Video Article

Comprehensive Endovascular and Open Surgical Management of Cerebral Arteriovenous Malformations

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Abstract

Arteriovenious malformations (AVMs) are associated with significant morbidity and mortality, and have a rupture risk of ~3% per year. Treatment of AVMs must be tailored specifically to the lesion, with surgical resection being the gold standard for small, accessible lesions. Pre-operative embolization of AVMs can reduce nidal blood flow and remove high-risk AVM features such as intranidal or venous aneurysms, thereby simplifying a challenging neurosurgical procedure. Herein, we describe our approach for the staged endovascular embolization and open resection of AVMs, and highlight the advantages of having a comprehensively trained neurovascular surgeon leading a multi-disciplinary clinical team. This includes planning the craniotomy and resection to immediately follow the final embolization stage, thereby using a single session of anesthesia for aggressive embolization, and rapid resection. Finally, we provide a representative case of a 22-year-old female with an unruptured right frontal AVM diagnosed during a seizure workup, who was successfully treated via staged embolizations followed by open surgical resection.

Video Link

The video component of this article can be found at https://www.jove.com/video/55522/

Introduction

Cerebral arteriovenous malformations (AVMs), abnormal connections between arteries and veins without intervening normal capillary beds, present unique neurosurgical challenges. Classified based on size, presence of deep draining veins, and involvement of eloquent cortex,[1] the risk of hemorrhage for previously unruptured AVMs ranges from 0.9 to 8% per year,[2] with an annual average rupture risk of ~3%.[3] Hemorrhages from AVMs are associated with a nearly 10% mortality rate and significant morbidity, with up to 34% of patients having moderate to severe disabilities.[4] Previously ruptured AVMs have increased annual hemorrhage rates,[2] but a relatively low immediate risk of re-rupture. Unless mass effect from a hematoma demands acute intervention, treatment is often performed on an elective basis after weighing the expected natural history of a lesion versus its treatment-associated risks.[5,6]

Surgical resection is the treatment of choice for small accessible AVMs as it immediately and definitively eliminates future hemorrhage risk. However, the high flow rate of AVMs, as well as the increased risk of AVM-associated aneurysms,[4,7] makes surgical resection amongst the most challenging of all neurosurgical cases. Pre-operative embolization of AVMs to reduce blood flow and remove high-risk AVM features can significantly reduce the technical challenges of resection.

Comprehensively trained vascular neurosurgeons are uniquely positioned to definitively treat AVMs by performing both the pre-operative angiogram and endovascular embolization, as well as the open surgical resection. Herein, we describe the protocol for management of surgically accessible cerebral AVMs (as defined by established grading scales[1,8] as well as surgeon and multidisciplinary conference evaluations) at our institution.

Protocol

All procedures described below are performed as standard of care for patients with cerebral AVMs, after obtaining informed consent as per institutional guidelines.

1. Initial patient evaluation and imaging

NOTE: Patients with unruptured AVMs often present after the malformation is discovered on imaging for headache or seizure workup. Patients with ruptured AVMs often present with acute onset of headache, nausea, vomiting, weakness, numbness, and/or vision changes.

1. Obtain a thorough history by interviewing the patient and/or family (to determine previous rupture status, family history) and perform a detailed neurologic exam evaluating level of consciousness and orientation, cranial nerve function, extremity motor and sensory function, and

reflexes. This exam may identify neurologic deficits as a result of occult vascular steal, local mass effect, and/or visual changes (with occipital AVMs). In cases of an AVM rupture, admit the patient to the intensive care unit (ICU), and care for according to American Heart Association (AHA)/American Stroke Association (ASA) guidelines in conjunction with the neurocritical care team.[9]

2. Obtain a non-contrast head computed tomography (CT) per institutional protocol to evaluate for acute hemorrhage, i.e., an area of abnormal intracranial hyperdensity, often with mass effect. Obtain vascular imaging via CT- or magnetic resonance (MR)-angiography per institutional protocol to define cerebral vasculature and any underlying vascular abnormalities.[10] Perform interpretation of all images by neurosurgical and radiology teams.
3. If the patient is neurologically stable, obtain informed consent and book the patient for definitive vascular imaging via six-vessel catheter angiography ± embolization (see sections 2 and 3 below). If the patient has progressive neurologic decline from a hemorrhage, place an intracranial pressure monitor and/or initiate osmotic therapies in accordance with AHA/ASA guidelines[9]. Pursue hematoma evacuation ± AVM resection (see section 4 below) prior to or immediately following diagnostic six-vessel catheter angiography.

2. Six-vessel angiography

1. Position the patient supine on the fluoroscopy table after administration of a light sedative if stable, or under general anesthesia if unstable with assistance from the anesthesiology team (typical induction for intubation with fentanyl [5-10 ucg/kg], midazolam [0.2-0.4 mg/kg], and 0.5 mg/kg rocuronium, followed by anesthesia maintenance with propofol at 50 -150 ucg/kg/min and remifentanil at 0.1-0.5 ucg/kg/min).[11]
2. Place a right femoral artery sheath using a micropuncture groin access kit and a modified Seldinger technique.[12]
    1. Clean (with 2% chlorhexidine gluconate and 70% isopropyl alcohol) and sterilely drape the groin.
    2. Palpate the femoral artery at the inguinal crease. Inject 1-2 mL of 1% Lidocaine HCl as a local anesthetic into the superficial subcutaneous tissue. Insert the micro-needle into the femoral artery lumen with the needle at a 45° angle to the skin.
    3. Advance a micro-wire through the micro-needle, and remove the micro-needle keeping the micro- wire in place. Make a 0.5cm skin puncture with a # 11 blade at site of microwire exiting skin.
    4. Insert a vessel dilator, and then remove the micro-wire and inner portion of the vessel dilator, keeping the outer portion of the vessel dilator in place.
    5. Insert a J-wire through the lumen of the vessel dilator, and remove the vessel dilator, keeping the J-wire in place.
    6. Insert a 5 or 6-French sheath over the J-wire into the femoral artery. Remove the J-wire, keeping the sheath in place in the artery.
3. Advance a 0.035 guidewire and 4-French diagnostic catheter cephalad under mono- or biplane fluoroscopy (3-5 frames per second) to the ascending aorta, and selectively catheterize and image via injection of 5-8 mL of radio-opaque contrast agent (240 mg/mL) the right external and internal carotid arteries, the right vertebral artery, the left internal carotid artery, the left external carotid artery, and the left vertebral artery.
4. Review recorded angiographic images of the above vessel runs to determine the feeding vessels and draining veins of the AVM.
5. If acute embolization not pursued, remove the diagnostic catheter and guidewire, and secure the femoral artery with a sealant device as per manufacturer instructions,[13] or by holding pressure for at least 10 min.

3. AVM embolization

NOTE: If the AVM is amenable to endovascular and subsequent surgical treatment (as defined by established grading scales[1,8] as well as surgeon and multidisciplinary conference evaluations), the initial embolization may be performed in a delayed fashion or in the same session as the diagnostic angiography. Embolizations are often staged to decrease rupture and stroke risk from rapidly altered flow dynamics.

1. Obtain informed consent. With assistance from anesthesia place the patient under general anesthesia as in 2.1, and position the patient supine on the fluoroscopy table (if not at same time as initial angiogram).
2. In conjunction with a neuro-monitoring team, establish baseline neuromonitoring via somatosensory evoked potentials (SSEPs), transcranial motor evoked potentials (TcMEPs), visual evoked potentials (VEPs), auditory brainstem responses (ABRs), and/or electroencephalography (EEG). Continue neuro-monitoring throughout the case to track in real-time the function of critical neural pathways. SSEPs, TcMEPs, and EEG are used as part of a standard neuro-monitoring protocol, with addition of ABRs for vertebral/basilar artery lesions, and VEPs for visual cortex lesions.[14]
3. Obtain femoral arterial access utilizing the modified Seldinger technique and insert a 6- French femoral sheath as in 2.2.
4. Introduce a pre-assembled co-axial system consisting of a 6-French guide catheter (a larger bore catheter on the outside of the system for stabilization), a 4-French diagnostic catheter (a smaller bore catheter positioned inside the 6-French guide for selective vessel catheterization), and a 0.035 guidewire (positioned within the lumen of the 4-French diagnostic catheter for system guidance) as one unit into the femoral sheath.
5. As in 2.3 advance the co-axial system cephalad and selectively catheterize the large-caliber cervical vessel (i.e. left or right internal carotid or vertebral artery) from which the desired feeding AVM vessel originates with the diagnostic catheter and advance the guide catheter to the appropriate cervical segment for support. Remove the diagnostic catheter, ensure adequate vessel runoff via rapid dispersion of a small injection of contrast, and perform a diagnostic angiogram (under mono- or biplane fluoroscopy, 3-5 frames per second) by injection of radio-opaque contrast (5-8 mL of 240 mg/mL) to assess the blood supply of the AVM. An overlay guidance image (superimposition of desired vessel run with real-time fluoroscopy) or roadmap image (vessel subtraction template) is then created to assist with micro-catheterization of the target AVM vessel.
6. Introduce a dimethyl-sulfoxide (DMSO) compatible microcatheter and microwire into the guide catheter at the groin, and advance the cephalad to selectively catheterize the desired feeding artery using overlay or roadmap guidance.
7. Once the embolization position is reached with the microcatheter it is flushed with (DMSO). Once flushed, embolize the AVM nidus and desired feeding artery via controlled injection of a radio-opaque liquid embolic agent under a negative roadmap image until reflux tolerance is reached. Total volume of embolisate used is dictated by the size of the lesion, penetration of the nidus, and allowable reflux. Take care to avoid embolisate reflux into non-AVM arteries, or distal embolization into draining veins. Once the embolization is complete, back aspiration on the embolization syringe is held and the catheter is removed under fluoroscopic visualization.
8. Repeat as needed by catheterizing other feeding vessels, with a goal of at least 50% pre-operative nidal embolization.[15] Generally, only one or two feeding vessels and <40% of the nidus are embolized in a single procedure, making staged embolizations common.

9. Perform final vascular imaging by contrast injection through the guide catheter as in step 3.5 to evaluate the AVM embolization and ensure patency of parent vessels.
10. Withdraw the guide catheter and close the femoral artery as in step 2.5. If the patient is being taken directly to the OR for resection, the femoral sheath may be left in place for intra-operative angiogram (described in step 4.8).

4. AVM resection

1. Obtain informed consent, with assistance from anesthesia place the patient under general anesthesia as in step 2.1, and position the patient based on location of AVM and desired craniotomy. Have blood consent and products available.
2. In conjunction with a neuromonitoring team, establish baseline neuromonitoring as described in 3.2, with continued monitoring throughout the case.
3. Sync pre-operative imaging with intra-operative neuro-navigation system using surface matching, marker, or pointer registration as per neuronavigation system specifications.
4. Obtain groin access as in step 2.2, if sheath is not already in place.
5. Perform a craniotomy tailored to the specific AVM location within the cranium using a high-power drill system, ensuring a wide bony exposure.
    1. Incise the skin and galea using a #15 blade. Obtain hemostasis by placement of Raney clips on the skin edges and/or with Bovie electrocautery using the coagulate setting (Bovie Medical Products, Clearwater, FL). If the planned incision involves underlying muscle, incise the fascia/muscle with electrocautery. Expose the cranium by elevating the incised soft tissue flap from the bone with a periosteal elevator. Alternatively, a pericranial graft can be separately harvested at this time to assist later with closure. Hooks are used for soft tissue retraction. Irrigate and obtain hemostasis.
    2. Create one or multiple burr holes on the periphery of the desired craniotomy with a 3 mm diameter matchstick drill bit using a high power drill system. Additional burr holes will allow for shorter bony cuts and for the dura to be stripped multifocally prior to performing the craniotomy.
    3. Strip the dura locally from the inside of the skull by scraping the inner surface of the bone with a bone elevator or footplate attachment, and complete the craniotomy by connecting the burr holes with a tapered drill bit with a footplate attachment for dural protection. If possible, plan the craniotomy to ensure early access to cerebrospinal fluid (CSF) cisterns for drainage.
    4. Alternatively, place an external ventricular drain into the lateral ventricle at either Frazier's or Kocher's point (after creating a small burr hole as in 4.5.1 and opening the dura sharply using a #11 blade) for CSF drainage. A lumbar drain placed in the lumbar thecal sac following puncture with a large bore Tuohy needle at approximately the L3-L4 or L4-L5 interspace may also be used for CSF drainage.

6. After removal of the bone flap and obtaining hemostasis through bipolar electrocautery, place dural tack-up sutures to close off the epidural space by drilling small holes in the bone around the craniotomy with a C1 drill bit, and securing the dura to the bone at these sites using 4-0 sutures. Then, open the dura sharply using a #11 or #15 blade. Take great care to not injure the underlying cortex or cortical vessels. Once a small durotomy has been created, open the remaining exposed dura in either a cruciate or c-shaped fashion using Metzenbaum scissors, with Gerald forceps used to elevate the dural edge and visualize the tips of the scissors while cutting to preserve underling cortical structures.
7. Using an operating microscope with a variable magnification capacity of approximately 1.5X to 17.0X with a 10X eyepiece, excise the AVM.[5] Other forms of surgical magnification, such as an exoscope, can also be used.
    1. Start microsurgical resection by first dissecting within the subarachnoid space (using a combination of blunt and sharp technique with bipolar forceps, a curved dissector, and microscissors) to define the AVM anatomy and expose its margins, free draining veins, and obtain proximal control by identifying and dissecting free all feeding arteries.
    2. Take great care to identify and preserve the draining veins early in the AVM dissection, as occlusion of the venous drainage prior to the arterial feeders results in engorgement of the AVM and increased rupture risk.
    3. After defining this anatomy, coagulate arterial feeding arteries as they enter the AVM in a proximal to distal fashion using bipolar electrocautery by gently holding the vessel between the tips of the bipolar forceps and using up to 30 watts of power, or by the placement of small aneurysm clips.
    4. Dissect circumferentially within the brain parenchyma immediately around the AVM nidus using bipolar forceps (for dissection and electrocautery) and a variable action suction tip. A brain retractor may be used to facilitate visualization for deep dissections.
    5. After completion of the AVM dissection, coagulate using bipolar electrocautery as in step 4.7.3 and/or clip any draining veins. Remove the AVM from the resection cavity. It is critical to remove the entire lesion to eliminate future hemorrhage risk.
    6. If surgical resection is being attempted post-hemorrhage, perform removal of the hematoma remote from the AVM nidus until the brain is decompressed, and feeding vessels and draining veins are identified. After these landmarks are identified, continue AVM nidal resection as in step 4.7.

8. After AVM removal, perform an intra-operative angiogram as in steps 2.1-2.4, using the arterial sheath placed in step 4.4. Use intraoperative single- or bi-plane angiography or C-arm fluoroscopy to ensure complete nidal resection.
9. Obtain meticulous hemostasis using bipolar electrocautery as in step 4.7.4 and by gently lining the resection cavity with absorbable hemostatic agents. Close or re-approximate the dura using 4-0 sutures and, if needed, a peri-cranial or synthetic dural graft. Replace and secure the bone flap using a plating system, and close the galea and skin using interrupted absorbable sutures for the deep layers and either staples or running suture for the skin. Remove the groin sheath and secure the groin as in step 2.5.
10. Extubate if able, and transfer the patient to the ICU for close neurologic monitoring and recovery.

5. Long term follow up

1. After a radiographically confirmed complete AVM resection (either via intra-operative or post-operative catheter angiography), obtain remote imaging via catheter angiography at 1- and 5-year post-treatment.

Representative Results

A 22-year-old previously healthy female presented with new onset seizures. Non-contrast head CT was negative for acute hemorrhage, but revealed an incompletely characterized right frontal lesion. MRI demonstrated an approximately 2.9 x 2.4 cm Spetzler-Martin Grade 3 AVM within the right superior frontal gyrus (**Figure 1**), with large draining cortical veins going to the superior sagittal sinus, and an arterial supply via large branches off the right middle cerebral artery. The patient underwent multiple staged endovascular embolizations, culminating in an embolization of a right anterior cerebral artery pedicle (**Figure 2**). At the completion of these staged embolizations there was residual supply to the nidus via distal right middle and anterior cerebral artery branches (**Figure 3**), and indirect supply from the left external carotid artery via distal superior temporal artery branches that anastomosed to the middle meningeal artery via transosseous collaterals.

The patient then underwent a frontotemporal craniotomy by the same comprehensively trained neurovascular surgeon, wherein the medial draining veins were identified early and protected. All arterial feeders were identified, bipolared, and cut to achieve sequential devascularization prior to removal of the AVM nidus. Intra-operative and post-operative catheter angiogram (**Figure 4**) confirmed complete resection. One month post-operatively the patient was stable neurologically and being weaned from anti-seizure medications, with plans for delayed cerebrovascular imaging at one year.

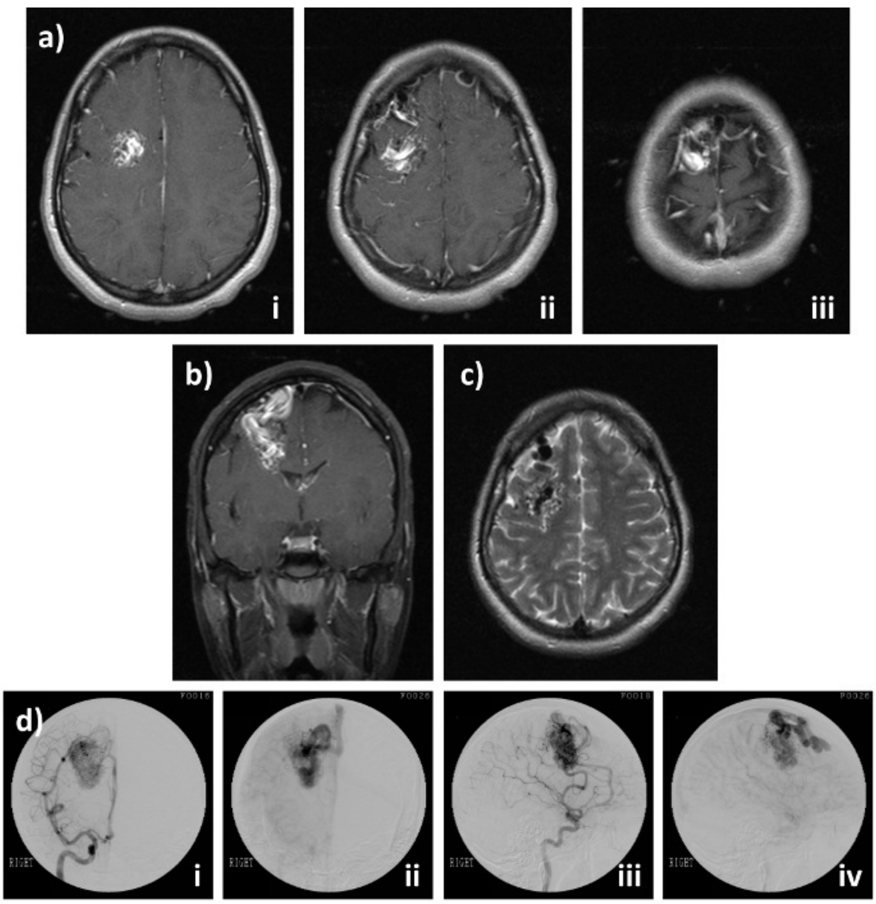

Figure 1: Initial imaging of a Spetzler-Martin Grade 3 unruptured right frontal AVM.
a) Serial axial (i-iii) and b) coronal post-contrast T1-weighted MRI images demonstrating the AVM nidus and medial draining veins. c) Redemonstration of nidus and draining veins on axial T2 Flair MRI imaging. d) Serial AP (i-ii) and lateral (iii-iv) right internal carotid catheter angiogram runs re-demonstrating the AVM nidus and draining veins. Please click here to view a larger version of this figure.

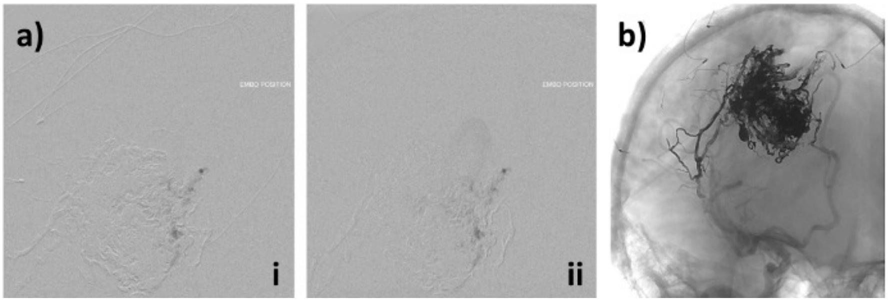

Figure 2: Catheter angiogram images from final AVM embolization.
a) Serial oblique views (i-ii) of microcatheter exploration of the distal right anterior cerebral artery (ACA) during establishment of embolization position in the right ACA pedicle exclusively supplying the AVM. (b) Oblique unsubtracted image demonstrating the Onyx cast within the AVM at the conclusion of the final embolization. Please click here to view a larger version of this figure.

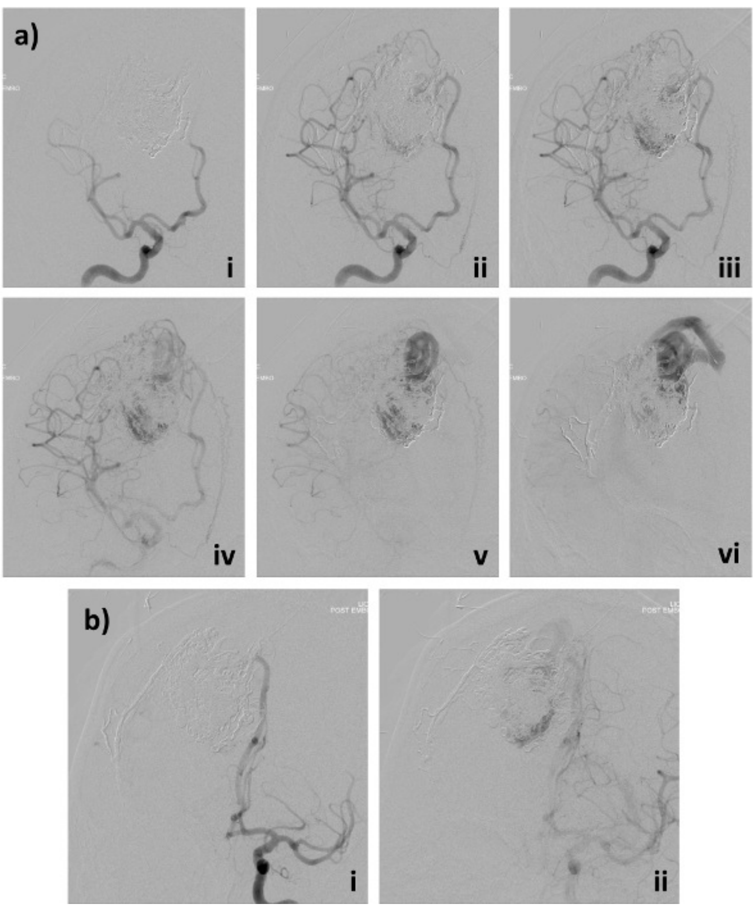

Figure 3: Catheter angiogram post final staged embolization demonstrating residual AVM nidal filling.
a) Serial oblique views of a right internal carotid injection (i-vi) following Onyx embolization of a right anterior cerebral artery pedicle via the left internal carotid and anterior communicating artery. b) Serial AP views of a left internal carotid injection following the above embolization (i-ii). Residual supply to the nidus is seen from distal right middle cerebral artery branches, and distal right anterior cerebral artery branches filling from both the left and right internal carotids. Please click here to view a larger version of this figure.

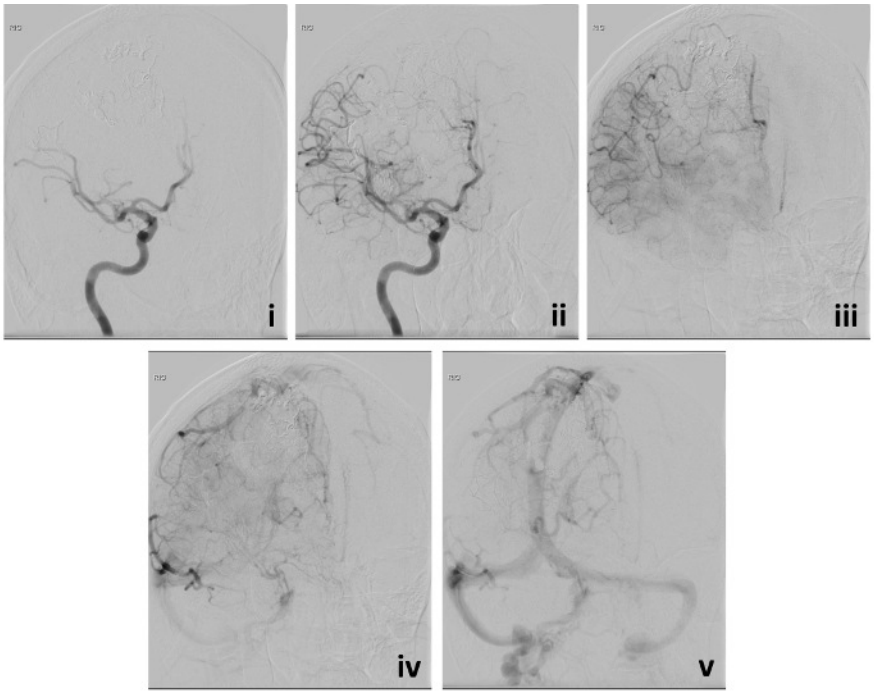

Figure 4: Post-operative catheter angiogram demonstrating complete AVM resection.
Serial oblique views of a right internal carotid injection (i-v) on post-operative day 1 demonstrating complete AVM resection. Please click here to view a larger version of this figure.

Discussion

Here we demonstrate a comprehensive approach to cerebral AVMs via combined endovascular and open surgical management. Catheter angiography is the gold standard for imaging AVMs, and is critical to surgical evaluation and planning. Pre-operative embolizations can simplify surgical resection, but requires communication between the surgical and interventional teams to develop an optimal strategic approach. For example, the AVM arterial feeders most easily embolized may also be the most surgically accessible. If, however, they are embolized prior to development of a comprehensive treatment plan, leaving only deeper more difficult to access arterial feeders, surgery becomes more difficult without further embolization and exposes the patient to potentially avoidable procedures.

The main advantage of comprehensively trained neurovascular surgeons is that the same individual is performing all of the above procedures. No two AVMs are exactly alike, and this heterogeneity demands a flexible, individualized treatment approach based on lesion morphology, patient characteristics, and clinical presentation. The above protocol ensures not only that the optimal pre-operative embolization strategy is pursued, but also gives the surgeon an intricate understanding of the lesion before resection is attempted. Additionally, as the risk of venous outflow obstruction and rupture increases with progressive AVM embolizations, this combined approach allows for a planned craniotomy and resection to immediately follow a final aggressive embolization, all during a single anesthesia session.

Critical steps for complication avoidance within this protocol include: i) appropriate patient selection based on a given AVMs expected natural history versus treatment risks,[5,6] ii) selective AVM embolization without compromise of the arterial supply of normal brain (to prevent iatrogenic strokes) or sacrifice of draining veins (to minimize treatment-associated hemorrhage risk), and iii) step-wise surgical resection to avoid massive hemorrhage or damage to surrounding parenchyma. Because the ultimate goal of this combined approach is a safe surgical resection, it is well suited for smaller, more superficial AVMs not involving eloquent cortex. For surgically inaccessible lesions, radiosurgery is often the treatment of choice as opposed to the embolization/surgical resection protocol described herein.

As evidenced by this multi-step protocol, the treatment of AVMs is complex, and requires cooperation across multiple teams. In addition to the neurovascular surgery team, critical contributions include neuroanesthesia to control intracranial pressure and ensure hemodynamic stability in case of AVM rupture, neuromonitoring to identify in real time neurologic changes and allow appropriate modification of the surgical or endovascular plan, and neurocritical care to help manage the intensive care unit (ICU) needs of these challenging patients. As such, management of AVMs is best undertaken at high-volume centers where this multi-disciplinary infrastructure is in place.

Disclosures

AAK holds consulting arrangements for physician training with Covidien. AAK has no direct financial interests related to this work. The remaining authors have no disclosures concerning the materials or methods used in this study or the findings specified in this paper.

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