Principles and strategies for step-by-step AVM excision

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Arteriovenous malformations (AVMs) are some of the most challenging surgical entities. Like any challenging surgical procedure, AVM surgery is a series of basic but fundamental steps, each with its own nuances. Despite a myriad of published material regarding AVMs, there are few succinct illustrated summaries of these steps with an accompanying elucidation of the most common pitfalls. This paper provides a step-by-step description and illustration of the basic surgical principles of AVM microsurgical resection, focusing on the main key points and addressing the critical issues that surround this surgery. Deep anatomical knowledge and presurgical planning of these basic steps, combined with good contingency management skills, are paramount for an effective and safe AVM surgery.

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ARTERIOVENOUS malformation (AVM) surgery is very challenging. Among neurosurgical procedures, it is probably the one that best summarizes all the characteristics that are an integral part of our specialty: psychological preparedness, planning strategy, and execution. Charlie Drake has been quoted as saying that "AVMs are nothing but hard work." Especially when we deal with complex AVMs, it is important to be psychologically ready for a fight. At the same time, AVM surgery requires prompt mental flexibility, as conditions can rapidly change during the procedure. Despite having a strategy in mind, execution is the crucial part, and AVM surgery is more unforgiving than any other surgical procedure.

With increased utilization of stereotactic radiosurgery and embolization as curative procedures, fewer AVMs are treated using surgery, to the detriment of surgical experience development for the management of these lesions. Although several studies describing AVM surgical principles are available, a practical and comprehensive, while at the same time succinct, step-by-step description of the basic principles of AVM surgery is lacking. In this report, we describe and illustrate the basic step-by-step microsurgical phases of AVM resection, focusing on practical pitfalls and lessons learned by the senior author (G.L.) over 30 years of training and clinical practice.

Exposure

The surgical principles of AVM resection are shown and summarized in the accompanying Video 1.

VIDEO 1. Clip showing step-by-step description of the basic principles of AVM surgery. Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved. Click here to view.

The skin incision and craniotomy must be adapted to the AVM size to ensure a complete exposure of the lesion. Despite today's emphasis on smaller incisions and craniotomies, complex AVMs—which often have a large, superficial cortical component—benefit from a large craniotomy. A large exposure allows for better understanding of the superficial vascular anatomy of the AVM and for inspection of primary and secondary draining veins. At the end of the resection, a wide exposure allows identification of possible residual shunting into secondary draining veins, which appears as early filling of the superficial vein or veins on indocyanine green (ICG) videoangiography.[1]

Clear visualization of the AVM boundaries in the subarachnoid space is of paramount importance. For this reason, the dura mater must be opened carefully under the microscope, releasing arachnoidal trabeculae that tether the dura to superficial AVM vessels. Adhesions between superficial AVM vessels (particularly large draining veins) and the dura are often present, especially if the patient has suffered prior hemorrhage. Some AVMs receive supply from dural vessels that must be addressed very carefully to avoid early subarachnoid bleeding. Such bleeding makes defining the plane between the brain and the AVM more difficult. If the large superficial draining vein contacts the dura, minuscule dural feeders forming micro-arteriovenous shunts are not uncommonly encountered while separating the dura from these superficial veins.

In the case of superficial AVMs, ICG videoangiography

is a useful tool to confirm proper identification of feeding arteries, the nidus, and draining veins by recognizing the different temporal phases of filling.

Dissection

AVMs extend into brain sulci and white matter. After initial analysis of the AVM vascular architecture, wide opening of cerebral sulci with sharp or blunt arachnoidal dissection under high magnification helps to unfold the spaces hiding the nidus and better expose deeper AVM portions lying underneath the cortical mantle (Fig. 1). The draining vein runs into the subarachnoid space, and retrograde dissection around the draining vein opens this space and assists in exposure and identification of the nidus. This phase of the dissection, which often proceeds parallel to the main draining vein, is facilitated by arachnoid thickening around the arterialized veins and by the increased tolerance to mechanical manipulation of the thickened wall of the arterialized draining veins.

This first part of the dissection is also very helpful from a psychological point of view. The beauty and cleanness of the arachnoid dissection under the microscope leads the operating surgeon into the flow of the operation. This portion has been eloquently defined as "the calm before the storm" by Lawton.[2] In this early stage of the microsurgical resection, it is common for the surgeon to feel that everything is proceeding smoothly. However, one should not lower one's guard, as this feeling can quickly be erased by difficult-to-control bleeding if careful microsurgical technique at the boundaries of the nidus is not respected. When confronted with bleeding from the nidus or deep feeders, it is important to stay focused, avoid pushing bleeding points into the parenchyma, and remember that, in most cases, bleeding can be controlled.

Main Feeders

Once larger feeders are identified, they can be followed toward the nidus and branches to the AVMs, coagulated, and divided sequentially. If necessary, temporary clips can be placed on some of the main feeders to induce deflation and softening of the nidus and draining veins. The circumferential sulcal dissection is progressively deepened, detaching the nidus from cerebral parenchyma and progressively exposing deeper feeders. One of the most critical phases of AVM surgery occurs when portions of the nidus extend below the cortical mantle and into the white matter. In such a case, the surgeon's skill lies in finding the correct balance between working along the boundary of the nidus and respecting the integrity of the surrounding brain (especially in eloquent areas) as much as possible (Fig. 1).

Isolation of an adequate length of a feeding artery is pivotal in planning its coagulation. For this reason, feeders are progressively dissected/skeletonized from the surrounding brain parenchyma/sulcal arachnoid in a distal-to-proximal direction (toward the AVM). During skeletonization of a large feeder, it is possible to identify small collaterals directed from the major feeder to the AVM that must be coagulated. These small AVM feeders emanating from the larger en passage trunk can be differentiated by
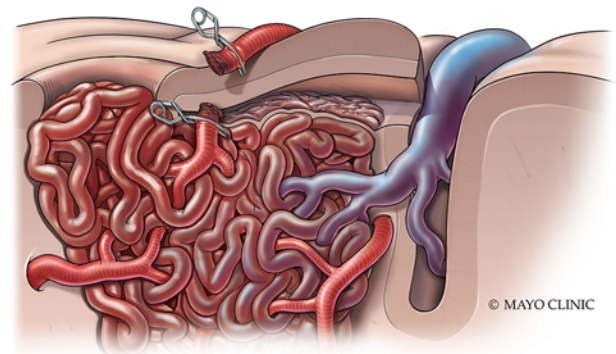

FIG. 1. Illustration of an AVM with subcortical extension. Many AVMs have a superficial cortical representation, but often the nidus extends under the cortical mantle and into surrounding white matter. In such a case, the surgeon's skill lies in finding the correct balance between working along the boundary of the nidus and respecting the integrity of the surrounding brain (especially in eloquent areas) as much as possible. Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved.
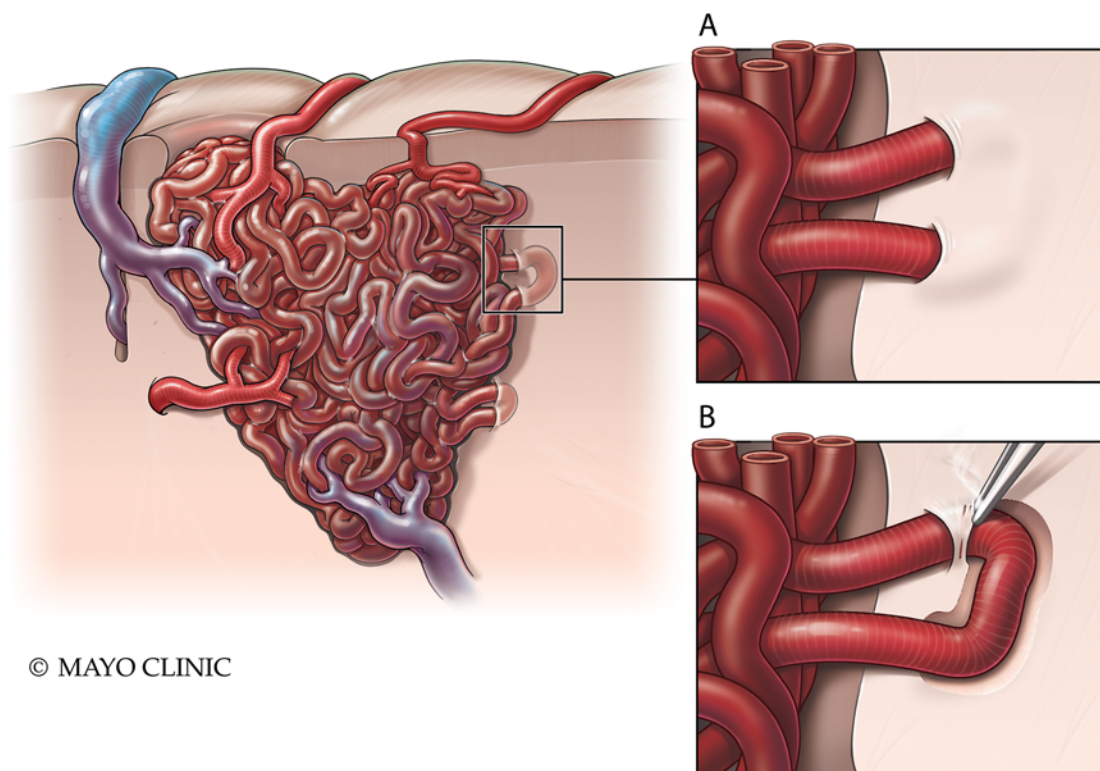
their characteristic tortuous corkscrew course, compared to normal arterial branches that are typically straight. Sequential identification and coagulation of these small feeders progressively reduces blood supply to the AVM. En passage vessels travel toward the cerebral parenchyma, passing through the AVM, and must be preserved.

Nidus Dissection

During AVM circumferential dissection, it is critical to stay outside of the nidus while avoiding direct coagulation of the nidus as much as possible. This can be problematic, as the boundaries of the AVM and the nidus itself are often not well defined, especially as the dissection proceeds toward the deeper portions of the AVM. Often, and especially in patients with previous silent bleeding, the deeper dissection of the AVM from the surrounding brain is aided by a gliotic plane surrounding the malformation. In the deeper portion of the AVM at the interface between the nidus and the white matter, bipolar cautery can be used to vaporize gliotic parenchyma immediately adjacent to the nidus, to facilitate visualization of small feeders embedded within the deep white matter. After the surrounding tissue has been removed, these vessels become apparent and can be cauterized and divided systematically. Furthermore, fragile AVM vessels commonly protrude externally from the nidus into the brain tissue, forming vascular loops (also called Hashimoto loops).[3] The apex of a nidus loop can be buried in the brain tissue, and its bilateral arms may mimic two individual vessels directed from cerebral parenchyma to the nidus. Dissecting the top loops from the surrounding tissue and preserving them is essential to avoid difficult-to-control bleeding (Fig. 2).

Deep Feeders

One of the most fearsome and difficult parts of AVM

FIG. 2. Illustration of a Hashimoto loop. It is common for fragile AVM vessels to protrude externally from the nidus into the brain tissue, forming vascular loops (also called Hashimoto loops). The apex of a nidus loop can be buried in the brain tissue, and its bilateral arms may mimic two individual vessels directed from cerebral parenchyma to the nidus (**A**). Dissecting the top loops from the surrounding tissue and preserving these vascular loops is essential to avoid difficult-to-control bleeding (**B**). Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved.

surgery is disconnection of deep, small perforating feeders that are encountered around deeper portions of the AVM. Because these small perforating feeders are deep, when one of them starts to bleed, its remaining proximal end acts like an open fire hose and may retract into brain parenchyma, causing occult intraparenchymal or ventricular hemorrhage that is not seen by the surgeon. Notably, when cauterizing these deep feeders, as well deep secondary draining venules, it is paramount to avoid inadvertent excessive traction on these vessels by pulling away the nidus to prevent avulsing the deep perforators inside brain parenchyma, with consequent intraparenchymal or ventricular hemorrhage. These feeders, with abnormal walls, typically do not respond well to regular bipolar coagulation. A few techniques can be very helpful in this situation to avoid problems. It is important to carefully and patiently skeletonize a sufficiently long segment of such deep feeders. Attempts to coagulate the feeder should then be made closer to the AVM nidus, leaving a long enough tail on the parenchyma side to prevent its retraction into deeper portions of white matter. After coagulation, sharp division using microscissors should stop before completely dividing the coagulated feeder, so that if incompletely obliterated, one has the chance to complete coagulation while the partially divided feeder is still tethered at the point of division, preventing its retraction into surrounding white matter.

These deep feeders often respond better to coagulation under flow arrest. This can be achieved by placing a vascular AVM microclip upstream of the coagulation point, on the parenchyma side of the feeder. Coagulation of deep, smaller feeders can also be better achieved using the dirty coagulation technique,[4] applying the bipolar coagulators to a thin layer of brain tissue surrounding the fragile walls of the feeders during coagulation.

Yasargil has been quoted as saying that "the secret of AVM surgery is in the ventricle." Conically shaped AVMs whose tips extend very near to the ventricle receive vascular supply from deep choroidal feeders through brain parenchyma closest to the ependyma (Fig. 3). Control and coagulation of these feeders is much easier on the ventricle side before they enter the white matter. Additionally, when the AVM is near the ependyma of the ventricle, there is almost always a deep-draining vein. These deep-draining veins must be identified, isolated, and coagulated, together with the deep feeders. This deep venous drainage in large AVMs may not be visible on the preoperative angiogram as it is overshadowed by the much higher flow in the more superficial and larger veins. This deep venous component must be suspected when the AVM comes close to the ependyma of the ventricle and can be inferred from close analysis of the T2-weighted thin slices of the axial MRI. If not suspected and/or recognized intraoperatively, this
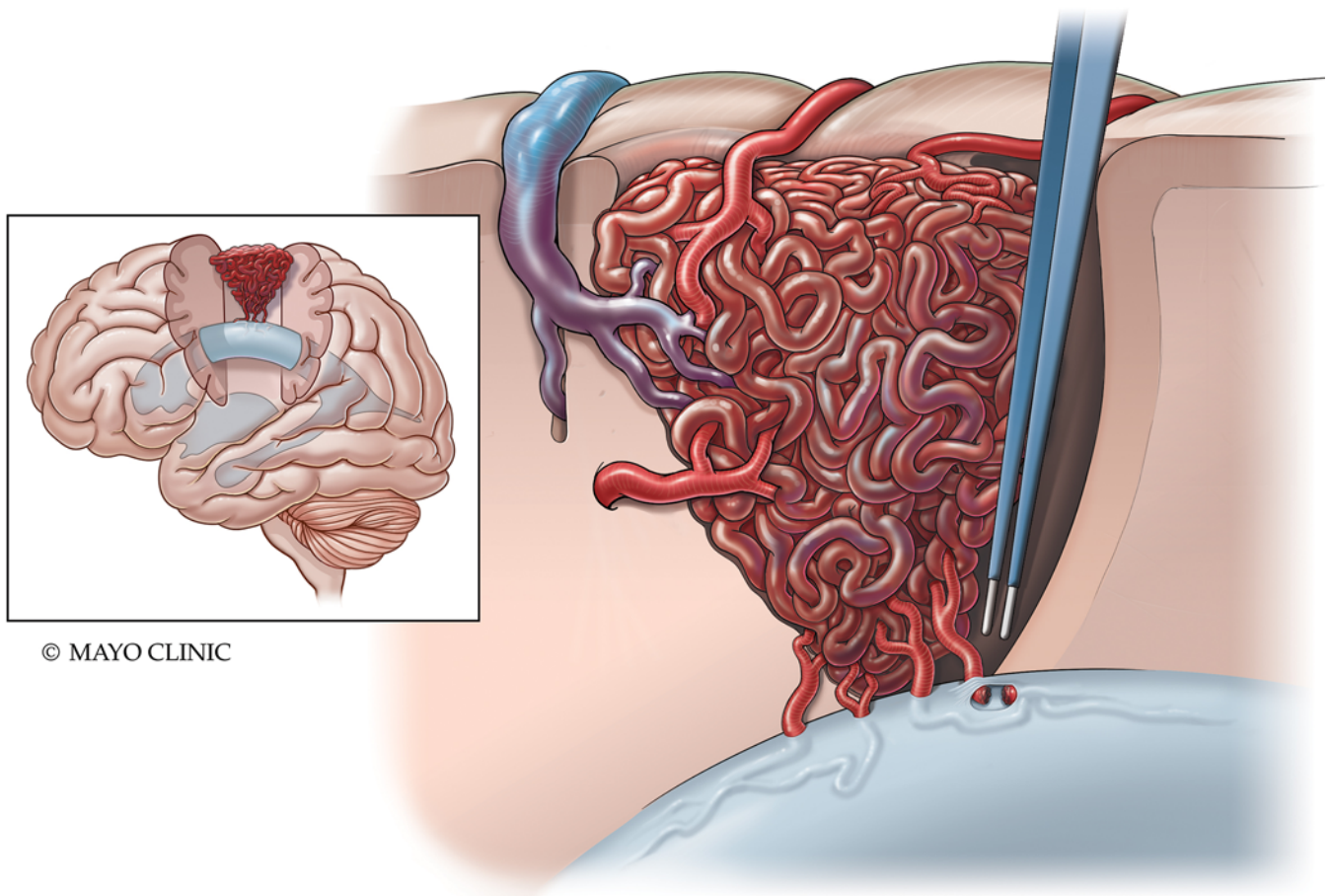
FIG. 3. Illustration of the ventricular component of the AVM. It is common for the apex of an AVM to extend to, or be adjacent to, the ependymal surface. When this occurs, there is supply from deep choroidal vessels that pierce through brain parenchyma closest to the ependyma. Control and coagulation of these feeders is much easier on the ventricle side before they enter white matter. Used with permission of Mayo Foundation for Medical Education and Research. All rights reserved.

portion is a very common site of residual arteriovenous (AV) shunting on the postoperative angiogram, as this deep portion of the nidus shunts directly into the smaller deep ependymal vein.

Addressing the deep feeders is also one of the most challenging phases of AVM resection, because they are encountered toward the end of the microsurgical dissection when the operator is fatigued, adding to the precariousness of this point of AVM resection. Traditionally, the deep feeders were thought to be best removed at the end of AVM surgery after the nidus had been disconnected from the surrounding parenchyma. In recent years, a new theory has emerged. Supporters of this theory claim that the more traditional way of circumferential disconnection and resection of the AVM from superficial to deep makes control of the deeper feeders much more difficult, because of the relative increase in the blood supply to the AV shunt from the deeper, smaller feeders after the larger and more superficial ones have been disconnected. The AVM nidus, as an abnormal direct AV shunt, is a low-pressure shunt that, in turn, creates a sump effect that actually sucks

blood as long as the AV shunt is in continuity. At the beginning of the surgery, when the large, usually more superficial feeders are still connected to the nidus, the higher pressure in these feeders provides increased resistance to lower flow coming from the much smaller deeper feeders. Supporters of such a theory suggest dissecting down toward the apex of the AVM conus in the early stages of the dissection, before disconnecting larger feeders. In this way, control of deeper feeders would be easier because of the lower amount of blood flowing through them, while the larger feeders are still providing the dominant supply to the AV shunt.

Intraoperative Pitfalls

During AVM resection, a relatively sudden swelling or change in the consistency of brain tissue bordering the nidus may underscore a contained intraparenchymal hematoma or intraventricular hemorrhage. In such cases, intraoperative ultrasound can facilitate identification of such a complication. It is the senior author's belief that some immediate postoperative hemorrhages observed after re-

section may instead represent unrecognized, occult intraoperative intracerebral or intraventricular hemorrhages occurring around the boundaries of the resection cavity during resection.

Draining Veins

As the dissection proceeds circumferentially, the main draining vein is maintained in continuity until the very end. However, secondary drainage veins can be sacrificed before full circumferential dissection is completed, to facilitate progression of the resection and better access to deeper portions of the AVM. Because the AVM is mostly disconnected, flow into the main draining vein may slow down to the point at which portions of the AVM may thrombose. This can be perceived as increased tension in the nidus, which may, in turn, become more difficult to retract and manipulate.

To prevent the risk of massive bleeding, the main draining vein is not sacrificed until all incoming feeders have been severed and the nidus has been completely disconnected from the surrounding parenchyma. The main draining vein should be skeletonized and followed to identify direct AV shunts into the main venous trunk. Arterial feeders are often present under the belly of the main draining vein. Skeletonization of the main draining vein becomes critically important in children with the so-called linear-type AVM to avoid residual AV shunting.[5] If there is any doubt that the entire AVM has been completely disconnected, it is helpful to temporarily clip the main draining vein before definitive coagulation and sectioning. Any nidus swelling, consistency changes, or bleeding after temporary clipping of the vein indicates persistence of unidentified feeders.

After excision of the main draining vein, the nidus is removed en bloc. The entire surgical cavity is systematically inspected, and accurate hemostasis is performed. In this phase, the surgeon must be wary of areas with significant charring from bipolar cauterization. These can represent areas of residual AVM, particularly in cases of diffuse AVM morphology. In cases of significant charring, it is pivotal to consider reexploring the interface of white matter just outside of the charred area. Additionally, ICG videoangiography is useful to verify the absence of residual nidus along the cavity or early filling of veins surrounding the surgical cavity, which indicate persistent AV shunting.[1] After hemostasis is obtained, asking the anesthesia team to perform a Valsalva maneuver helps verify adequate hemostasis. Tight control of systolic arterial pressure in the immediate postoperative period is recommended, as the brain surrounding the surgical cavity adapts to the hemodynamic changes induced by the removal of the AV shunt represented by the AVM.

Conclusions

AVM surgery can be unforgiving. It requires deep anatomical knowledge, presurgical planning combined with good contingency management skills, and perfect execution. Careful adherence to several basic steps and knowledge of the numerous nuances of the disease are key ingredients to success.

Acknowledgments

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Disclosures

Author Contributions

Conception and design: Lanzino, Agosti. Acquisition of data: Lanzino, Agosti. Analysis and interpretation of data: Lanzino, Agosti. Drafting the article: Lanzino, Agosti. Critically revising the article: Lanzino, Agosti. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Lanzino. Administrative/technical/material support: Lanzino, Graepel. Study supervision: Lanzino.

Supplemental Information

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