Chapter 9

Surgery for Vascular Lesions of the Brainstem

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Abbreviations

AICA	Anterior inferior cerebellar artery
AVM	Arteriovenous malformation(s)
BA	Basilar artery
BRAT	Barrow Ruptured Aneurysm Trial
BT	Basilar trunk
BVR	Basal vein of Rosenthal
CM	Cavernous malformation
CN	Cranial nerve
CSF	Cerebrospinal fluid
CST	Corticospinal tracts
CT	Computed tomography
CTA	Computed tomography angiography
DSA	Digital subtraction angiography
DTI	Diffusion tensor imaging
IA	Intracranial aneurysm
IAC	Internal auditory canal
ISAT	International Subarachnoid Aneurysm Trial
ISUIA	International Study of Unruptured Intracranial Aneurysms
MAPonMesV	Median anterior pontomesencephalic vein
MCP(s)	Middle cerebellar peduncle(s)
mOZ	Modified orbitozygomatic
MRA	MR angiography
MRI	Magnetic resonance imaging

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OA-PICA EC-IC	Occipital artery-posterior inferior cerebellar artery external carotid-internal carotid
OZ	Orbitozygomatic
PCA	Posterior cerebral arteries
PCP	Posterior clinoid process
PICA	Posterior inferior cerebellar artery
SAH	Subarachnoid hemorrhage
SCA	Superior cerebellar artery
SCIT	Supracerebellar infratentorial
SPetrV	Superior petrosal vein
SPS	Superior petrosal sinus
SS-EPI	Single-shot echo planar imaging
T2∗GRE	T2∗-Gradient Recalled Echo
VA	Vertebral arteries
VBJ	Vertebrobasilar junction

9.1 Introduction

Vascular lesions of the brainstem are rare entities that pose significant challenges to surgical management. The dense eloquence of the brainstem significantly increases the risk of surgery compared to similar lesions in the supratentorial space. The intimate relationship of critical perforating arteries and the limited working corridors magnify these challenges. Preoperative evaluation requires consideration of multiple treatment modalities, including microsurgery, endovascular therapy, or radiotherapy, alone or in combination. The risks of intervention must be balanced against the natural history of these lesions, which, generally speaking, have higher rates of rupture than their supratentorial counterparts. Although increased rupture rates and the devastating sequelae of a brainstem hemorrhage often support an aggressive surgical posture, close observation of unruptured brainstem-associated vascular lesions is sometimes preferred. Decision-making for ruptured lesions is frequently much more straightforward, given the ruinous consequences of re-rupture.

Elegantly described by Rhoton, the posterior fossa can be considered in groups of threes. There are three segments of the brainstem: midbrain, pons, and medulla [1]. Each of these is associated with a respective segment of the large vessels of the posterior circulation (basilar artery [BA] apex, basilar trunk [BT], and vertebral arteries [VA]/vertebrobasilar junction [VBJ], respectively) and associated branch vessels (superior cerebellar artery [SCA], anterior inferior cerebellar artery [AICA], and posterior inferior cerebellar artery [PICA]). Likewise, the three neurovascular complexes are associated with a group of cranial nerves (CN) and their associated nuclei: CN III-V are related to the midbrain, CN VI-VIII with the pons, and CN IX-XII with the medulla. Using this organization, aneurysms, arteriovenous malformations (AVM) and cavernous malformations (CM) will be considered regionally. The following chapter outlines the general approach to the diagnosis and management of vascular lesions of the brainstem; a full technical description of the surgical nuances is beyond the scope of this chapter.

9.2 Natural History

The risk of symptomatic rupture has been described extensively for aneurysms, AVMs, and CMs, and, in general, the risks of rupture are known to be higher for brainstem locations. Posterior circulation aneurysms represent 15% of all intracranial aneurysms (IAs), and the increased risk of rupture relative to size-matched anterior circulation aneurysms has been described. In the International Study of Unruptured Intracranial Aneurysms (ISUIA) trial, small posterior circulation aneurysms (<7 mm) had a 5-year cumulative rupture rate of 2.5% (compared to 0% for anterior circulation aneurysms), and these rates ranged up to 50% for giant aneurysms [2]. Brainstem AVMs account for 2–6% of all intracranial AVMs. The majority of AVMs in this location present with ruptured status and have substantially higher annual rupture rates (15–17.5%/year) than generally quoted for supratentorial brain AVMs (1–4%/year) [3]. While brainstem AVMs may have an intrinsically higher rate of rupture, including an increased chance of harboring nidal aneurysms, it has been posited that the absence of cortical findings, such as seizures, decreases the likelihood of discovering brainstem AVMs prior to rupture [4]. Similarly, brainstem CMs have been shown to have a substantially higher rate of hemorrhage than supratentorial CMs. A recent meta-analysis by Taslimi et al. showed nearly a 10-fold higher annual rupture rate of brainstem CMs compared to non-brainstem CMs (0.3%/year vs. 2.8%/year) [5]. Patients presenting with ruptured brainstem CMs had an annual rupture risk of 32.3%/year compared to 6.3%/year for non-brainstem locations [5]. Given the chronic deposition of blood products (evidenced by prominent susceptibility artifact on T2∗-gradient recalled echo [T2∗GRE] magnetic resonance imaging [MRI]), it is likely that CMs undergo regular micro-rupture in addition to frank intralesional and intraparenchymal hemorrhagic events, accounting for the increased rate of symptomatic presentation. Furthermore, these estimates of rupture rate may significantly underestimate the true annual rate. Documented *de novo* formation for all three pathologies has been demonstrated, decreasing the denominator in event rate calculations. Overall, the high rates of hemorrhage and consequences thereof for brainstem vascular lesions argues for an aggressive surgical posture.

9.3 Presentation and Diagnosis

9.3.1 Clinical Presentation

Presentation varies by the type of vascular lesion and its location within the brainstem. Hemorrhagic brainstem vascular lesions generally result in a more critical clinical condition than those in the supratentorial space, regardless of the particular pathology [6–8]. This is largely due to the comparatively smaller volume of the posterior fossa, as well as the highly eloquent nature of the brainstem parenchyma. Furthermore, posterior fossa AVMs and aneurysms presenting with subarachnoid hemorrhage (SAH) are more likely to be complicated by hydrocephalus and have been shown to require higher rates of permanent cerebrospinal fluid (CSF) diversion. Likewise, CMs of the brainstem tend to present with clinical deficits with a smaller volume of parenchymal hemorrhage, or with a purely intralesional hemorrhage.

Focal neurologic deficits, either from CN compression, parenchymal mass effect or vascular steal phenomenon, are dependent on the particular location within the brainstem. As stated earlier, cranial neuropathies can result from compression of the cisternal segment of the affected nerve and, thus, are always ipsilateral to the lesion. By comparison, cranial neuropathies resulting from parenchymal injury can be remote from the lesional site relative to the level of the brainstem associated with the cisternal segment of that nerve. An example of this is facial numbness occurring as a result of injury to the spinal trigeminal nucleus in the medulla (despite the association of CN V with the pontomesencephalic junction based on its surface anatomy). Similarly, deficits from parenchymal injury can be either ipsilateral or contralateral to the lesion, depending on the presence or absence of tract decussation. As such, the need for a thorough neurologic examination and localization cannot be overstated and is the cornerstone of preoperative and postoperative evaluation.

9.3.2 Imaging

Initial imaging workup also depends heavily on the presentation and suspected type of lesion. Imaging workup for patients presenting with SAH or symptoms concerning for brainstem hemorrhage should begin with non–contrast-enhanced computed tomography (CT) of the head as the initial modality of choice. The diagnosis may be suggested but is rarely confirmed by head CT alone. For patients with potentially life-threatening hemorrhages requiring emergent decompression, CT angiography (CTA) is considered the vascular imaging study of choice due to its rapid acquisition. In the senior author's practice, CTA is frequently sufficient to guide decision-making in aneurysms presenting either unruptured or with SAH (particularly to guide clip versus coiling allocation) and is particularly useful in understanding the relationship of a given aneurysm to the skull base bony anatomy. However, the gold standard remains cerebral digital subtraction angiography (DSA), particularly for those aneurysms with complex morphologies or those that may potentially necessitate revascularization as part of the treatment [9]. While the risk of major neurologic complications associated with DSA is extremely low, improvements in resolution of CTA on modern scanners may obviate the need for invasive imaging for more and more aneurysms. Conversely, given that endovascular treatment of cerebral aneurysms related to the brainstem is considered the first-line treatment at many centers, DSA still plays a major role in the evaluation and treatment of most brainstem-associated aneurysms.

By contrast, we recommend the use of DSA for all AVMs, except for those necessitating emergent surgery. While advances have been made in noninvasive imaging of AVMs, such as the so-called "4D imaging" techniques, DSA remains essential for several reasons [10]. First, the resolution of DSA has not been matched by noninvasive imaging techniques and is essential for identifying anatomical landmarks associated with the malformation to help guide the resection. Likewise, AVM surfaces fed by small parenchymal feeding vessels (coined “little red devils” by Charles Wilson) are much more easily identified on DSA. The architecture of these vessels makes them much more challenging to coagulate and divide than larger feeding arteries and generates a diffuse nidal surface, the presence of which increases the risk of perioperative morbidity and mortality. As such, identification of this feature is essential and has been included into the Lawton-Young Supplementary AVM scale to aid preoperative decision making [11]. Secondly, AVMs are dynamic lesions by nature, and noninvasive imaging techniques have yet to replicate the ability to see the flow from arterial feeders, through nidus, and into draining veins as clearly as with DSA. The ability to translate radiographic features of both arterial and venous anatomy in one’s mind while developing a surgical plan is critical, and DSA aids substantially in differentiating these vessels within the teeming mass of the AVM. Finally, formal angiography allows for the use of preoperative embolization. Despite the evolution of endovascular embolization, such as transvenous or “pressure cooker” techniques, cure rates remain low with embolization alone [12]. However, preoperative embolization frequently improves the safety and efficiency of surgical resection whenever it can be performed without placing normal vessels at risk. One must pay careful attention, though, because normal perforating arteries may not be well visualized, and the consequences of inadvertent embolization can be devastating.

MRI has different applications for each of the three main types of vessel malformations. For aneurysms, MR angiography (MRA) can be useful as a screening tool and for long-term noninvasive follow-up imaging, but does not have sufficient resolution to guide operative decision-making alone in most cases [13]. However, in those patients with large or giant aneurysms with significant brainstem compression, such as dolichoectatic basilar aneurysms, MRI offers the best brain tissue contrast of any available imaging modality. Similarly, MRI is essential for delineating the parenchymal surface of a brainstem AVM. For AVMs that are purely pial, total resection may be a viable strategy, whereas those with a significant parenchymal component may benefit from *in situ* disconnection, radiosurgery, or observation [14]. For CMs, however, MRI plays much more of a fundamental role. Until its development in the 1980s, CMs were an under-recognized entity, with a variety of names applied to these “occult” lesions. Subsequent description of its MRI appearance (including four radiographic subtypes in the Zabramski classification) drove broader understanding of these lesions as a clinical entity and as a target for surgical intervention. The advent of diffusion tensor imaging (DTI)-based tractography has aided the identification of the associated fiber tracts and the displacement or disruption thereof [15]. Anatomical MRI and tractography should be interpreted cautiously, however. The superparamagnetic properties of deposited hemosiderin result in a substantial susceptibility artifact in T2-weighted scans. This biophysical property is utilized in T2∗GRE imaging, producing “blooming” of susceptibility artifact in the region of hemosiderin due to use of magnetic gradient instead of radiofrequency refocusing pulses. Unfortunately, the single-shot echo planar imaging (SS-EPI) sequences on which DTI is based are also affected by the susceptibility

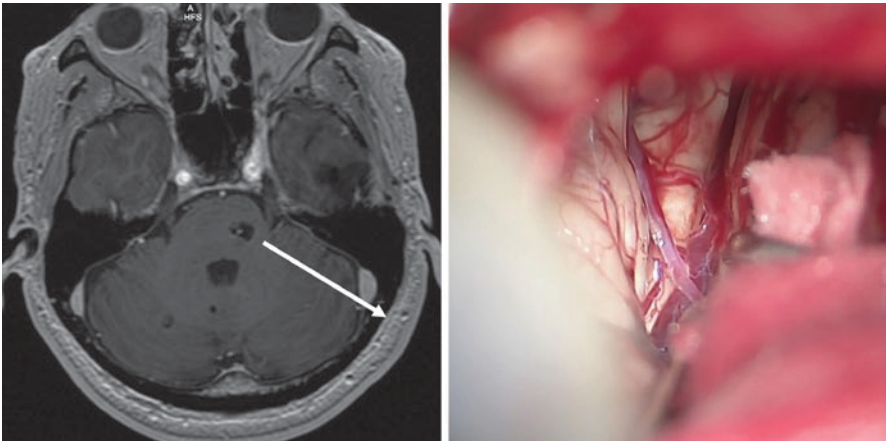

Fig. 9.1 Cavernous malformations residing in the lateral aspect of the pons are safely approached through the middle cerebellar peduncle (MRI left). Projecting this trajectory back onto the skull suggests that a retrosigmoid craniotomy is best suited for resecting this lesion. Opening the petrosal fissure of the cerebellum (right) establishes a more posterior entry point into the MCP, allowing for a more favorable trajectory into the brainstem. Used with permission from Barrow Neurological Institute

artifact, affecting the reliability of tractography around a CM with significant hemosiderin staining, an effect that scales with field-strength. We recommend careful evaluation of non–contrast-enhanced T1-weighted images prior to planning surgical intervention, as lesions that appear to reach the pial surface on T2-weighted sequences can often be up to several millimeters deep to the surface on T1-weighted images, changing the surgical approach or risk profile of the surgical intervention.

Finally, the optimal imaging evaluation for a brainstem vascular lesion should include consideration of neuronavigation. Aneurysms, including those of the posterior circulation, can often be approached using a standard array of workhorse approaches and anatomical dissection, rendering image guidance superfluous in many cases. Conversely, large and giant aneurysms of the posterior circulation, and all AVMs and CMs of the brainstem, benefit from the routine use of navigation. Complex skull base approaches may also benefit from the use of CT scans to guide the extent of bone drilling. With brainstem surgery, trajectory planning, pial entry and depth of surgical resection are all aided with the use of image guidance. Tackling pontine CMs through a trans-middle cerebellar peduncle (MCP) approach is a classic example in which image guidance aids in the identification of the ideal entry point in the MCP (Fig. 9.1).

9.4 Regional Management Strategies for Brainstem Vascular Lesions

Surgery for vascular pathology of the brainstem requires a working knowledge of an array of surgical approaches. We have considered only open transcranial approaches here, as opposed to endoscopic endonasal approaches. While some groups have advocated endoscopic surgery for brainstem vascular lesions [16], we feel that the technology necessary for safe treatment of posterior circulation aneurysms or intraparenchymal dissection is currently unavailable. That said, technological advancements in endoscopes, instruments, and robotic assistance may make endonasal approaches more practicable in the future. It should also be noted that the ideal approach is often dictated by subtle anatomical variations, so thorough review of imaging should be performed before selecting an approach for a given patient.

9.4.1 Midbrain

9.4.1.1 Aneurysms

Aneurysms associated with the midbrain most frequently include those arising from the BA apex, SCA, and proximal posterior cerebral arteries (PCA), constituting 5–10% of all IAs and over 50% of posterior circulation aneurysms [17], and are closely associated with the cerebral peduncles. Aneurysms of the distal PCA or SCA (and their associated branches) are rare by comparison and necessitate approaches to the lateral or dorsal midbrain. Endovascular treatment of these aneurysms is considered first-line in many centers, due to its relative ease compared to clipping in this location [18]. The intimate relationship with the perforating arteries arising from the BA apex and P1 PCAs makes dissection of BA and proximal PCA aneurysms particularly challenging, and the consequences of including even a single perforator in a clip construct can be devastating. However, aneurysm recurrence after endovascular treatment and the need for revascularization often drive the demand for microsurgery for these aneurysms.

Until the pioneering work of Charles Drake at the University of Western Ontario, aneurysms of the BA apex were considered beyond the realm of treatment. Since then, surgery for these aneurysms has become a key part of the armamentarium of vascular microneurosurgeons. Drake advocated the use of a subtemporal approach with division of the tentorium posterior to the entry point of CN IV [19]. This approach has the advantage of permitting a clear view along the posterior wall of BA aneurysms, aiding perforator dissection, but is limited by the temporal lobe retraction necessary to reach the BA apex and the exposure of the contralateral PCA. Yaşargil, by contrast, made use of the pterional transsylvian approach, and the need for access to high-riding BA apex aneurysms led to the development of the orbitozygomatic (OZ) osteotomy and its many modifications [20]. While some have advocated that the modified OZ (mOZ) achieves nearly the same degree of upward exposure with less cosmetic deformity, we believe that there are several reasons to justify the use of a full OZ in most aneurysms in this location [21, 22]. Removal of the zygomatic arch allows for inferior mobilization of the temporalis muscle, broadening the angle of attack to the ventral midbrain. This maneuver also aids in posterolateral mobilization of the temporal lobe to achieve a pretemporal approach, which can be increased by division of the subtemporal veins and, when necessary, division of the anterior temporal and/or posterior communicating artery (Fig. 9.2). This in turn enables wide visualization of the BA apex and exposes the P2A PCA in the oculomotor-tentorial

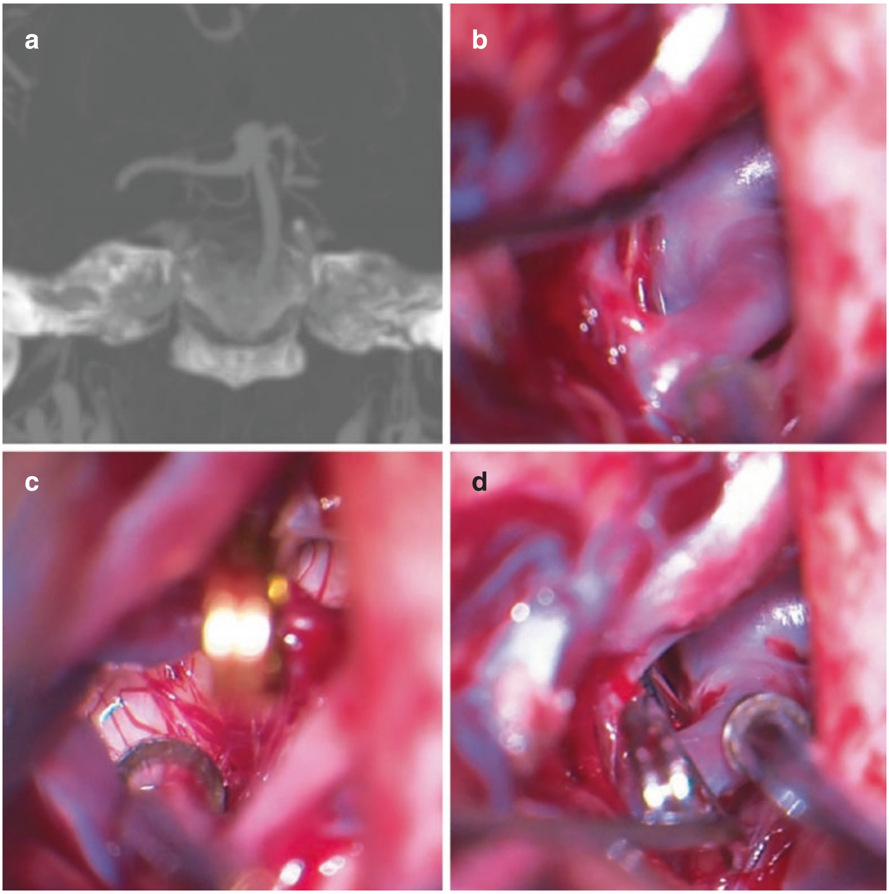

Fig. 9.2 An unruptured basilar apex aneurysm (**a**) was approached through a right-sided full orbitozygomatic craniotomy. Mobilization of the temporal lobe is accomplished by division of the bridging veins and dissection along the course of the anterior choroidal artery, bringing the basilar apex into view (**b**). The pretemporal trajectory allows for a tangential view to the P1s and enables visualization of the basilar perforators arising posterior to the aneurysm dome (**c**). A single fenestrated clip encircles the PCA and completely closes the aneurysm (**d**). Used with permission from Barrow Neurological Institute

triangle in cases where revascularization is necessary. Establishing proximal control on the BA is often aided by drilling the posterior clinoid process (PCP), or the addition of transcavernous approaches (as advocated by Krisht and others) [23]. The Kawase anterior petrosectomy has also been used to approach low-lying basilar aneurysms down to the level of the internal auditory canal (IAC) [24]. Distal PCA and SCA aneurysms can be addressed through a variety of approaches, including subtemporal and variations of the supracerebellar infratentorial (SCIT) approaches.

Since the publication of the International Subarachnoid Aneurysm Trial (ISAT) in 2002, there has been a substantial shift in the treatment of aneurysms arising at the basilar terminus. This trial demonstrated an improvement in early outcomes with coiling compared to clipping, with favorable outcomes achieved in 76.5% and 69.1% of coiling and clipping patients, respectively, at 1 year after treatment [25]. Unfortunately, ISAT only included 17 BA apex aneurysms out of 2143 patients, limiting its applicability. The Barrow Ruptured Aneurysm Trial (BRAT) included a much larger cohort of BA apex aneurysms (4.7% of enrolled patients), and also demonstrated improved clinical outcomes for posterior circulation aneurysms at 1-, 3- and 6-year time points, though the large proportion of PICA aneurysms in the clipping group may skew these results. For all aneurysms, clipping achieved a 96% complete occlusion rate compared to 48% for coiling at 6 years [6]. The majority of BA aneurysms are now treated by endovascular coiling in most of the developed world. In spite of this, the relatively few series published on clipping of basilar apex aneurysms after the publication of ISAT seem to suggest that favorable outcomes were achieved at higher rates than in older series (58–92%) and similar to contemporary series of coiled patients (78–95%), with lower occlusion rates in the coiling series [26]. Though, the overall data generally favor coil embolization for these aneurysms. However, patients with small aneurysm domes, severe allergy to nickel, poor vascular access, and PCA configurations that make branch vessel preservation difficult have clear indications for microsurgery, and younger patients may benefit from the higher long-term occlusion rates with clipping.

9.4.1.2 Arteriovenous Malformations (AVMs)

As with all brainstem AVMs, midbrain AVMs are located in an eloquent region and drain into the deep venous system. However, in the senior author’s experience, up to 70% of brainstem AVMs are located on the brainstem surface, in a pial or epipial location, as opposed to intraparenchymal [4]. In the patients undergoing surgical resection in that series, one quarter of brainstem AVMs were located in the mesencephalon. AVMs of the midbrain can be divided into two main groups, anterior and posterior midbrain AVMs. Despite the relatively large surface area, AVMs located on the lateral surface of the midbrain were not encountered [27].

Anterior midbrain AVMs are defined as those located in the cerebral peduncles, on their surface, or in the interpeduncular space. They are fed by feeders arising from the P1 and P2A PCA (and their associated perforating arteries) and lie in close association with one or both third nerves. Drainage is into tributaries of the basal vein of Rosenthal (BVR), such as the median anterior pontomesencephalic (MAPonMesV) and peduncular veins. While the anterior surface of the midbrain can be seen with a standard pterional transsylvian approach, we recommend the use of a full OZ for these lesions to expand the Sylvian corridor. The primary working window is the oculomotor-carotid triangle, but additional access can be obtained medially through the optico-carotid triangle, superiorly through the supra-carotid triangle, or laterally through the oculomotor-tentorial triangle. Arterial dissection identifies nidal feeding vessels while preserving critical normal perforating arteries. Circumdissection is carried out and the aneurysm is either resected from its pial plane or occluded *in situ* without parenchymal dissection depending on its specific anatomy.

Posterior midbrain AVMs are located in the tectum and may sit in the quadrigeminal cistern in a primarily exophytic configuration. They are closely associated with the trochlear nerve. Feeding arteries arise from the circumflex perforators of the P1 and P2 PCA segments, as well as from the cerebellomesencephalic segment of the SCA. Venous drainage is into the vein of the cerebellomesencephalic flexure and tectal vein, which in turn drain into the vein of Galen. They are approached through a torcular craniotomy/SCIT approach, which exposes the dura across the bilateral transverse sinuses and distal superior sagittal sinus. The exposure of the sinuses allows a curvilinear dural flap to retract the transverse sinuses upward, expanding the operative corridor. We favor placing the patient in the sitting position when feasible, as gravity retraction greatly expands the operative corridor. While surgeon fatigue is a concern in this position, the added exposure is generally a worthwhile tradeoff. Patients with patent foramen ovale (confirmed by bubble test with echocardiogram), older patients at higher risk for dural tear and air embolism, or those with large AVMs requiring prolonged operative times may be better suited for prone positioning. Occlusion of the arterial inputs begins inferiorly and laterally, with circumdissection progressing toward the draining veins arising superiorly in the field. As with anteriorly located AVMs, the decision to resect the AVM versus *in situ* occlusion is made intra-operatively depending on the pial plane. In the senior author's experience, outcomes from surgical resection of posterior midbrain AVMs have not been favorable, with 50% of patients experiencing neurological decline or death [4].

9.4.1.3 Cavernous Malformations (CMs)

CMs of the midbrain may present with symptoms isolated to the structures in this region and may also extend cranially into the thalamus or caudally into the pons when they reach larger dimensions. Ventrally located lesions frequently present with weakness or diplopia due to involvement of the cerebral peduncles or fibers of the third nerve. Dorsally located lesions often present with dysconjugate gaze and cerebellar ataxia due to involvement of the superior colliculus and superior cerebellar peduncle, respectively. The dorsolateral location is accompanied by facial and body numbness from compression of the trigeminothalamic tract and medial lemniscus in the midbrain tegmentum.

Facility with a variety of surgical approaches is necessary to safely address mesencephalic CMs. For CMs centered in the cerebral peduncle or posterior to the interpeduncular cistern, the OZ approach (or its variants) are favored. Dorsolaterally situated lesions are best approached through a lateral/extreme-lateral SCIT approach, which can be used to reach as anteriorly as the lateral mesencephalic sulcus, whereas midline dorsal CMs are approached from a traditional midline SCIT approach [28] (Fig. 9.3). Given the reach achieved by these workhorse approaches, use of the more limited subtemporal approach (with or without anterior petrosectomy) to the lateral midbrain is rarely necessary. For the posterior fossa approaches to the midbrain, we favor use of the sitting position when it can be performed safely. While it can be challenging to operate in the sitting position for

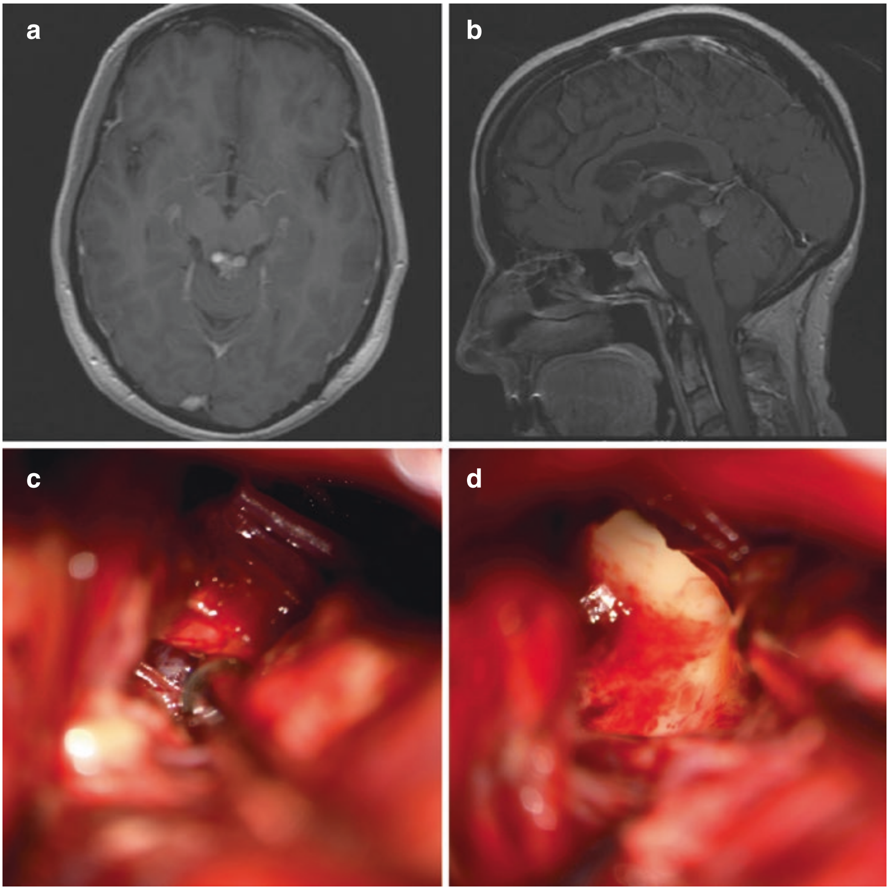

Fig. 9.3 A patient presenting with diplopia and paresthesia was found to have a dorsal midbrain CM with a classic "popcorn" appearance on axial (**a**) and sagittal (**b**) MRI sequences. A supracerebellar-infratentorial craniotomy was planned to approach this lesion. Even with the patient in the sitting position, to maximize gravity retraction of the cerebellum, the CM was not completely visible. Resection of a small area of the medial cerebellar hemisphere exposed the lesion in the cerebellomesencephalic flexure (**c**). This partially exophytic CM enabled resection without transgression of normal brainstem (**d**). Used with permission from Barrow Neurological Institute

prolonged cases, the wide corridor afforded by this approach provides excellent exposure of the midbrain surface along its craniocaudal extent. Conversely, SCIT craniotomies performed in the prone or lateral positions may necessitate resection of a small notch of the cerebellar hemisphere in order to reach down into the pontomesencephalic flexure.

Spetzler and colleagues have described a number of safe entry zones into the midbrain for lesions that do not approach the pial surface of the midbrain [29]. For ventrally located CMs, the interpeduncular and anterior mesencephalic sulcus safe entry zones have been described. These two entry zones are centered on either side of CN III. When the anterior mesencephalic zone is used as an entry point, the pial incision is situated medially on the peduncle through the frontopontine fibers while sparing the corticospinal tracts (CST) occupying the middle 3/5th of the peduncle. The safe entry zone into the dorsolateral midbrain is entered in the lateral mesencephalic sulcus and is directed between the fibers of the medial lemniscus and the substantia nigra. For dorsally located lesions, vertically oriented intercollicular incisions and horizontally oriented supra- and infra-collicular approaches have been described [30].

9.4.2 Pons

9.4.2.1 Aneurysms

Aneurysms associated with the pons are among the most challenging cerebrovascular lesions. VBJ and BT aneurysms are situated ventrally along the brainstem, for which working corridors are frequently limited or necessitate increasingly morbid transpetrous approaches to increase anterior exposure. For smaller AICA aneurysms, the narrow corridor afforded by middle fossa Kawase anterior petrosectomy or the limited ventral exposure of the extended retrosigmoid approaches may be sufficient. The intimate association of these aneurysms with critical pontine perforating arteries demands meticulous dissection and limits the tolerance to temporary clipping or Hunterian ligation.

For the above reasons, there has been significant growth in the use of endovascular techniques for the treatment of these aneurysms. Successful treatments of these aneurysms have been reported with coiling, stent-assisted coiling, flow-diversion, or flow-diversion assisted coiling [31]. While avoiding invasive skull base approaches is appealing, endovascular techniques are faced with two major challenges for aneurysms associated with the pons. First, the presence of pontine perforating arteries can cause significant complications when flow diversion is employed. Perforating artery flow can be maintained when flow diverting stents are well-opposed to the parent vessel wall, but thrombosis can be devastating if not. For this reason, stent-assisted coiling may be preferable to flow diversion for ventrally projecting VBJ aneurysms [32]. Longer follow-up is necessary to understand the lifetime cumulative risk of perforator strokes in this situation. Second, these aneurysms frequently present with symptoms of pontine mass effect. Coiling procedures for large or giant aneurysms add significant mass effect, decreased compliance to the aneurysm dome, and are associated with high rates of recurrence. The up-front risks of open procedures may be well-justified to reduce brainstem compression. More limited approaches, such as the “macrovascular decompression” may achieve the desired goal of decompression in patients harboring unclippable aneurysms [33].

Dolichoectatic basilar aneurysms warrant particular consideration, and, despite widespread advances in open and endovascular techniques, remain the single most daunting cerebrovascular lesion [34]. Their size, fusiform morphology, brainstem compression, and presence of calcification and intraluminal thrombosis present significant challenges to any therapeutic technique. However, the dismal outcomes associated with both natural history and surgical interventions to date demand innovation for this disease. Evolution of the senior author's practice has resulted in preference for a strategy combining revascularization of the basilar apex (preferentially with 3rd or 4th generation intracranial-intracranial bypass techniques), thrombectomy and brainstem decompression, and proximal occlusion below the AICA origins (Fig. 9.4). The recent addition of rapid ventricular pacing to our practice enables controlled hypotension to aid aneurysm dissection.

9.4.2.2 Arteriovenous Malformations (AVMs)

Pontine AVMs are also divided into two groups, anterior and lateral. Malformations arising on the dorsal pons have not been encountered. Both groups are preferentially approached through the use of an extended retrosigmoid craniotomy, in which a limited mastoidectomy skeletonizes the sigmoid sinus and enables its anterior mobilization. This serves to widen the corridor by several millimeters and enables a more anterior trajectory onto the pons. In patients with supple necks, supine positioning with an ipsilateral shoulder bump is preferred in order to reduce obstruction of the shoulder on the surgeon's hand. For patients with constrained neck mobility, lateral or park bench positioning is used.

Anterior pontine AVMs are centered in the quadrangular space bordered by the basilar impression medially, trigeminal nerve root entry zone laterally, and the pontomesencephalic and pontomedullary fissures cranially and caudally, respectively. They are unilateral in location, and blood supply is from both the s1 SCA and a1 AICA segments. Additional feeders may arise from the BA or from the meningohypophyseal trunk branches tracing back along CN V. Drainage may be directed superiorly to BVR via the MAPonMesV, or laterally into the superior petrosal vein (SPetrV) and superior petrosal sinus (SPS). Arterial disconnection of the AICA feeders is performed in the infratrigeminal triangle, while the SCA feeders are visualized in the supratrigeminal triangle. Coverage of the lateral border by the trigeminal root limits its dissection. Limited exposure and dense eloquence of the ventral pons has resulted in overall poorer outcomes compared to laterally situated AVMs and favors a more conservative approach for these lesions [4].

Lateral pontine AVMs, by contrast, have much more favorable operative and clinical outcomes and represent 25% of all encountered brainstem AVMs. These lesions are centered on the transitional zone between the lateral pons and the MCP and are bounded medially by the CN V root entry zone. They can lie on the pial surface or intraparenchymally, though the brachium pontis is particularly tolerant of

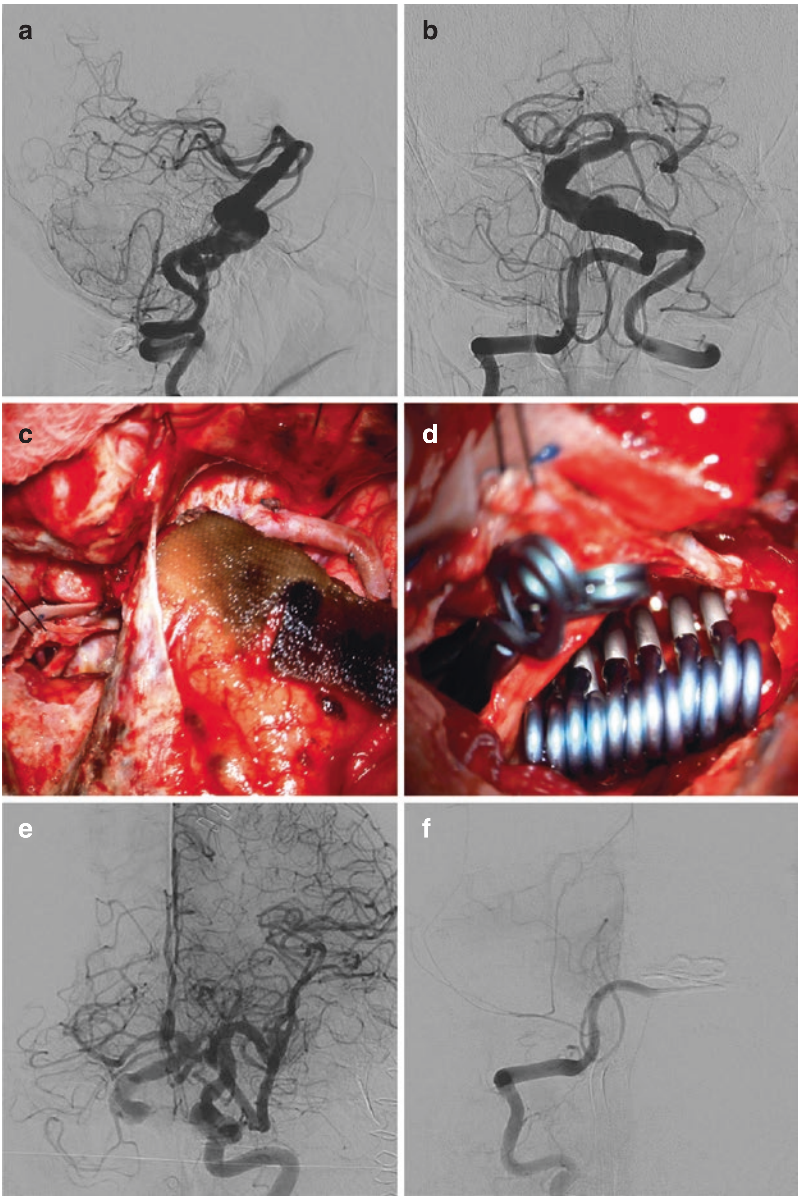

Fig. 9.4 A patient with symptoms of pontine compression was found to have a giant partially thrombosed dolichoectatic basilar trunk aneurysm on angiography (lateral and AP views; **a** and **b**). Given the wide diameter and basilar perforators/AICAs arising from the dolichoectatic segment, flow diversion or clip trapping were not feasible options. A combined skull base approach was utilized to enable high-flow revascularization of the basilar apex and trunk as well as aneurysmorrhaphy/thrombectomy and proximal occlusion. A full orbitozygomatic craniotomy allowed for M2-P2 intracranial-intracranial bypass with a radial artery interposition graft (**c**). A transcochlear craniotomy with facial nerve transposition was used for proximal occlusion at the VBJ. Multiple stacked clips closed the arteriotomy after thrombectomy (**d**). Postoperative angiography demonstrates patency of the bypass with spontaneous thrombosis of the aneurysm below the AICAs (**e**) and complete occlusion of inflow through the VAs proximally (**f**). Used with permission from Barrow Neurological Institute

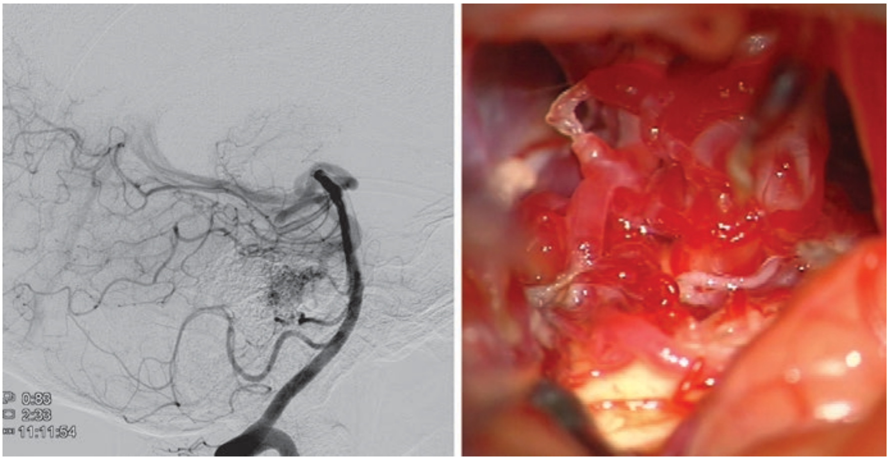

Fig. 9.5 An unruptured petrosal AVM was discovered incidentally and found to be fed by duplicated AICAs on cerebral angiography (left). A retrosigmoid craniotomy exposed the AVM, which was dissected by establishing the pial plane laterally at the pontine/MCP interface and then rolling the AVM away from the pontine surface (right), enabling gross total resection. Used with permission from Barrow Neurological Institute

parenchymal dissection. Unlike anterior pontine AVMs, laterally located lesions receive blood supply exclusively from the AICA, which is identified in the infratrigeminal triangle. Likewise, drainage into the SPetrV does not obstruct the operative field as with anterior AVMs. Furthermore, these AVMs are bounded by non-eloquent cerebellum, which frees dissection along these surfaces and improves control over the eloquent surfaces along the pons and MCP. All of these AVMs accommodate parenchymal dissection, and *in situ* occlusion is unnecessary (Fig. 9.5).

9.4.2.3 Cavernous Malformations (CMs)

CMs of the pons are found ventrally within the basis pontis from the pontomesencephalic fissure to the pontomedullary fissure. The majority of this region is formed by the MCPs, transverse pontine fibers, central pontine nuclei, and CST. Dorsally located lesions within the pontine tegmentum are defined in relation to the central tegmental tract, medial longitudinal fasciculus, medial lemniscus, and the nuclei and associated tracts of CN V-VIII. The superior part of the floor of the fourth ventricle overlies these structures, and the pontine part of the fourth ventricle is found from the opening of the cerebral aqueduct to the facial colliculus (with transitional and medullary zones found caudally).

The majority of ventral pontine CMs are approached through an extended retrosigmoid craniotomy. Lesions that reach the pial surface of the pons are easily identified and can be entered, decompressed, and circumferentially dissected. For deeper ventral lesions, however, entry through normal brainstem structures is necessary to reach the CM. The MCP is remarkably tolerant to transgression and permits safe entry into the basilar pons as it continues into the transverse pontine fibers. Careful preoperative evaluation of imaging is essential for precise localization, particularly as extensive hemosiderin staining may obscure the true location of the CM on T2-weighted images. Dissection of the petrosal fissure extends the entry point into the MCP laterally, enabling a shallower approach into the peduncle and minimizing morbidity associated with cerebellar retraction or transgression of the CST. Peritrigeminal and supratrigeminal safe entry zones have been described and function as medial extensions of the trans-MCP approach [29]. Anterior petrosectomy or SCIT approaches can be used to treat cranially located transitional lesions, while a far-lateral trans-pontomedullary sulcus approach can access caudal pontine transitional CMs.

Dorsal pontine CMs are reached by means of a midline suboccipital craniotomy. While transvermian approaches have been described classically, we prefer transventricular approaches without transgression of the vermis whenever feasible. Opening the telovelar membrane allows access to the lateral recess of the fourth ventricle, and doing so bilaterally enables elevation of the vermis and wide exposure to the rhomboid fossa. Entry into the floor of the fourth ventricle for lesions that do not reach the ependymal surface has been described, via superior fovea, suprafacial-collicular, and median sulcus entry zones. However, we would recommend caution in patients whose CMs do not approach the ependymal surface, as the floor of the fourth ventricle tends to be exquisitely sensitive to manipulation. Overall, outcomes from CM resection in the pons have been favorable, with 80–90% of patients achieving stable-to-improved neurological status postoperatively [35].

9.4.3 Medulla

9.4.3.1 Aneurysms

Both PICA and V4 VA aneurysms arise in close proximity to the medulla. Patients presenting with ruptured aneurysms in these locations have significantly worse clinical outcomes than those in the anterior circulation or more distally in the posterior circulation. Their close association with the medulla and lower CNs has prompted growth in endovascular approaches, particularly for ruptured aneurysms. However, the complex morphology of these aneurysms can make definitive endovascular treatment challenging. This is particularly true for PICA aneurysms, in which the PICA frequently arises from the aneurysm dome, or the aneurysm arises more distally on the PICA. These anatomic variants favor the use of bypass techniques to enable definitive treatment and preservation of VA and PICA blood flow. A wide variety of bypass configurations have been applied to PICA aneurysms, including PICA-PICA side-to-side, PICA-VA reimplantation, excision-reanastomosis, and occipital artery-PICA external carotid-internal carotid (OA-PICA EC-IC) bypasses [22]. These revascularization techniques frequently simplify the clipping strategies or make an otherwise unclippable aneurysm curable [36] (Fig. 9.6). Endovascular treatment of PICA aneurysms is associated with relatively high rates of recurrence

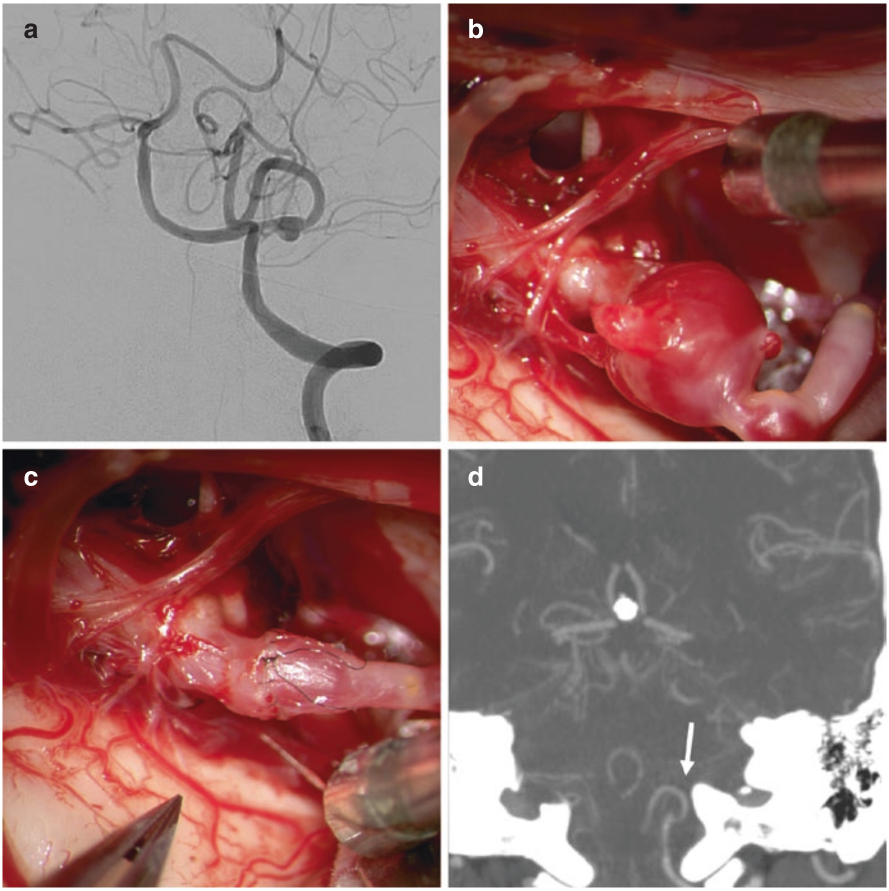

Fig. 9.6 A patient presenting with subarachnoid hemorrhage was found to have a fusiform aneurysm at the junction of the p1 and p2 segments of the left PICA (**a**). A far-lateral craniotomy exposed the aneurysm (**b**). An undiseased segment of PICA was identified proximal to the aneurysm without associated perforators, enabling aneurysm excision and end-to-end reanastomosis (**c**). Postoperative CTA demonstrated patency of the bypass and confirmed complete excision of the aneurysm (**d**, arrow). Used with permission from Barrow Neurological Institute

or PICA occlusion, and the value of partial treatment has not been definitively established (particularly for ruptured aneurysms).

On the other end of the spectrum, V4 aneurysms tend to be fusiform in nature, frequently as a result of intracranial dissection. When ruptured, these aneurysms frequently have friable domes that poorly accommodate primary clip occlusion and may necessitate parent vessel sacrifice, clip-wrap, or bypass techniques. While experience is limited compared to the many years of open approaches, there is certainly promise to the use of flow diversion for these aneurysms [37]. Deployment is generally straightforward in this segment of the VA. The major limitation tends to be enlargement of the VA at the V3/V4 junction beyond the maximal nominal diameter of the stent, resulting in poor wall apposition, foreshortening, and device migration. Experience with ruptured dissecting VA aneurysms is still relatively limited, and justifiable concerns exist about the risk of re-rupture after placement of a device that does not immediately occlude an aneurysm and demands dual antiplatelet therapy. Likewise, concerns about occlusion of a jailed PICA or VA perforators are valid, although published reports suggest that PICA occlusions tend to be asymptomatic in this situation [38]. Long-term follow-up is necessary to clearly define the ideal approach to these aneurysms.

9.4.3.2 Arteriovenous Malformations (AVMs)

As with the pons, AVMs of the medulla are divided into anterior and lateral groups (again, we have not encountered posterior medullary AVMs). Anterior medullary AVMs sit medial to the anterolateral medullary sulci and below the pontomedullary fissure, taking blood supply from perforating arteries arising at the VBJ and distal V4 VAs. There is no open approach that provides sufficient exposure to this surface of the medulla, and endoscopic transclival approaches do not afford sufficient bimanual dexterity or precise vascular control to make this a viable approach. In the senior author's operative series, only one patient was considered a viable operative candidate, presenting with a medullary hemorrhage that had dissected dorsally permitting a suboccipital posterior approach, but without such severe deficits that would negate the value of resection.

Conversely, lateral medullary AVMs permit a more aggressive surgical posture. They are located lateral to the anterolateral sulcus and rootlets of CN XII and are approached through a far-lateral craniotomy. Arterial inputs are from the V4 VA and from the p1 and p2 segments of the PICA. Venous drainage through the lateral medullary vein may be visualized early on, whereas the medial medullary vein may not be visible until significant dissection of the AVM has been performed. These AVMs tend to be small and respect the pia, allowing for complete resection in two-thirds of cases, while *in situ* disconnection was performed in the remaining cases. Good outcomes were achieved in 75% of patients in the senior author's experience [4] (Fig. 9.7).

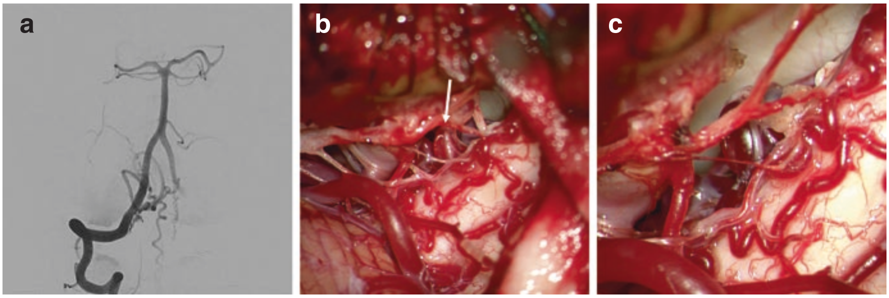

Fig. 9.7 A patient presenting with symptoms of cervical myelopathy was found to have a lateral medullary AVM. Digital subtraction angiography suggested that the malformation was fed predominantly from a single feeding artery (**a**), which was confirmed intraoperatively (**b**, arrow). *In situ* disconnection without pial resection (**c**) resulted in angiographic cure postoperatively. Used with permission from Barrow Neurological Institute

9.4.3.3 Cavernous Malformations (CMs)

CMs of the medulla are approached through either a far-lateral craniotomy for anterolaterally located lesions, or a midline suboccipital craniotomy for dorsally located CMs. Safe entry zones for deep-seated CMs are relatively limited in the medulla compared to the midbrain and pons. The trans-anterolateral sulcus approach has been described for ventrally located CMs, and identification of the CSTs with DTI is particularly useful for surgical planning for these lesions. For transitional lesions at the cervicomedullary junction, division of the median sulcus between the gracile fasciculi is also feasible, as well as through the posterior intermediate and posterolateral sulci [29]. Otherwise, we would recommend caution when considering intervention on smaller CMs that do not approach the pial surface. This is particularly true in the medullary fourth ventricular surface, where lower CN nuclei are intolerant to manipulation, which can result in significant morbidity. While resection of lesions in the medulla can be associated with high rates of tracheostomy, feeding tube placement, and/or ventilator dependence, surgical resection drastically reduces the risk of recurrent brainstem hemorrhage compared to the natural history of these lesions [39].

9.5 Conclusion

Vascular lesions of the brainstem are among the most technically demanding surgical pathologies in neurosurgery. Clinical decision-making in patients presenting with these lesions is predicated based on a thorough understanding of the natural history of various vascular lesions (particularly when located in the posterior fossa/brainstem). Successful treatment requires detailed knowledge of the anatomy, including vascular, surface and parenchymal structures. Furthermore, facility with an array of skull base approaches necessary to safely access the various regions and surfaces of the brainstem is essential. Likewise, surgeons should have a clear understanding of endovascular and radiosurgical techniques, used as alternative or combined treatment approaches, as well as a clear understanding of the surgical goals for a particular patient. Surgical intervention is associated with significant perioperative and long-term risks, but treatment results in drastic reduction of hemorrhage compared to the natural history of the disease in many patients. With dedication to developing surgical skills and decision-making, vascular lesions of the brainstem can be treated safely.

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