomical and pathological details of MRI make neuroradiology essential to surgical strategizing. These plans are needed first to calculate the surgical risk, which hangs in the balance with natural history risk to arrive at a therapeutic recommendation. Heuristics like the two-point method were devised to select the surgical approach (► Fig. 1.4). This method places the first point at the center of the lesion, and the second point is where the lesion comes to a pial or an ependymal surface. The line connecting these two points defines the lesion's axis. Extending this line outward to the cranium suggests an operative corridor that might lead inward to the lesion. The lesion's axis is compared with operative trajectories from the menu of surgical options, and the best match is selected. The two-point method is a crude guide at best. It relies on simple geometries on single MRI slices to draw the lesion axis, rough approximations of surgical axes, and inclusion by the neurosurgeon of appropriate approaches from the operative menu.

Taxonomy offers a completely different approach. Instead of jumping immediately to the surgical plan, the cavernoma is classified on the basis of the pathoanatomical MRI appearance. The lesion's type and subtype then indicate the best

Brain CM Subtypes

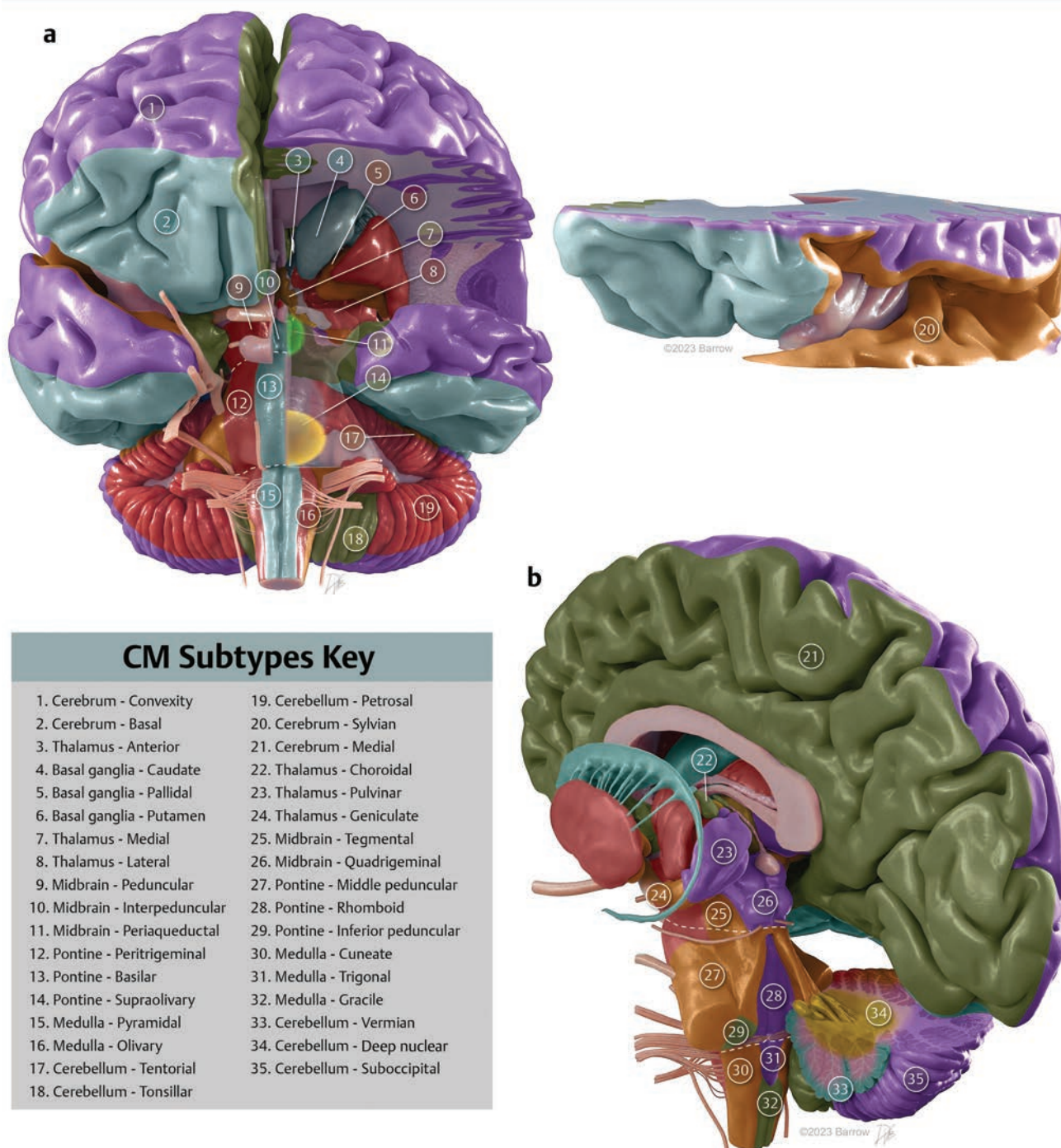


Fig. 1.2 Comprehensive taxonomy for seven cavernoma types and 35 subtypes. (a) The cerebrum, brainstem, and cerebellum are shown from an anterior view. An axial section of the left frontal, parietal, and temporal lobes is removed at the level of the sylvian fissure and insula to show some of the basal ganglia and thalamic subtypes. (b) The right cerebrum and cerebellum, left basal ganglia and thalamus, and brainstem are shown from a posterior oblique view. Cavernoma types and subtypes are numbered in the subtype key (*inset*). (Reproduced with permission from Barrow Neurological Institute, Phoenix, AZ.)

Brainstem Subtypes: Anterior

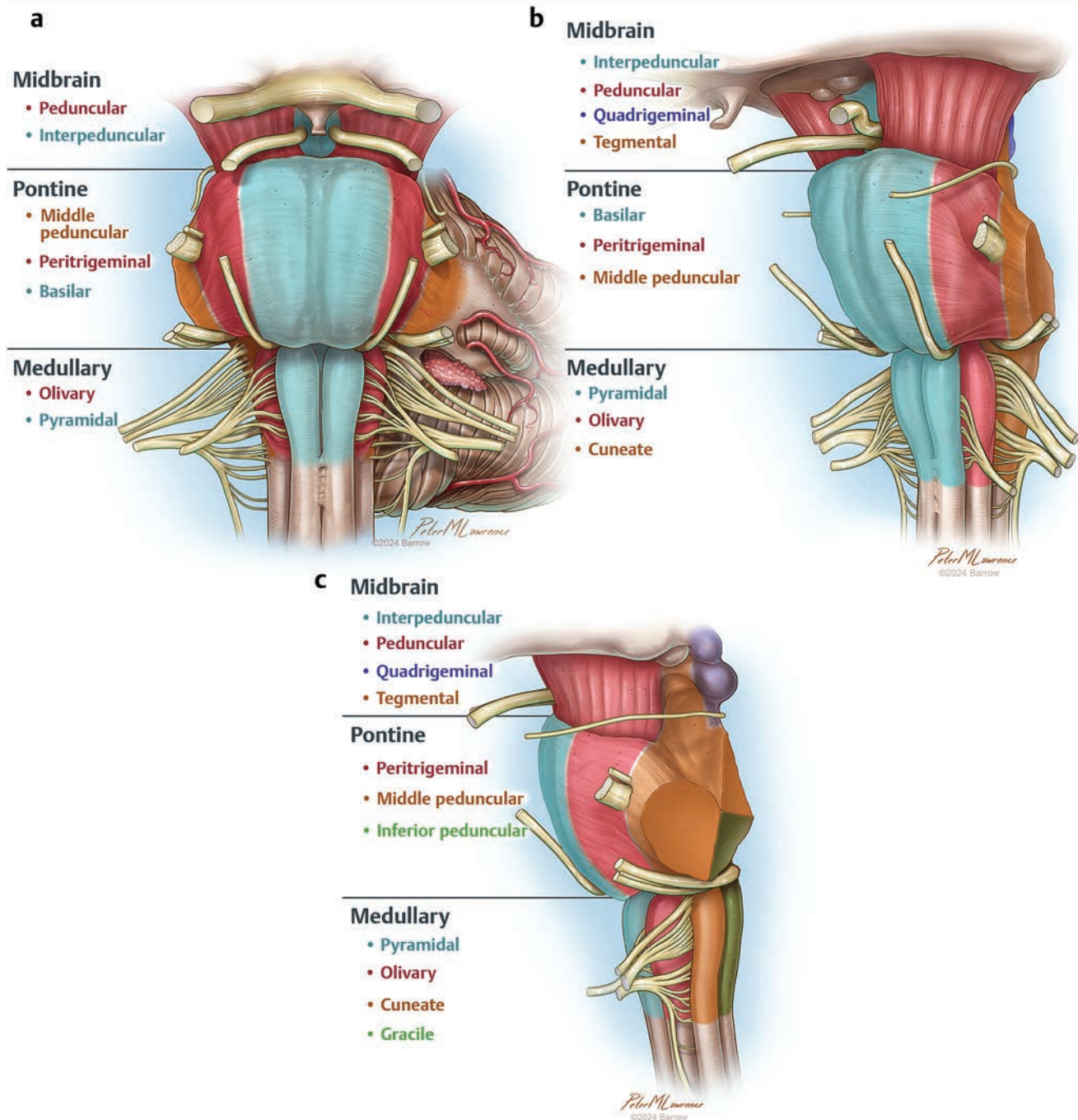


Fig. 1.3 The taxonomy for brainstem types and subtypes is shown in various perspectives: (a) anterior, (b) anterolateral, (c) lateral,

(Continued)

craniotomy and surgical approach based on surgical experience and clinical evidence (► Table 1.2). The recommendations tabulated for the various cavernomas in the taxonomy were derived from the combinations of Dr. Robert Spetzler's and my surgical experiences, as well as in others' works, described in this textbook and the 7 *Cavernomas* series of

articles published in the *Journal of Neurosurgery*. Accurate analysis and taxonomic interpretation of a patient's lesion on MRI is the first step that initiates a cascade of suggestions and decisions. Therefore, neuroradiological imaging is critical in translating pathoanatomy into an individualized classification that clarifies the course of management.

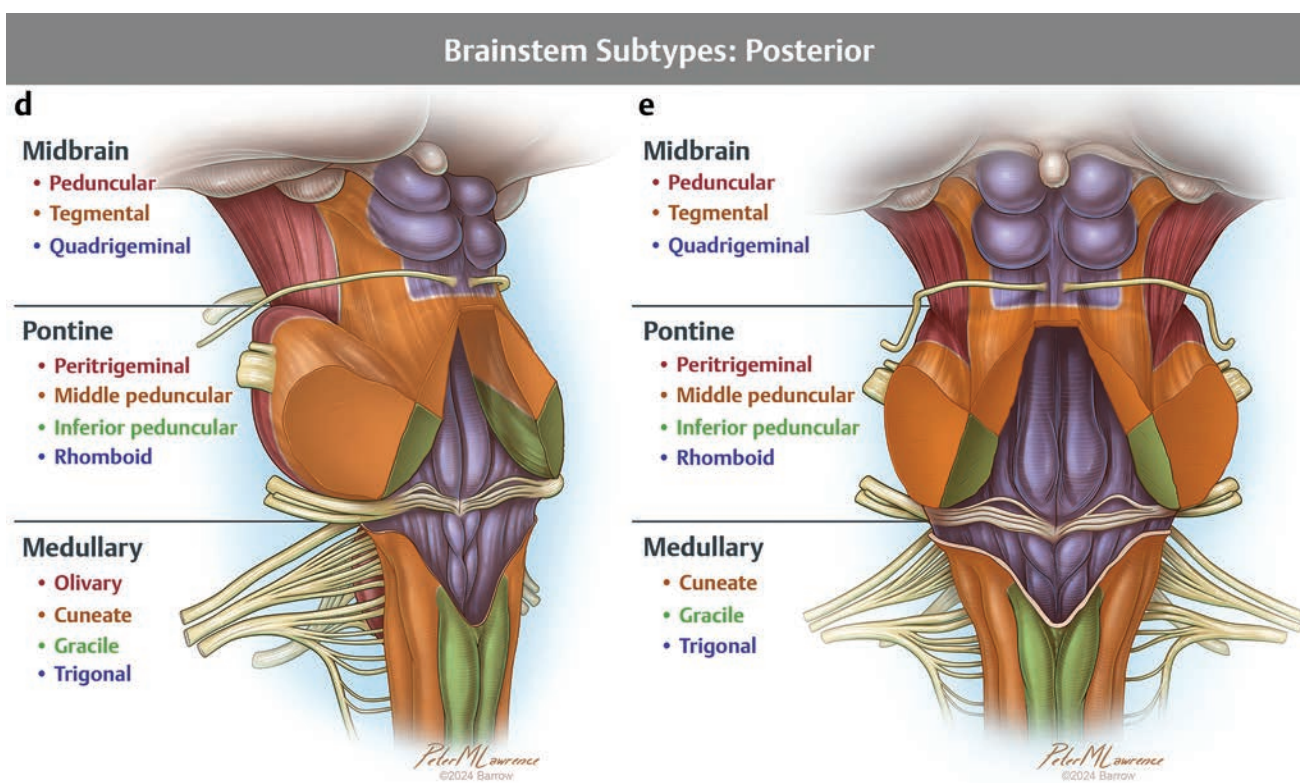


Fig. 1.3 (Continued) (d) posterolateral, and (e) posterior. (Reproduced with permission from Barrow Neurological Institute, Phoenix, AZ.)

1.5 Neurology

Findings from a neurological examination can localize and classify the cavernoma even before the brain MRI is ordered. Neurosurgery has always been the subspecialty of neurology focused on disorders and diseases requiring surgical treatment. This surgical focus encourages the incorporation of sophisticated equipment, advanced imaging, innovative devices, and high technology, often de-emphasizing fundamental skills like bedside examination. However, neurological findings are remarkably accurate at localizing lesions, especially in areas densely packed with tracts, cranial nerves, and their nuclei. In his remarks at the opening of the new building of the Boston Medical Library in 1901, Sir William Osler said, "Listen to your patient, he is telling you the diagnosis." Nowhere is this truer than in the patient with a brainstem cavernoma. For example, diplopia and the presence of an isolated abducens nerve palsy are clues that the patient has a supraolivary pontine CM. In addition, the presence of a preoperative deficit resulting from cavernoma hemorrhage may influence the approach selection. A patient with abducens nerve palsy without contralateral hemiparesis or hemiplegia (i.e., without Millard-Gubler syndrome) may be a better candidate for a far lateral craniotomy and trans-pontomedullary sulcus approach than an extended retrosigmoid craniotomy and transmiddle cerebellar peduncle approach because the former avoids transgressing a laterally displaced corticospinal tract. Therefore, taxonomy may boost the value of bedside acumen in neurosurgical practice. The

examination findings of our patients are often minimized or overlooked in fast-paced clinical rounds and operative routines. However, they may lead to the classification of the cavernoma long before reviewing the MRIs or confirming the subtype suggested by the images.

Osler was described as one of the greatest diagnosticians ever to wield a stethoscope. The list of signs, symptoms, and diseases that bear his name is long, including Osler's sign (artificially elevated systolic blood pressure readings due to calcified atherosclerotic arteries), Osler's nodes (raised tender nodules on the pulps of fingertips and toes in the setting of subacute bacterial endocarditis), and Osler-Weber-Rendu disease (hereditary hemorrhagic telangiectasia with arteriovenous malformations in brain, lung, and liver), to name a few. Like Osler wielding the stethoscope, skilled neurologists wielding the reflex hammer, flashlight, and pin can localize a stroke from the findings on a neurological examination. Weber's, Wallenberg's, and Dejerine's syndromes arose from the constellation of symptoms and signs resulting from strokes in ascending and descending tracts, decussations, and cranial nerve nuclei. Knowledge of these classic stroke syndromes and the ability to diagnose them on the basis of subtle bedside clues is empowering. The examination becomes a puzzle of localization and a valuable tool, challenging and reinvigorating our understanding of underlying neural circuitry.

Stroke syndromes might have been abandoned in the MRI era, but cavernoma taxonomy could revive their use (► Table 1.3). Midbrain CMs cause Claude's, Weber's, Nothnagel's, and

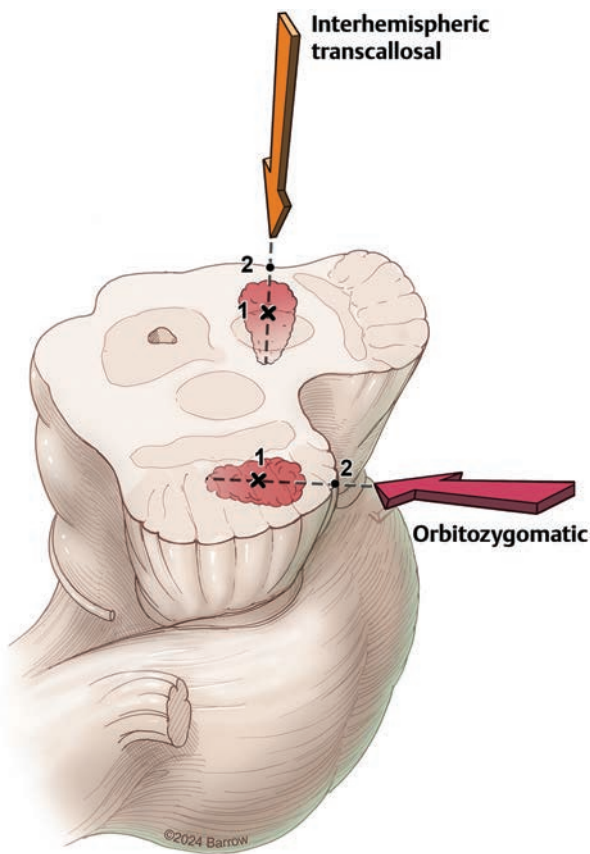


Fig. 1.4 Two-point method to determine the gross surgical approach to avoid the disturbance of eloquent brain parenchyma. The surgeon determines the center of the longest axis of the cavernoma and marks the center (x) as point 1; point 2 is then placed where the lesion comes to a pial or ependymal surface or nearest the least eloquent entry point closest to the surface of the brainstem. The line connecting these two points defines the lesion's axis. Extension of this line outward to the cranium suggests an operative corridor that leads toward the cavernoma (orange and red arrows). The cavernoma's axis is compared with the operative trajectories from the menu of surgical options considering the cavernoma's taxonomy and anatomical triangles, and the best match is selected. (Reproduced with permission from Barrow Neurological Institute, Phoenix, AZ.)

Parinaud's syndromes with interpeduncular, peduncular, quadrigeminal, and periaqueductal lesions, respectively. Pontine CMs cause locked-in, Marie-Foix, Millard-Gubler, and Foville's syndromes with basilar, middle peduncular, rhomboid, and supraolivary lesions, respectively. Medullary CMs cause Dejerine's and Wallenberg's syndromes with pyramidal, olivary, and cuneate CMs. In addition, novel syndromes can be defined by lesional hemorrhage by a particular subtype. For example, a new lemniscal syndrome can be described for tegmental midbrain CMs characterized by contralateral hemisensory loss of vibration and fine touch sensations, contralateral loss of pain and temperature sensations, contralateral facial hemisensory loss, and contralateral hearing impairment and tinnitus. CMs here affect the medial

lemniscus, trigeminal lemniscus, lateral lemniscus, and spinothalamic tracts, where they ascend to the thalamus. Similarly, a novel trigonal medullary syndrome can be characterized by dysphagia or dysphonia, nausea, vomiting, and tongue weakness associated with CMs in the medullary floor of the fourth ventricle. A stroke cannot cause this syndrome because the vascular territory of the medullary perforators precludes it, and consequently, this syndrome has not been reported previously.

Bleeding from a CM is like a stroke, affecting a discrete area of the brain or brainstem to cause focal deficits, but is often more focal. A stroke's effect is determined not only by the location of the arterial blockage but also by the downstream ischemia in the blocked vascular territory. In contrast, a cavernoma's effect is determined only by the location of the lesion. For example, Wallenberg's or lateral medullary syndromes are caused by a posterior inferior cerebellar artery occlusion and infarction involving the entire lateral medulla, including the inferior cerebellar peduncle, spinal trigeminal nucleus and tract, vestibular nuclei, dorsal motor nucleus of cranial nerve X, solitary nucleus, and nucleus ambiguus. Olivary CMs reside in the anterolateral portion of the medulla, and cuneate CMs reside in the posterolateral portion of the medulla. Together, olivary and cuneate CMs produce the classic Wallenberg syndrome; individually, each produces either the anterior or posterior signs and symptoms of Wallenberg's syndrome, respectively. Therefore, cavernoma syndromes have greater specificity than stroke syndromes, and the definition and redefinition of cavernoma syndromes associated with the subtypes are presented throughout the book to increase our neurosurgical acumen and empower us as diagnosticians.

1.6 Neurosurgery

Taxonomy is most valuable while designing and executing surgical strategies in the operating room. Neuroanatomy organizes and simplifies the spectrum of pathology, neuroradiology translates individual cavernomas into one of the 35 subtypes, and neurological findings confirm the classification. These steps ultimately lead to a specific surgical plan that includes craniotomy, approach, anatomical triangle, safe entry zone, arterial address, and arterial dissection codes. In short, taxonomy integrates neuroanatomy, neuroradiology, and neurology to inform neurosurgical intervention.

The goals of cavernoma surgery are twofold: first, curative resection of the pathology and, second, no surgical morbidity. Prevention of future hemorrhage and protection from its harmful effects cannot be accomplished without complete resection, which is easier for cavernomas than for other pathologies in vascular and skull base surgery, like brain arteriovenous malformations, petroclival meningiomas, and acoustic neuromas. Cavernomas are not fed by arteries and can be confronted without significant bleeding. They can be entered, decompartimentalized, and resected piecemeal, unlike arteriovenous malformations. The resection technique is basic and similar for all subtypes, and the discussion of the resection technique is limited to a single chapter in this book. The second goal is not as easy to achieve. Surgical morbidity can result from many situations. The journey from craniotomy to subarachnoid corridor to triangle to target can be long and deep, with pitfalls and traps along the way.

Table 1.2 Comprehensive taxonomy for all cavernoma types and subtypes and their associated craniotomies, approaches, and anatomical triangles

Type, subtype	Craniotomy	Approach	Triangle
Cerebral			
Convexity	Convexity	TGyr, TSul	None
Medial	Bifrontal, biparieto-occipital	TGyr, TSul	None
Basal	Various	TGyr, TSul	None
Sylvian	Pterional	TSyl-TGyr, TSyl-TSul	None
Basal ganglia			
Caudate	Bifrontal	cTCal-Vent	Caudate-thalamostriate
Putaminal	Pterional	TSyl-Alns	None
Pallidal	Orbitozygomatic	TSyl-SCIF	Supracarotid
Thalamic			
Anterior	Bifrontal	cTCal-iFor	Septocaudate
Medial	Bifrontal	cTCal-cTChor, cTCal-iTChor	None
Lateral	Pterional	TSyl-Plns	None
Choroidal	Bifrontal	iTCal-Vent	None
Pulvinar	Torcular	SCIT-Para	Infragalenic
Geniculate	Torcular	cSCTT	Infragalenic
Midbrain			
Interpeduncular	Orbitozygomatic	TSyl-IntPed, cTSyl-IntPed	Carotid-oculomotor
Peduncular	Orbitozygomatic	TSyl-Ped	Oculomotor-tentorial
Tegmental	Retrosigmoid	SCIT-Lat	Supra- and infratrochlear
Quadrigeminal	Torcular	SCIT-Mid	Infragalenic
Periaqueductal	Bifrontal	TCal-TChor	None
Pontine			
Basilar	Orbitozygomatic	Kaw, TSyl-Cav-Pon	Kawase/infratrigeminal, carotid-oculomotor
Peritrigeminal	Retrosigmoid	xRS-CPA	Supra- and infratrigeminal, GCT
Middle peduncular	Retrosigmoid	xRS-MCP	Interlobular
Inferior peduncular	Suboccipital	SOcc-TeVe	Subtonsillar
Rhomboid	Suboccipital	SOcc-Vent	Vallecular
Supraolivary	Far lateral	FL-PMS	Vagoaccessory (suprahypoglossal)
Medullary			
Pyramidal	Far lateral	FL-PreMed	Junctional
Olivary	Far lateral	FL-Med	Vagoaccessory (supra- or hypoglossal-hypoglossal)
Trigonal	Suboccipital	SOcc-Vent	Vallecular
Gracile	Suboccipital	SOcc-Magna	Vallecular
Cuneate	Suboccipital	SOcc-TeVe	Subtonsillar
Cerebellum			
Suboccipital	Suboccipital	SOcc-Para	None
Tentorial	Torcular	SCIT-Mid, SCIT-Para	None
Petrosal	Retrosigmoid	xRS-CPA	Interlobular
Vermian	Suboccipital	SOcc-Mid	None
Tonsillar	Suboccipital	SOcc-Magna	Vallecular
Deep nuclear	Suboccipital	SOcc-TeVe, SOcc-SupraTons	Vallecular

Table 1.3 Summary of brainstem taxonomy and associated neurological syndromes

Type, subtype	Syndrome
Midbrain	
Interpeduncular	Claude; Benedikt
Peduncular	Weber
Tegmental	Lemniscal syndrome
Quadrigeminal	Parinaud
Periaqueductal	Nothnagel; Claude
Pontine	
Basilar	Medial pontine; locked in
Peritrigeminal	Peritrigeminal pontine syndrome
Middle cerebellar peduncular	Marie-Foix (lateral pontine)
Supraolivary	Millard-Gubler; Foville
Rhomboid	INO; reverse INO; one-and-a-half; eight-and-a-half (facial colliculus syndrome)
Inferior cerebellar peduncular	Acute vestibular syndrome
Medulla	
Pyramidal	Dejerine
Olivary	Anterior Wallenberg
Trigonal	Trigonal medullary syndrome
Gracile	Leg numbness
Cuneate	Posterior Wallenberg

Normal tissue overlying the cavernoma might need to be transgressed to reach the lesion because the adherent capsule might not separate from the adjacent eloquent brain, and the mobilization of normal tissue might be needed to visualize hidden portions of the cavernoma within the working corridor. Achieving zero morbidity during the various phases of the operation demands meticulous dissection technique and skill. It also demands forethought and insight before entering the operating room to orchestrate a proverbial surgical strike.

The surgeon's surgical strike takes the most direct pathway from the skin to the cavernoma, opens a wide corridor to the target, exposes critical neurovascular structures, exposes pathology throughout the resection, and optimizes the chances of a cure. In the words of Al Rhoton, "a well-designed surgical strike should be accurate, simple, and safe." During beautiful surgery, strategic preoperative planning is probably more important and harder to see than meticulous operative technique. Surprisingly, the strategic aspects of cavernoma surgery are easier to teach in the pages of a book than the technical

aspects. Taxonomy attempts to codify surgical strategy to choose the best approaches, guide the execution, and optimize intraoperative performance to improve patient outcomes. It might be fair to say that cavernoma surgery is the ultimate game of surgical strategy because the design and execution of the strategy have a greater effect on the results than the surgeon's resection of the pathology. That said, CM taxonomy organizes the many surgical strategies and approaches into a coherent and applicable framework.

1.7 Seven Cavernomas Framework

With 7 types and 35 subtypes in the taxonomy for cavernomas, the 7 cavernomas framework may seem complex and impractical. However, the subtypes are intuitive and easy to remember. The interconnections between taxonomy, neuroanatomy, neuroradiology, neurology, and neurosurgery are shown in ► Table 1.2, which is a Rosetta stone of sorts that decodes the seven cavernomas framework and summarizes the topics covered in this book. Armed with the correct subtype for the patient's cavernoma, a surgeon can consult this table, which guides surgical planning and execution. Anatomical classification leads to a unique set of recommendations for each of the 35 subtypes in the taxonomy.

We are advancing rapidly toward a future where artificial intelligence on computers and smartphones will guide these steps. I worry that we will be beholden to our workstations, feeding MRIs into a black box and waiting for the algorithm to deliver the subtype and surgical directive. Neurosurgeons would be reduced to nonthinking technicians, much like drivers who rely on dashboard navigation to prompt the next turn or exit. I prefer a future where neurosurgeons embrace the metacognitive challenges of cavernoma surgery and apply their knowledge of neuroanatomy and heuristics like taxonomy and grading systems to practice the art of neurosurgery. The more we engage in the analysis and strategy for every patient, the more adept we become at achieving our goal of safe and curative surgery. Real drivers study their road maps, design their routes, and anticipate key turns. They know their travel times, fuel needs, and arrival times. These drivers actively orienteer their way to their destination, in contrast with those who passively follow their technology for directions. The cartography metaphor is meant to encourage the learning and application of the seven cavernomas framework in pursuit of elegant and safe neurosurgery. It is also meant to encourage neurosurgeons to take the high road of thinking and strategizing their way through the subarachnoid space rather than the low road of just following directions.