Challenging Dogma in Arteriovenous Malformation Surgery: Personal Reflections and Lessons Learned from 350 Cases

Aaron Cohen-Gadol¹,²

Complex arteriovenous malformations (AVMs) (Model 1) are the ultimate form of neurosurgical engagement. Their resection offers worthy challenges, and their safe removal defines our valuable technical victories. It is the only form of surgery that exposes the most beautiful scene of a special oddity of nature. However, this beauty is often deceiving, as engagement with it can result in an intracranial disaster almost anytime during the operation.

The following is a candid discussion of AVM resection techniques I have learned through my experience with more than 350 cases. Numerous case series have established the outcomes of surgery; however, an honest personal reflection and confession of moments of agony and elation can be helpful to novice surgeons. In this Perspective, I review the timing of microsurgical intervention, elaborate steps in circumferential disconnection, and share my own thoughts on the topic. These reflections are personal perspectives and should therefore be interpreted as such. Neither institutional review board/ethics committee approval nor patient consent was sought or required for the data presented here.

INDICATIONS AND TIMING OF OPERATIVE INTERVENTION

The candidacy of the patient for surgical intervention on an elective basis for a nonhemorrhagic AVM is based on the patient’s age (cumulative risk of hemorrhage) invasion/proximity of the AVM relative to the eloquent cortices, and diffuseness of the nidus. The presence and the size of deep draining veins are not major constraints for resective surgery. Standardized grading of AVMs can be restrictive for complete appreciation of the risks and benefits of surgery.

Certain studies have promoted the previously held dogma that surgery for hemorrhagic AVMs should be delayed,¹⁻⁴ whereas others have advocated acute intervention.¹ This philosophy has been applied to AVMs that do not require emergent evacuation of a hematoma. I believe that surgery should be conducted during the acute phase of hemorrhage for patients who present with a ruptured AVM and are in a relatively reasonable neurologic condition, even though they might experience focal deficits as a result of the hemorrhage (Figure 1). Early removal of the compressive hematoma confers the following benefits:

1. The surgery facilitates recovery from neurologic consequences of the compressive hemorrhage.
2. The patient can recover from adverse effects of the hemorrhage and the AVM resection simultaneously.
3. An acute hemorrhage provides reasonable dissection planes, but chronic gliosis from a previous hemorrhage can make the procedure more challenging.

However, acute symptomatic cerebral edema that results from AVM rupture or acute hemodynamic alterations within the malformation necessitates a delay in surgical care. Edematous brain is friable and vulnerable to injurious operative maneuvers.

THREE-DIMENSIONAL UNDERSTANDING OF THE AVM AND DEFINITION OF THE TRUE NIDUS

Along with angiographic findings, the surface landmarks, large draining veins, and embolic material are used intraoperatively as guides to localize feeding arteries and correlate the dissection roadmap. Computed tomography angiography is used for navigation during surgery. The immediate cortical borders of the AVM define the initial boundaries of nidal dissection and disconnection (Figure 2). Pial artery-to-artery connections that are not part of the subcortical nidus are spared.

A fear of intraoperative bleeding and violating the nidus has led some surgeons to dissect far from the nidus and, in some cases, to even consider lobar resection. This strategy can compromise unaffected brain tissue and is not possible during resection of a deep-seated AVM. The true extent of the nidus can be appreciated precisely only during microsurgical dissection and by strategic circumferential nidal disconnection.
Artery-to-artery connections within the perimeter of the nidus can lead the surgeon to overestimate the true size of the pathologic nidus. In addition, some of the small and deep sections of the white matter feeders of the AVM can thrombose spontaneously after resection of the majority of the AVM and disconnection of the draining veins. Using good judgment and drawing from past experience to avoid a residual nidus are critical when employing this surgical strategy, or postoperative hemorrhage might occur. Any evidence of difficulty with achieving hemostasis after resection should lead the surgeon to suspect the presence of residual nidus, which has to be identified and resected.

The principle of subtotal epipial AVM resection has been applied to spinal cord and brainstem AVMs. In contrast, an AVM nidus that remains after resection prevents adequate hemostasis and can lead to delayed postoperative hematoma formation. Small deep white matter feeders should not be confused with an AVM nidus, and the practice of “tight-AVM” circumferential disconnection can spare a significant amount of normal brain tissue (Video 1). The surgeon can stay right on the surface of the nidus and adjust the dissection planes as he or she gets too close to the nidus. This practice has facilitated the resection of deep-seated AVMs with minimal transgression of brain tissue.
Figure 2. A large right-sided temporoparietal convexity arteriovenous malformation (AVM) is shown. The embolic materials mark the superior and anterior borders of the AVM (lateral internal carotid artery arteriogram) (upper left image). A primary vein is traveling superoposteriorly. Magnetic resonance image shows the vicinity of the lesion to the functional cortices and ventricular chambers and the deep white matter feeders to the trigone (upper right image). Computed tomography angiogram sequences provide information regarding the vascular anatomy (including the deep draining vein) in relation to the parenchyma and skull landmarks for intraoperative planning (center left and center right images). The true nidus of the AVM proved to be smaller than indicated on the catheter angiogram (bottom image). The primary draining vein can wrap around the deeper parenchymal sections of the AVM and should be carefully protected during AVM disconnection. (Used with permission from The Neurosurgical Atlas by Aaron Cohen-Gadol, M.D.)
This strategy requires efficient skills in reaching hemostasis by using appropriate nonstick bipolar forceps and the mouthswitch of the microscope. Use of the mouthswitch is critical for enabling the operator to dynamically maintain the exact point of bleeding in focus (often shifting quickly at the depth of the AVM operative field) and freeing both hands to ergonomically handle the bleeding. An agile response to bleeding and tolerance for some "controllable" bleeding are some of the most paramount skills for a neurosurgeon to master AVM surgery. The operator’s sitting position during microsurgery and use of the chair’s armrest can significantly minimize fatigue and help maintain steady hands.

**AVM DISSECTION**

As mentioned before, the dissection should start as close to the nidus as possible where the white matter strands can be peeled off the nidus. As circumferential dissection continues, when bleeding from the perinidal area is encountered, the operator should then remove a small amount of additional peri-AVM brain tissue at the bleeding site to step away from and protect the nidus and coagulate those deep white matter feeders that have coagulable walls (see Managing Deep White Matter Feeding Arteries below). *With this method, the AVM nidus might be significantly smaller than indicated with angiography (Video 2).*

The primary draining veins are naturally protected, but the surgeon has to remain flexible and sacrifice secondary veins when some of the nidus is disconnected. This technique untethers and enables tilting of the nidus and avoids operative blind spots. These blind spots can make the operator pay a high price if torrential bleeding occurs within a narrow surgical corridor and if the tethered nidus compromises visualization of the bleeding point, especially in the case of a parasagittal AVM with multiple draining veins. Fluorescence angiography can assist with relative flow measurements within secondary veins.

Resection of an AVM around and within the eloquent cortices offers another layer of complexity and an opportunity for the operator to use his or her unique set of technical skills. Any cerebral sparing technique is a welcome addition. In such cases, I stay on the AVM “capsule” circumferentially while tolerating some bleeding from the nidus. The nidus can be entered in certain locations; however, the bleeding point can be sealed by using small pledgets of thrombin-soaked cotton or occasionally with bipolar coagulation (see below). The trade-off between increased blood loss and preservation of maximal cerebral tissue has to be considered carefully (Video 1 and Figure 3). The importance of protecting the en passage arteries cannot be overemphasized.

**MANAGING DEEP WHITE MATTER FEEDING ARTERIES**

The most daunting task in AVM surgery is handling the unexpected rupture of a white matter feeder. Mishandling such feeders and their simple tamponade can lead to deep hematoma formation, brain swelling, and other undesirable consequences.

Radiosurgery transforms delicate-walled white matter feeders to readily coagulable vessels. The gliotic white matter changes that are induced by radiation with imaging provide a clue regarding thickening of the wall of the fine white matter vessels.

Certain AVMs possess nodules of nidi on their subcortical boundaries that primarily contain a tangle of white matter feeding vessels or white matter networks (Model 1). These small networks or nodules are difficult to manage, and their efficient removal is required so that normal-caliber vessels can be found and coagulated. Recognizing these nodules preoperatively is unlikely. During surgery, the operator can find himself or herself in the midst of numerous white matter feeders simultaneously bleeding briskly.

**BLEEDING FROM THE NIDUS**

Coagulation of the nidus before its complete disconnection should be avoided. If a bleeding defect in the nidus wall is apparent as the operator inadvertently wanders too close to the nidus lobules that project into the brain, he or she can place a very small piece of thrombin-soaked cotton to plug the defect. Patiently providing gentle tamponade will seal the defect. Aggressive coagulation of the leakage site on the nidus may acutely alter its internal hemodynamics and intraluminal flow pattern and can lead to rupture and brain swelling.

The primary vein might wrap around the deeper sections of the nidus before the vein reaches the cortical surface. One must avoid the temptation to coagulate the vein during the parenchymal steps of dissection to create more space. Any bleeding from the deeper portions of the vein should be covered with a piece of cotton and controlled with gentle tamponade. If the primary vein is inadvertently injured and its partial coagulation leads to progressive AVM swelling, immediate resection of the AVM (a “commando operation”) is necessary.

**EFFICIENT EXCISION OF THE AVM**

I analogize the final steps in AVM removal to landing a plane under turbulent weather conditions. One cannot fear the turbulence associated with altitude change and avoid landing. The final steps of dissecting a large AVM often involve some bleeding from the resection bed and the nidus. The surgeon must remain in control and remember that timely removal of the AVM is the best method of hemostasis. A phenomenon known as having “too dry of an operative field” during the final stages of resection can occur. Efficient AVM resection might demand short episodes of controllable and relatively low-volume bleeding.

AVMs that are near the ependyma incorporate ependymal and plexal feeding vessels, despite nonremarkable angiographic findings near the periventricular region. Therefore, to avoid the recurrence of an AVM with periventricular components, especially in pediatric patients, I extend circumdisssection to the level of the ventricle and disconnect the ependymal/plexal feeding vessels.

I have been surprised in a number of cases when I attempted to disconnect what I thought was a vein at the depth of the resection cavity when I had actually truncated a deep section of the AVM nidus. Careful inspection of the ventricular wall can prevent these errors and the delayed/future risk of hemorrhage or AVM recurrence.

Choroidal arteries are controlled more easily with bipolar electrocautery. If a choroidal feeding artery at the periventricular zone retracts on coagulation, it typically avulses and gets away, causing unrecognizable bleeding into the ventricle and risking...
Figure 3. Sagittal magnetic resonance image showing an arteriovenous malformation located in the angular gyrus and immediate vicinity of the language cortex (red arrow) (upper left image). The span of the arteriovenous malformation toward the ventricle is shown on axial magnetic resonance image (upper right image). Angiograms (anteroposterior and lateral views) illustrate the true size of the lesion and the feeding vessels from the middle cerebral artery (center row images). Numerous en passage middle cerebral artery branches have to be protected. Resection was undertaken via minimal cerebral tissue transgression (lateral angiogram and axial magnetic resonance image) (bottom images). The patient had only subtle language difficulties 6 weeks after surgery, which had resolved at the 3-month follow-up visit. (Used with permission from The Neurosurgical Atlas by Aaron Cohen-Gadol, M.D.)
brain herniation. Therefore, unexpected brain herniation at this step of the operation should alert the surgeon to examine the ventricle, evacuate the blood, and deal meticulously with the bleeding ependymal feeding vessels, often within the operative blind spot at the apex of the AVM.

I have also been surprised by the presence of functionally significant feeding arteries that reside next to a primary draining vein. In compulsively protecting the vein, a surgeon can leave these feeding vessels unnoticed and prevent the vein from turning blue. Therefore, if the entire AVM is disconnected except for the primary draining vein, but the vein is still arterialized, a hidden feeding artery in close proximity of the vein should be sought and severed.

Intraoperative angiography is quite helpful for ensuring complete obliteration of arteriovenous shunting in most medium-to-large AVMs. Subtle “luxury perfusion” associated with minor arteriovenous shunting away from the nidus, especially in pediatric patients, does not warrant an aggressive pursuit; rather, long-term monitoring is recommended.

After the AVM is extracted, coagulation of the friable white matter “ooze” should be minimized because this maneuver will lead to more bleeding. Multiple rounds of irrigation and patience are needed to achieve meticulous hemostasis. Irrigating with pure thrombin solution can also be effective for slow ooze from the friable white matter resection walls.

**FINAL THOUGHTS**

Packing the bleeding points from the white matter feeders of the AVM during the parenchymal phase of dissection almost never works and leads to increased brain tension because of occult or remote foci of intracerebral hemorrhage. Addressing the bleeding source immediately and managing it patiently is wise. It is not advisable to leave one bleeding site and cause bleeding at another site by diverting attention elsewhere.

AVMs in pediatric patients differ from those in adults. Such AVMs are frequently immature and partly diffuse, and their definite borders are not easily identifiable even on a preoperative angiogram. These diffuse lesions are at substantial risk of recurrence, even after their angiographically proven gross total resection. Post-resection intraoperative angiography can confirm gross total resection of a pediatric AVM, but postoperative angiography can reveal a small newly identified early draining vein, sometimes slightly away from the resection cavity. An aggressive approach to such “minor” arteriovenous shunts might not be warranted, even though their natural history is not clearly defined.
I rarely perform embolization of AVMs. Selective embolization of some of the arterial pedicles is advised if they are not easily accessible early in the surgery (e.g., P2 feeders in the case of a large tentorial AVM in which the tentorial draining vein obstructs early access to these feeders). The accessible pedicles should be left alone to avoid the AVM’s proliferation of white matter feeders (Figure 4). It is important that the planning for embolization be conducted through direct communication between the neurosurgeon and the endovascular interventionalist. Naturally, the option of embolization immediately (within 7–10 days before resection) is reasonable to avoid proliferation of white matter feeders and is advised for less experienced surgeons.

The surgeon has to have a high tolerance for controlled intraoperative bleeding and be able to gauge the fine line between a controllable bleed and an uncontrollable torrent. This understanding can lead to the efficient resection of large AVMs without need for staged operations. As mentioned previously, removal of the AVM is the most effective method of hemostasis.

A superior AVM surgeon 1) is able to instantaneously translate three-dimensional anatomy to intraoperative findings; 2) applies appropriate surgical judgment refined by humility and “surgical intuition”; 3) has manual dexterity; 4) maintains endurance; 5) is mentally tough; 6) shows calm composure while dealing with disasters; and, ultimately, 7) has extensive experience.

There is no place to prepare for the battle when you are already fighting it. The AVM surgeon must intimately understand the roadmaps of an AVM and its difficult territories before starting the operation. AVM resection should be executed without hesitation but gracefully. Despite encountering torrential bleeding, the operator is in control and has undoubtedly convinced the team that no matter how difficult the moment, the operator can prove his or her commanding omnipresence.

AVM surgery tests not only the operator’s technical prowess but also his or her perseverance and efficiency. This fact distinguishes AVM surgery from all other surgeries in our profession.

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REFERENCES

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