Chapter 22
Neurosurgery at the Crossroads: Integrated Multidisciplinary Management of 449 Patients with Brain Arteriovenous Malformations

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INTRODUCTION

Safe, effective treatment of brain arteriovenous malformations (AVMs) remains a challenge despite advances in endovascular technology, surgical technique, and stereotactic radiosurgery. Patients typically present between 20 and 40 years of age with hemorrhage, seizures, neurological deficits, or headaches (8). AVMs have an annual hemorrhage rate of 1 to 4% and a rehemorrhage rate of 6 to 18% in the year after hemorrhage, returning thereafter to an annual hemorrhage rate of 1 to 4%. The morbidity and mortality rates associated with AVM rupture are as high as 53 to 81% and 10 to 18%, respectively (8, 13, 21, 32). In light of these hemorrhage risks, the treatment of AVMs is an important priority for cerebrovascular specialists, with the goal of resecting or obliterating the nidus with acceptably low therapeutic risk, and thereby avoiding neurological deficits or deaths that accompany hemorrhage. Other less threatening symptoms, such as seizures, progressive neurological deficits, and headaches may also warrant consideration for treatment.

Individually, the disciplines of neurosurgery, endovascular surgery, and radiosurgery have made technical and technological advances that have improved patient outcomes. Together, a multidisciplinary approach to AVM management has improved prognosis for patients. Unlike other pathologies, for which therapies from these different disciplines may be competitive, and management recommendations may be controversial, AVMs offer a unique opportunity for these clinical specialists to join together and use integrated treatment strategies. Therefore, AVMs represent an excellent example of the theme, “Neurosurgery at the Crossroads.” In addition to the collaboration between disciplines in clinical management, there is collaboration between the neurosurgical subspecialties, such as cranial base surgery to select optimal operative approaches, and tumor and functional neurosurgery to incorporate techniques such as intraoperative motor and speech mapping. Collaboration between neurosurgeons, neurologists, and epidemiologists has identified factors influencing hemorrhage risk and patient selection. Finally, collaboration between neurosurgeons and basic scientists facilitates the investigation of biological factors that determine AVM formation, clinical behavior, and response to therapy. In this review, we present the multidisciplinary approach to managing patients with brain AVMs used at the University of California, San Francisco (UCSF), which has arisen from collaboration between neurosurgeons, interventional neuroradiologists, radiation oncologists, neurologists, and neuroanesthesiologists.

MATERIALS AND METHODS

Clinical data were collected as part of the UCSF Brain Arteriovenous Malformation Study Project, which has a registry of all AVM patients evaluated and treated at UCSF, maintained by the Center for Cerebrovascular Research. AVM studies are approved by the Institutional Review Board and conducted in compliance with Health Insurance Portability and Accountability Act (HIPAA) regulations.

Patient demographics were obtained from the medical records. AVM characteristics (diameter in centimeters, eloquence of location, and venous drainage pattern [45]) were determined from preoperative angiograms and confirmed by surgical observation. Neurological assessments were performed by a nurse clinician, under the supervision of a neurologist, at multiple time points: before any treatment, preoperatively, 3-months postoperatively, and during the follow-up period. The Modified Rankin Scale (MRS) (49) was used to grade outcomes. For comparison with other reports in the neurosurgical literature, outcomes were also graded using the Glasgow Outcome Scale (GOS) (23).

The multidisciplinary management of AVM patients was reviewed during the period when the senior author (MTL) was directing the Cerebrovascular Diseases Program in the Department of Neurosurgery. Between August 1997 and July 2004 (7 years), 449 patients were evaluated and managed (Table 27.1). Among these patients, 246 were managed surgically (55%).

SINGLE MODALITY TREATMENT

Single modality management of AVMs (surgical resection, embolization, or radiosurgery alone) is becoming uncommon with increasing recognition of the advantages of multimodality management: increased therapeutic efficacy, decreased risks, and improved patient outcomes (Table 27.2). Concurrently, the development of novel embolization agents, sophisticated radiosurgical devices, and more accurate radiosurgical target planning has not translated to increases in single modality cures. Therefore, multimodality management is the standard for the majority of AVMs, however, there are special circumstances described below where single modality management is indicated.

Microsurgical Resection

Microsurgical resection alone without any adjunctive therapy was used in 36 patients (8%). The most common indication was neurological deterioration caused by intracerebral hematoma that produced mass effect and/or increased intracranial pressure (ICP). In these patients, the need for immediate evacuation of the hematoma and relief of high ICP often prevented preoperative embolization, which might have delayed surgery or compromised outcomes. Other indications for microsurgery alone included distally located AVMs with poor endovascular access; and AVMs fed by small arteries that originated perpendicularly from parent arteries, such as lenticulostriate arteries, thalamoperforators, or brainstem perforators. Embolization of perforating arteries was technically difficult and associated with high risk. In some cases, superficial feeding arteries, such as those from cortical middle cerebral artery (MCA) branches, were accessible endovascularly, but easy surgical accessibility made embolization unnecessary.

Older series, where AVMs were not embolized preoperatively, report rates of complete obliteration (80–83%), permanent neurological morbidity (5–17%), and operative mortality (1.6–12.5%) that are inferior to contemporary series, in which AVMs are routinely embolized preoperatively (24, 35). The beneficial effects of preoperative embolization, combined with procedural morbidity rates that are now quite low, have made this surgical adjunct standard practice except in these special situations.

Embolization

Embolization alone without any adjunctive therapy was used in 21 patients (5%). Embolization with complete, curative AVM occlusion is rare. There are reports in the literature of cure rates between 10 and 13%, but these are probably overestimates (12, 39, 51). Aggressive embolization with the intent to cure is associated with high rates of morbidity (4–38%) and mortality (0–6.9%) (5, 22, 47) that can increase further with deep AVMs (morbidity rate, 40%; and mortality rate, 20%) (40). These cures are only observed when there is a small nidus with a single feeding artery, often distally located away from other critical branch arteries. In addition to small AVMs, pial arteriovenous fistulas can also be cured with endovascular techniques, but these lesions are rare.

Therefore, endovascular AVM obliteration is exceptionally uncommon and single modality therapy is intended for other indications, mainly for palliation of symptoms related to large, high-flow AVMs and cerebral steal (fluctuating neurological deficits, seizures, and intractable headaches). In selected cases where surgical therapy is too risky, palliative embolization can reduce nidus flow or venous hypertension to improve symptoms, despite significant persistent arteriovenous shunting. It is worth emphasizing, however, that palliative embolization confers no protection against AVM hemorrhage, with some studies documenting no significant difference in hemorrhage rate or improvement in clinical outcomes in treated patients compared with untreated patients (26). Other studies have documented increased hemorrhage rates after palliative embolization (34). Therefore, palliative embolization should be considered only with AVM patients who have no other good treatment options and whose symptoms have become disabling.

The treatment of feeding artery or flow-related aneurysms is another indication for single modality endovascular therapy. These aneurysms are often remote from the circle of Willis and difficult to access surgically. In addition, the proximity of the AVM or its draining veins to the aneurysm can complicate an otherwise straightforward aneurysm clipping. In these cases, treatment often consists of coil occlusion of the aneurysm and simply observing the AVM, particularly when the AVM is high grade. In patients presenting with subarachnoid hemorrhage rather than intracerebral hemorrhage, the aneurysm is usually the ruptured lesion and aneurysm coiling alone is the appropriate management.

With some ruptured AVMs that have intranidal aneurysms, endovascular occlusion of the nidus aneurysm may reduce the risk of rehemorrhage. These cases are typically the high-grade AVMs with elevated surgical risks, where a decision has been made not to resect the AVM.

Stereotactic Radiosurgery

Stereotactic radiosurgery alone without any adjunctive therapy was used in 62 patients (14%), making it the most common of the three single-modality treatments. Stereotactic radiosurgery refers to a single-session treatment method in which the entire AVM nidus is irradiated. Hypofractionated stereotactic irradiation and volume-staged radiosurgery have also been described, but involve more than one treatment session and are generally used for AVMs with diameters greater than 3 cm, or volumes greater than 10 cm3. Radiosurgery can be performed with a variety of devices including a gamma knife unit, a linear accelerator, or particle beams. Gamma knife and linear accelerator units using photon irradiation are the most commonly used radiosurgical devices, whereas particle beam facilities are few in number and not commonly used for clinical treatments.

The indications for radiosurgery include small nidus size, surgical inaccessibility, and high surgical risk. Small AVMs

are well suited to radiosurgery because therapeutic doses can be delivered effectively with high obliteration rates. In contrast, large volume niduses have lower obliteration rates after radiosurgical treatment and longer intervals from treatment to obliteration. A relationship was reported by Kjellberg for particle beam therapy (25) and, more recently, by Flickinger et al. for other radiosurgical therapies (11) between targeted nidus volume, radiation dose, and a fixed risk of permanent complications of 3%. For example, larger AVMs require lower radiation doses to keep the complication rate below this limit. Therefore, AVMs with a diameter less than 3 cm can be treated with 20 to 25 Gy doses and have obliteration rates between 65% and 95% at 3 years (8, 42, 46). In contrast, larger AVMs treated with 15 to 20 Gy doses have obliteration rates between 33% and 58% at 3 years (46). Lunsford et al. also reported a direct relationship between nidus volume and radiosurgical obliteration, with an obliteration rate of 100% after 2 years in AVMs with volumes less than 1 cm3; an 85% obliteration rate in AVMs with volumes between 1 and 4 cm3; and a 58% obliteration rate in AVMs with volumes greater than 4 cm3 (31).

Our series of large AVMs treated with a linear accelerator system confirmed this relationship, with an obliteration rate of 58% for AVM volumes of 4 to 14 cm3 and 23% for volumes greater than 14 cm3 (mean and median volumes of 15.3 and 8.4 cm3, respectively). Preradiosurgery embolization was a negative predictor of obliteration, and no AVM treated with a dose less than 14 Gy was obliterated. A similar direct relationship between radiation dose and radiosurgical obliteration was observed, with obliteration rates of 50 to 57% with 15-Gy doses, 67 to 70% with 20-Gy doses, and 88% with 25-Gy doses.

Surgical inaccessibility is another important indication for radiosurgery, and AVM locations that are difficult to access include the thalamus, basal ganglia, medial temporal–occipital region, and brainstem. AVMs in these deep locations with critical surrounding neural structures elevate the associated surgical risks. AVMs in these locations that are also small make ideal radiosurgical targets.

Another AVM associated with elevated surgical risks is the large, high-grade AVM. However, for the reasons discussed above, large AVMs are not well suited to standard radiosurgery. Hypofractionated stereotactic radiotherapy (HSRT) and volume-staged radiotherapy have been introduced as options for large AVMs deemed too risky for surgical resection. Both of these techniques rely on multiple treatment sessions to deliver the therapeutic doses of radiation needed for AVM obliteration while minimizing adverse effects. Aoyama et al. found that HSRT is as effective as radiosurgery in terms of obliteration rates and magnetic resonance imaging (MRI) changes, with similar complication rates (1). In another study from these authors, HSRT was used for AVMs larger than 2.5 cm in diameter or in eloquent brain locations, whereas stereotactic radiosurgery was used for AVMs less than 2.5 cm in diameter and in noneloquent locations. The obliteration rates at 3, 5, and 6 years were no different between techniques, despite differences in AVM size between the groups, and the posttreatment T2-weighted signal changes on MRI were similar in both groups (64% for HSRT and 59% for stereotactic radiosurgery). Furthermore, radiation necrosis and cyst formation were higher in the radiosurgery group (3% versus 7%).

We have used volume-staged radiotherapy in 44 patients with large AVMs, 26 of whom have more than 3 years of follow-up. The AVM nidus volume was divided into two components, and each component was treated separately 3 to 6 months apart. The mean treatment volume was 34.1 cm3 and the median dose was 15 Gy for each of the treatment sessions. Despite these large target volumes, 34% of treated lesions were obliterated, and 58% were reduced in size, such that microsurgical removal could be considered. During more than 260-person-years of follow-up, five patients experienced AVM hemorrhage (1.9% per year) and three patients died from recurrent hemorrhage

(11%). Seventy-eight percent of patients had T2-weighted signal changes on MRI and 38% were symptomatic. Volume staging might offer a management strategy for high-risk, high-grade AVMs, with radiosurgery intended not to obliterate the AVM, but to reduce its volume and the risks associated with microsurgical resection.

MULTIMODALITY TREATMENT

In the absence of special circumstances that dictate single modality treatment, multimodality treatment of brain AVMs is routine, because an integrated approach increases obliteration rates, decreases therapeutic risks, and improves patient outcomes (Table 27.2). At UCSF, 67% of patients with treated AVMs underwent multimodality therapy, which can consist of any combination of two modalities or of all three, with variations in the sequence of therapies. The more common combinations consisted of embolization–microsurgical resection, embolization–radiosurgery, radiosurgery–microsurgery, and radiosurgery–embolization–microsurgical resection.

Embolization and Microsurgical Resection

Preoperative embolization with microsurgical resection was the most common multimodality management approach, with 186 patients (41%) having this combination. Other cerebrovascular centers have reported a similar reliance on preoperative embolization, ranging from 30 to 99% of patients undergoing microsurgical resection in recent series (19, 20, 28). The major advantage of preoperative embolization is the reduction of blood flow to the AVM, which can decrease nidus turgor and make it more tolerant of surgical manipulation. Feeding arteries that have been embolized are often easier to coagulate. In addition, intraluminal embolic agents can help the neurosurgeon identify feeding arteries that need to be occluded, as distinguished from normal arteries en passage that need to be preserved. Reduction of blood flow to an AVM preoperatively produces the added advantages of reductions in blood loss and operative time.

Embolization is particularly worthwhile when operating on medium and large AVMs with high blood flow and cerebral steal, because the stepwise occlusion of large feeding arteries in different vascular territories redirects blood flow to dysautoregulated arteries in adjacent brain in a staged manner, rather than all at once during surgery. This strategy of staged embolization before surgical resection enables these dysautoregulated arteries to readjust to increases in blood flow and can reduce the risk of normal perfusion pressure breakthrough bleeding postoperatively. We typically limit embolizations to one vascular territory per day, meaning that larger lesions with, for example, feeding arteries from the MCA and anterior cerebral artery require preoperative embolization in two separate sessions. The strategy of staged feeding artery occlusion is relevant for higher Spetzler-Martin grade AVMs. With difficult Grade IV and V AVMs, morbidity and mortality rates of 12 to 22% and 17 to 38%, respectively, can be achieved with this strategy (14, 15, 17, 45).

Embolization should be tailored to the individual AVM and surgical approach, with embolizations targeted at those feeding arteries that are deepest, most inaccessible surgically, or accessible only at the end of the dissection. Often the superficial and easily accessible feeding arteries do not require embolization, but endovascular occlusion of major feeding arteries that reach the nidus on the side opposite the surgical approach can greatly facilitate resection. Communication between the neurosurgeon and endovascular surgeon is critical in establishing these priorities. The timing of embolization varies at different centers, and there are conceptual arguments for both immediate surgery and delayed surgery. Some embolic agents, such as polyvinyl alcohol, are only occlusive for 3 to 4 weeks, making it

difficult to delay surgery for long. Other embolic agents, such as cyanoacrylate glues, are more permanent and enable surgery to be delayed. We tend to perform embolization and surgery during the same hospitalization, frequently on sequential days.

Recent surgical series incorporating preoperative embolization report higher obliteration rates (94–100% for small AVMs less than 3 cm in diameter) and lower morbidity and mortality rates (1.5–7.8% and 0–1.3%, respectively), compared with surgical resection or embolization alone (8, 17, 43). However, the decision to embolize an AVM preoperatively must be made after carefully weighing the surgical benefits against the added risks of embolization.

Embolization and Radiosurgery

Embolization and radiosurgery were performed together in 28 patients (6%), but this combination of therapeutic modalities has fallen out of favor at our institution. Preradiosurgical embolization might reduce the nidus size and/or arteriovenous shunting, which has the theoretical benefit of enhancing the efficacy of radiosurgery. Reduction in nidus size by 10 to 95% has been reported in embolized AVMs (12, 16, 33). However, in 30% of patients who had their AVMs embolized, the nidus increased in size on the subsequent angiogram performed for radiosurgical targeting (33). More worrisome is the finding that 12% of embolized AVMs recanalized within a year (12). Recanalization of embolized and occluded portions of the AVM that may have been outside the radiosurgical target results in persistent arteriovenous shunting and treatment failure. Indeed, Smith et al. found that all patients with Spetzler-Martin Grade III to V AVMs who underwent incomplete embolization and subsequent radiosurgery had incomplete obliterations (44). Unlike surgery that removes an AVM within several weeks, radiosurgery takes 2 to 3 years to induce AVM obliteration, allowing sufficient time for the embolized AVM to recanalize, remodel, or recruit new feeding arteries.

The results reported for combined embolization and radiosurgery are not stellar, with some clinical series identifying preradiosurgical embolization as a negative predictor of AVM obliteration (36). The combination of embolization and radiosurgery results in complete AVM obliteration in 47 to 55%, permanent neurological deficits in 5 to 12%, and mortality in 1.5 to 2.7% of patients (12, 16, 33). Therefore, the efficacy of combined embolization and radiosurgery is comparable to that of radiosurgery alone. Furthermore, combined embolization and radiosurgical treatment does not provide any protection against AVM hemorrhage during the latency period, with comparable risks of hemorrhage in treated and untreated AVMs. In short, the combination of embolization and radiosurgery does not offer any advantages over radiosurgery alone and may have significant disadvantages. Therefore, this particular approach is not recommended and no longer practiced at our institution.

Radiosurgery and Microsurgery

Microsurgery was used as a salvage technique in conjunction with radiosurgery in 19 patients (4%) when radiosurgery failed to achieve complete obliteration. Causes of failed radiosurgery were analyzed by Kwon et al. and included poor target localization (36%), inadequate definition of nidus (16%), re-expansion of nidus (8%), recanalization after embolization (12%), large nidus volume (20%), suboptimal radiation dose (32%), radioresistance (12%), and intranidal fistula (12%) (27). In our cases, radiosurgery resulted in obliteration of some of the nidus, reduction of blood flow through the nidus, and/or shrinkage of the nidus size, all of which facilitated surgery. In addition, arteries feeding the AVM and within the nidus often evidenced structural changes in response to radiation that thickened their walls and made them easier to coagulate. Some vessels or portions of the AVM were

thrombosed. The brain surrounding the AVM was often gliotic, which also facilitated the dissection around the AVM and the isolation of feeding arteries. Therefore, microsurgical resection of previously irradiated AVMs was either made possible by taming a once formidable AVM, or facilitated by the radiation-induced changes.

This favorable experience in operating on AVMs after failed radiosurgery has been observed by others. Steinberg et al. described considerable experience with these AVMs and achieved complete obliteration in 85% of patients, with permanent neurological deficits in 12% (46). However, the resection of some AVMs may be complicated by previous radiosurgery. The most devastating scenario is the patient whose AVM hemorrhages during the latency period, which we observed six times in this clinical series. In these patients, the surgery was not made more difficult than before the hemorrhage, and in fact, may have been facilitated by the presence of a hematoma that was not there previously. The hematoma can create an easy route of access to the nidus, dissect a plane of separation between the nidus and adjacent brain, and after evacuation, leave a cavity that can be used to widely expose the nidus. Therefore, the hematoma creates important surgical advantages. However, the hemorrhage is typically injurious to the patient and produces deficits that can compromise outcomes. Often, radiosurgery is chosen over microsurgery when patients are neurologically intact and worried about a postoperative deficit. Thus, in these patients, radiosurgery and a hemorrhage during its latency period are particularly disappointing and negatively affect therapeutic results.

Another complicating effect of previous radiosurgery is the subsequent recruitment of new feeding arteries to the AVM. As the nidus obliterates over time, adjacent arteries can enlarge to keep blood shunting through the AVM, and the boundaries of the AVM can become less sharply defined and more difficult to dissect. The dilated feeding arteries are often more difficult to coagulate than the large arteries that initially fed the AVM. In addition, the diffuse nidus is treacherous because finding the correct planes between brain and nidus is more challenging. Fortunately, these unfavorable side effects of radiosurgery are infrequent.

Volume-staged radiosurgery was discussed above as a technique to treat large AVMs with high Spetzler-Martin grades that are poor candidates for surgical resection. AVMs treated in this manner are likely to obliterate incompletely, but they may then become more eligible for safe surgical resection. This approach is relatively novel and none of these patients has come to surgical resection to date. However, we anticipate that many of these patients will become surgical candidates, and we are hopeful that the microsurgical results with these high-grade AVMs will be superior to the results currently obtained without previous radiosurgery.

Embolization, Microsurgery, and Radiosurgery

The combination of all three therapeutic modalities was used rarely (10 patients; 2%). In some of these cases, the intention was to treat only with embolization and microsurgery, but the anatomy at surgery prevented the AVM from being resected completely and safely. These AVMs typically had deep feeding arteries in vital brain structures that were difficult to coagulate, such as lenticulostriate arteries coursing through the basal ganglia and white matter tracts, or thalamoperforating arteries coursing through the thalamus. Rather than attempt to get around these deep portions of the nidus, the resection was halted and these deep remnants were radiated. In other cases, the nidus was diffuse or the surgical exposure limited, again making continued resection risky.

All three modalities were integrated as a planned strategy when it was possible to identify upfront those AVMs unlikely to succumb to embolization and microsurgery alone. This recognition is useful because embolic agents need

to be chosen appropriately. An AVM that will not be resected completely and will require postoperative radiosurgery needs to be embolized with long-lasting embolic agents, such as glue.

The results with this multimodality approach have generally been good. The most dangerous part of the microsurgical resection is avoided, thereby lowering the risk of neurological morbidity. In addition, the likelihood of radiosurgical obliteration is enhanced because most of the large, high-flow feeding arteries are surgically interrupted, leaving just the deep, smaller arteries that tend to be more responsive to radiation. There are no reports in the literature directly comparing aggressive surgical resection with a more conservative approach that combines embolization, microsurgery, and radiosurgery. However, Smith et al. reported excellent obliteration rates (43–60%) and low morbidity rates (2%) for a collection of difficult Spetzler-Martin Grade III to V AVMs using a similar multimodality approach (44). AVM obliteration rates tend to be higher when a multimodality treatment was used instead of a single modality. For example, obliteration rates with single-modality treatment for Spetzler-Martin Grades II, III, IV, and deep (thalamus, basal ganglia, brainstem) AVMs were 88%, 61%, 0%, and 43%; these rates improved to 97%, 92%, 40%, and 72%, respectively, when multimodality regimens were used (18, 30). With deep AVMs, treatment-associated risks were comparable with single and multimodality therapy (7% to 11%, respectively, with no mortality) (30). These results and our experiences suggest that combined therapy in carefully selected cases of high-grade and deeply located AVMs is efficacious, safe, and preferable to an overly aggressive surgical approach.

Summary of Multimodality AVM Management

The various ways that embolization, microsurgery, and radiosurgery can be used alone or in combination can make the design of appropriate AVM management difficult. An algorithm summarizing our approach is presented (Fig. 22.1). When presented with a patient with an AVM, the first decision is between microsurgery, radiosurgery, or observation. The Spetzler-Martin grading system is an essential part of this first decision, with low-grade AVMs (Grades I, II, and III) usually considered for microsurgical resection, and high-grade AVMs (Grades IV and V) usually observed. Amongst the low-grade AVMs are those in inaccessible locations, highly eloquent locations, and/or nonhemorrhagic presentations that have not produced any neurological deficits, and some of these lesions might be better suited to stereotactic radiosurgery.

AVMs that are deemed good candidates for surgical resection are then evaluated for embolization, and those that can be embolized with low associated risk and clear benefit to the surgical resection are treated. AVMs that cannot be embolized without significant risk or because of other clinical issues (e.g., hematoma and elevated ICP) are managed without this adjunct. AVMs deemed good radiosurgical lesions are either small-volume niduses with a high probability of obliteration, in which case traditional single-stage radiosurgery is used, or are large niduses that require volume-staged radiosurgery.

Patients with AVMs that will be observed need to be evaluated for associated aneurysms on feeding arteries, in the circle of Willis, and within the nidus. Aneurysms that are at least 7 mm in diameter are often treated. In addition, aneurysms that are associated with high-flow AVMs, are exposed to increased hemodynamic stress, or have a dysplastic morphology are also considered for treatment. Untreated aneurysms associated with AVMs are monitored careful with serial imaging and those that enlarge are treated.

After an AVM has been treated microsurgically (with or without preoperative embolization) or radiosurgically,

angiography is used to determine whether the AVM has been obliterated. Nothing short of complete angiographic obliteration can be considered curative or protective against future hemorrhage. Patients with a residual AVM are re-entered into the algorithm to determine how best to manage the remaining nidus, and, often, AVMs that were incompletely obliterated with one modality are considered for another modality. Thus, incompletely obliterated AVMs are considered for microsurgery after previous radiosurgery, and vice versa. Sometimes, residual arteriovenous shunting after microsurgical resection represents a technical error that is addressed immediately with reoperation, particularly when venous outflow has been altered by the resection or the patient presented with rupture. Similarly, after radiosurgery, some residual AVMs remain poorly accessible surgically and are treated with an additional radiation dose. However, many of the three-modality strategies were developed when individual modalities incompletely obliterated the AVM and the management “crossed over” to other modalities.

SURGICAL CONSIDERATIONS FOR COMPLEX AVMS

Most AVMs in this clinical experience were superficially located on a cortical surface and were approached through an overlying craniotomy and an approach through adjacent cortex or subarachnoid spaces. With these AVMs, generous exposures were used that accessed all planes around the nidus to carefully identify and occlude the feeding arteries early on, to preserve uninvolved en passage arteries, to minimize the disruption of adjacent brain, and to safeguard the draining veins until the end of the dissection. Unlike these simple AVMs, complex AVMs located in deep or eloquent locations or measuring more than 6 cm in diameter required special considerations, including the application of cranial base surgical techniques and intraoperative neurophysiological mapping.

Deep AVMs

Deep AVMs are not located on the cerebral convexities and are, therefore, more difficult to access surgically. Consequently, they are often referred for radiosurgical therapy without giving adequate consideration to microsurgical options. Deep locations include medial temporal lobe (uncus, hippocampus, and parahippocampus), insula, cingulate gyrus/corpus callosum, choroid plexus/ventricle, parasellar, basal ganglia, thalamus, region of the vein of Galen, cerebellum, and brainstem. In our experience, 88 patients had AVMs in these locations that were considered deep. Of these 88 patients, 12 AVMs (14%) were located in the medial temporal lobe, 4 (5%) were insular, 12 (14%) involved the cingulate gyrus/corpus callosum, 12 (14%) were ventricular, 14 (16%) were parasellar, 6 (7%) involved the basal ganglia, 5 (6%) were thalamic, 1 (1%) was Galenic, 21 (24%) were cerebellar, and 3 (3%) involved the brainstem. For each of these deep locations, surgical exposures can provide access to the AVM and safe microsurgical resection can be performed with acceptably low morbidity and mortality rates. Many of these surgical exposures involve cranial base techniques and include the orbitozygomatic, anterior interhemispheric, posterior interhemispheric, supracerebellar-infratentorial, retrosigmoid, transpetrosal, far lateral, and suboccipital approaches (Figs. 2–6). With many of these deep AVMs, there is an associated subarachnoid plane and/or brain surface that, when adequately exposed, allows the AVM to be circumferentially dissected as if it were a superficial AVM.

For medial temporal lobe AVMs, the orbitozygomatic approach provides wide exposure of the temporal pole and medial surface along the tentorial incisura. Wide splitting of the Sylvian fissure separates the temporal lobe from the frontal lobe and allows the temporal lobe to be mobilized laterally and posteriorly. Then, access to feeding branches from the anterior choroidal artery and the posterior cerebral artery enables their interruption early in the dissection. The trajectory of this approach is in line with the tentorium, making it more tangential to the nidus than the

perpendicular trajectories of subtemporal or transtemporal approaches. The disadvantage of this orbitozygomatic approach is that posteriorly located draining veins are not well visualized until late in the dissection, but the advantage is that the overlying temporal lobe is left intact and not elevated. Corticectomy or lobectomy is avoided, risk of injury to the vein of Labbe is negligible, and lateral temporal lobe retraction is better tolerated than superior retraction (7). This advantage is particularly important in the dominant hemisphere, where Wernicke's speech area and memory areas can be near these subtemporal and transtemporal approaches. The orbitozygomatic/tangential approach works well with small- and medium-sized compact AVMs, but limitations of posterior exposure make it less favorable with large and diffuse AVMs. For simple AVMs in the lateral temporal lobe, uncus, or temporal pole, a simple pterional approach is sufficient.

For Sylvian and insular AVMs, the transsylvian approach with a wide splitting of the Sylvian fissure usually provides adequate access to the nidus. The difficulties with this lesion relate to the challenging vascular anatomy. Typically, there are numerous en passage MCAs that need to be separated from the pathological arteries that feed the AVM. Dissection from distal to proximal along these MCA branches can help to identify these en passage arteries. In addition to these large caliber arteries, the smaller lenticulostriate arteries often feed the AVM and can be difficult to occlude safely. These thin-walled arteries are notoriously resistant to coagulation, and when they bleed, can draw the surgeon into important white matter tracts. Similar difficulties can be encountered when the anterior choroidal artery participates in the supply of the AVM. Liberal use of AVM microclips often works better than bipolar cautery in closing these feeding arteries. The venous system that drains the AVM often overlies the nidus, requiring dissection between these important venous trunks. With AVMs within the insular cortex, the normal MCA candelabra often overlies the nidus, requiring dissection between arterial trunks. This dissection is more difficult than with Sylvian AVMs, where the candelabra vessels are typically deep to the nidus. In the dominant hemisphere, Wernicke's and Broca's speech centers flank the AVM, increasing the risks of surgery. A strong clinical indication for surgery is needed for these highly eloquent AVMs.

The medial hemisphere is easily accessed through either an anterior interhemispheric approach or a posterior interhemispheric approach. The anterior approach exposes the anterior two-thirds of the medial hemisphere, down to the level of the corpus callosum. AVMs in the first third are exposed directly, and those in the second or middle third are exposed obliquely, with a trajectory underneath the critical bridging veins overlying the Rolandic cortex. The approach to these AVMs is similar to a transcallosal approach, with the patient positioned supine, the head turned 90 degrees to the side, and angled upwards 45 degrees from the horizontal plane. A trap-door shaped scalp flap is made and the craniotomy is positioned two-thirds in front of and one-third behind the coronal suture, extending across the midline. This position allows gravity to retract the inferior hemisphere and open the interhemispheric fissure, providing excellent visualization of feeding arteries and draining veins. The dissection typically passes by draining veins that ascend to the superior sagittal sinus and must be preserved until all feeding arteries have been occluded. The pericallosal and callosomarginal arteries are the predominant feeding arteries, and they can be skeletonized along their course while preserving distal, en passage flow. The nidus may have feeding arteries that reach it posteriorly, climbing over the splenium. The corpus callosum often harbors small feeding arteries that can be missed if not pursued. In addition, deep draining veins that course to the lateral ventricle should be visualized, because they can be a source of persistent arteriovenous shunting if not deliberately dissected and occluded. Dissection near the ventricle can be dangerous because the dissection is underneath the nidus, where visualization may be compromised. Bleeding from the nidus or from feeding arteries may be difficult to control, can quickly fill the ventricles, and can close the operative field if the brain begins to herniate outward.

A similar surgical approach is used for AVMs located in the lateral ventricle, usually originating from the choroid plexus and fed by the medial and lateral posterior choroidal arteries (Fig. 22.3). These AVMs are deeper than cingulate and corpus callosum AVMs, and although their surgical exposure is similar, a contralateral approach often gives the optimal trajectory. With the contralateral transcallosal approach, the ventricle harboring the AVM is positioned on the upside, and the dissection proceeds between the down hemisphere and falx, through the corpus callosum into the opposite ventricle, and to the AVM. A contralateral approach obscures visualization of draining veins coursing to the sagittal sinuses, but intraventricular and choroidal AVMs tend to drain to the deep veins within the ventricle. These AVMs lie on top of the thalamus and fornix, making careful dissection of the deep plane the critical part of the case.

The posterior interhemispheric approach is used for AVMs located in the region of the vein of Galen (Fig. 22.4). It provides access to the medial occipital lobes, splenium, pineal region, posterior thalamus, distal posterior cerebral arteries, and Galenic venous complex. A lateral position is used, with the head flexed and rotated towards the floor approximately 30 degrees. This position again brings the midline plane parallel to the surgeon's hands and allows gravity to open the interhemispheric fissure. A lumbar drain is usually placed to drain CSF and relax the brain. A torcular craniotomy that crosses the superior sagittal sinus and both transverse sinuses is required to expose these sinuses and maximize the dural opening. Without complete exposure of the torcular herophili, edges of the craniotomy will overlie the interhemispheric fissure and compromise the exposure. In older patients with adherent dura, a craniotomy performed in two separate pieces enables safe dissection of the dura and sinuses from the inner table of the cranium over the torcular herophili. Dural flaps based on the transverse and superior sagittal sinuses, and extending to their junction, liberate the occipital pole and enable gravity to open the fissure. This trajectory to the AVM brings the draining vein into view early in the dissection. The falx and tentorium can be cut to widen the exposure and visualize anatomy on the contralateral side and in the infratentorial compartment. A panoramic exposure to a deep and treacherous region is created for dissecting the AVM safely.

The surgical exposure for cerebellar AVMs depends on the nidus size and location. Four approaches are used individually or in combination, including a midline suboccipital approach, a supracerebellar–infratentorial approach, a far lateral approach, or an extended retrosigmoid approach. The standard suboccipital craniotomy extending from the foramen magnum to the transverse sinuses, and including a C1 laminectomy, is typically adequate for posteriorly located AVMs in the cerebellar hemispheres. AVMs that are located in the superior vermis or under the tentorium need a supracerebellar–infratentorial approach, with a craniotomy that extends above the transverse sinuses. This additional superior exposure enables the dura flap to elevate the torcular herophili and widen the plane between the tentorium and cerebellum. More inferiorly and more laterally located AVMs involving the tonsils, inferior cerebellar hemisphere, tonsillo-medullary fissure, and foramen magnum with supply from the posteroinferior cerebellar artery are exposed with a far lateral approach (Fig. 22.5). AVMs located on the anterior aspect of the cerebellar hemisphere, opposite the petrous face, are exposed with an extended retrosigmoid approach (Fig. 22.6). The extended retrosigmoid approach incorporates a posterior mastoidectomy to fully expose the sigmoid and transverse sinuses, to eliminate the ledge of bone that can limit the opening into the cerebellopontine angle. This widened craniotomy allows the dural flap to pull the sigmoid sinus forward and gain an extra centimeter of exposure anterior to the cerebellum.

Brainstem AVMs often require more elaborate cranial base exposures, typically one of the transpetrosal exposures

(retrolabyrinthine, translabyrinthine, or transcochlear drilling). These transpetrosal exposures can be combined with a temporal craniotomy (the so-called combined supratentorial and infratentorial approach), and/or a far lateral craniotomy (the so-called combined–combined approach) for increasing operative exposure. Small AVMs around the inferior medulla may only require a simple far lateral craniotomy. In selecting brainstem AVMs for surgical resection, it is important that they are limited to the surface of the brainstem and not buried within it (29).

Eloquent AVMs

Eloquent AVMs are those that receive a point in the Spetzler-Martin grading scale for their location in Rolandic (somatosensory and motor) cortex, language centers, visual cortex, hypothalamus, thalamus, internal capsule, brainstem, cerebellar peduncles, and deep cerebellar nuclei. AVMs in some of these locations are associated with a higher likelihood of a postoperative deficit than others. Schaller et al. reported a 40% risk of permanent neurological deficit associated with resection of “highly eloquent” AVMs in precentral cortex, basal ganglia, and brainstem. In comparison, there was an 18% risk associated with “less eloquent” AVMs in postcentral cortex, occipital lobe, dominant temporal lobe, and corpus callosum, and a 3% risk associated with noneloquent AVMs (41). Therefore, resection of AVMs in highly eloquent locations might benefit from intraoperative techniques to identify and preserve critically functional brain.

Motor mapping, speech mapping, and motor evoked potential (MEP) monitoring are intraoperative neurophysiological techniques that may be advantageous during AVM resection. Motor mapping is applicable to AVMs in Rolandic cortex, particularly those that are not right at the cortical surface. Speech mapping is applicable to AVMs near Wernicke’s area in the dominant temporal lobe, near Broca’s area in the dominant frontal lobe, and near the angular gyrus in the dominant parietal lobe. MEP monitoring is applicable to basal ganglia, thalamic, and brainstem AVMs through which the corticospinal tract passes. These techniques have not been embraced by AVM surgeons as they have been by tumor surgeons, because of the discrete separation between an AVM nidus and adjacent brain. Most neurosurgeons feel that by preserving the plane between the nidus and the adjacent brain, they will prevent any postoperative neurological deficit after resection. However, there are instances where an overlying lobule of brain impedes the dissection of a deep plane, or where a diffuse or difficult border requires wide dissection to avoid disrupting the nidus. In these cases, knowing exactly where highly eloquent brain is located can guide the dissection, increase the surgeon’s confidence in developing safe planes, and improve patient outcomes.

Intraoperative stimulation mapping is superior to preoperative functional imaging and frameless stereotaxy when dealing with AVMs. Structural anatomy is inadequate for identifying eloquent brain because cortical function is reorganized by the presence of an AVM. Baciu et al. found that 59% of patients with tumors or vascular malformations had reorganization of their motor area on functional MRI studies (2). Vates et al. showed that 33% of patients with Rolandic AVMs had a shift in the somatosensory homunculus based on magnetic source imaging (50). Therefore, the eloquence of brain adjacent to an AVM cannot be judged by anatomy alone, even when frameless stereotactic navigation increases the accuracy of that judgment. The identification and subsequent protection of critical areas increases the safety of AVM resection, and in some cases of motor and speech area AVMs, might lead the surgeon to abort the procedure. This information enables the surgeon to make these critical decisions, rather than proceeding blindly and observing unexpected postoperative deficit.

Motor mapping is used for AVMs adjacent to the motor cortex, particularly those that lie below the cortical surface or

deep in a sulcus. Motor mapping requires the careful administration of nonparalyzing anesthesia, wide exposure of the motor cortex, careful patient positioning to observe motor responses, and electrode placement in distal muscles. The conduction of impulses is measured and observed from motor cortex, down the corticospinal pathways, to the extremities. Whereas motor mapping is performed with patients asleep, speech mapping requires patients to remain awake, making it more difficult to execute, particularly with larger AVMs that might take longer to resect. The patient is not intubated endotracheally, and instead is anesthetized with an intravenous mixture of propofol, remifentanyl, and alfentanyl. Draping must allow easy access to the patient for verbal communication. A dedicated neuropsychologist is used to perform the repetitive language tasks, and electrocorticography is routinely used. The electrical stimulation of speech cortex produces changes in language function, indicating the location of the speech center. Standard cortical mapping uses the Ojemann stimulator applied to the brain surface with a constant current generator producing biphasic square wave pulses that range from 2 to 6 mA at a frequency of 60 Hz (4).

Transcranial motor evoked potentials (TcMEPs) are used when resecting AVMs in the basal ganglia, thalamus, or brainstem. TcMEPs are elicited by scalp electrodes that stimulate the underlying motor cortex and generate an impulse that conducts down the corticospinal pathway to the anterior horn and peripheral nerves. Compound action potentials are measured with recording electrodes in extremity muscles. This technique allows the motor pathway to be monitored during the AVM resection, providing feedback when the dissection proceeds close to this tract (38). Changes in TcMEPs indicate retraction injury, compromised cerebral blood flow, or surgical dissection that is affecting the corticospinal pathway directly. These findings inform the surgeon to take corrective measures, and have been particularly useful in selected aneurysm cases (38).

Although these techniques have obvious appeal, they still are used sparingly. In a consecutive series of 224 AVMs operated on by the senior author (MTL), 40 patients had AVMs near the motor cortex and motor mapping was used in 6 patients. Similarly, 36 patients had AVMs near the speech cortex and speech mapping was used in 1 patient. We prefer to perform stimulation mapping as an adjunct at the time of AVM resection. Others have staged the speech mapping and AVM resection, with the initial operation performed with the patient awake to first identify and mark the speech areas. A second procedure then allows the patient to be asleep during the AVM resection. Burchiel et al. performed this staged mapping and AVM resection in eight patients with good results in seven patients (12% rate of new neurological deficits) (6).

Giant AVMs

Giant AVMs typically have high Spetzler-Martin grades (Grade IV or V) and increased risks associated with surgical management. Therefore, patients are selected for treatment only when compelling clinical indications exist, namely repeated hemorrhage or progressive neurological deficit. This conservative posture with high-grade AVMs has been widely embraced (15), but the danger of associated feeding artery aneurysms should be remembered and addressed.

Giant AVMs that fit the criteria for treatment usually require staged embolization, microsurgery, and radiosurgery in a multimodality strategy, as described above. Whether radiosurgery precedes embolization and microsurgery or vice versa depends on the clinical presentation. Embolization and microsurgery are performed first when the AVM has ruptured and the neurological deficits are significant. With less severe presentations, volume-staged radiosurgery is often the preferred initial therapy. The decision to stage an AVM resection or limit surgery to an incomplete resection

is typically made intraoperatively. Brain edema, feeding arteries that are difficult to control, or poor surgical exposure may lead the surgeon to this decision. In addition, nidus that extends into deep-seated regions or intraoperative changes in neurophysiological monitoring can also curtail the resection. Staged AVM resection is beneficial to the surgeon because it provides the surgeon with a break in what otherwise might be a long and arduous dissection.

PATIENT SELECTION

Discriminating patient selection is the secret to success with AVM surgery. The Spetzler-Martin grading system offers an estimation of the overall surgical risk for a patient and might guide therapeutic decisions, but, ultimately, the decision to treat depends on a variety of factors, including anatomic findings not accounted for in the grading scheme, whether an AVM has hemorrhaged, the patient's neurological condition at presentation, the patient's emotional status, and the neurosurgeon's technical skills. Therefore, patient selection for AVM surgery is an art form that challenges the neurosurgeon's judgment and skills like no other lesion in neurosurgery. Experience in AVM surgery breeds conservatism, and there are several telltale features of AVMs where cautious restraint is recommended: selected Grade III AVMs, AVMs with complicating anatomy, and unruptured AVMs in neurologically normal patients.

Grade III AVMs and the Modified Spetzler-Martin Grading System

Experience with the Spetzler-Martin grading scale has demonstrated two distinct groups of patients. Low-grade AVMs (Grades I and II) have low morbidity rates associated with their resection (0–5%) and, consequently, these are frequently treated surgically. High-grade AVMs (Grades IV and V) have high morbidity rates associated with their resection (12–38%) and, consequently, these are frequently observed. In the border zone between AVMs requiring surgical and nonsurgical management are the Grade III AVMs. This group of AVMs is the most heterogeneous, with four different combinations of size, venous drainage, and eloquence, and one-third of all combinations of these elements of the grading scale. In addition, many of these AVMs are challenging to remove, perched at the brink of what many neurosurgeons are willing to accept in terms of technical difficulty and potential morbidity. Therefore, Grade III AVMs present unique challenges in selecting patients for surgery.

On the basis of an analysis of 76 patients with Grade III AVMs undergoing microsurgical resection by the senior author (MTL) during a 5-year period, patient outcome varied between types of Grade III lesions. The overall surgical risk for Grade III AVMs was 8.0%, comparable to other series. In his two publications on patient outcomes after AVM resection, Spetzler reported a combined risk of 8.2% in 61 Grade III patients. Heros et al. measured the surgical risk of Grade III AVMs to be 11.4% in their 44 patients. However, in the senior author's (MTL) cohort of 76 patients, the surgical risk associated with small lesions (S1V1E1) was 2.9%; the risk associated with medium-sized, deep lesions (S2V1E0) was 7.1%; and the risk associated with medium-sized, eloquent lesions (S2V0E1) was 14.8%. The surgical risk for small Grade III AVMs was minimal and more similar to that of Grade II lesions. In contrast, the morbidity/mortality rate for medium-eloquent lesions was dramatically increased, approaching that of high-grade AVMs (Grades IV and V). Medium-deep lesions have a surgical risk that is similar to that reported for Grade III AVMs overall.

On the basis of these data, Grade III AVMs are a heterogeneous entity with each subtype possessing different risks, rather than a homogenous entity with equivalent risks among each subtype. To emphasize these differences, a modification of the Spetzler-Martin grading scale was proposed. Grade III− AVMs (S1V1E1) can be treated Safely

with microsurgical resection; Grade III+ AVMs (S2V0E1) have higher than expected surgical risks, and might be better managed conservatively, such as many high-grade AVMs; and Grade III AVMs (S2V1E0) require carefully individualized treatment recommendations and planning. Grade III* AVMs (S3V0E0) are either nonexistent or exceedingly rare, with a surgical risk that is unclear, requiring further study. This modification of the Spetzler-Martin grading scale recognizes the subtle differences between types of Grade III lesions, enabling better risk prediction for patients, more careful selection criteria for neurosurgeons, and better definition of the gray zone between AVMs that can be better treated surgically or nonsurgically. This modification has proven to be useful within our multidisciplinary team when making treatment recommendations.

Complicating Anatomy

Certain anatomic features of AVMs can make their resection more difficult, including diffuse borders, lenticulostriate or thalamoperforator feeding arteries, previous embolization or radiation, and the degree of eloquence. Unlike compact AVMs with well-defined borders and planes of dissection, diffuse AVMs have ill-defined borders with fragile feeding arteries overlying adjacent cortex and tufts of AVM extending into adjacent brain. This anatomy may be either inherent or the result of recruitment and hypertrophy after previous embolization or radiation. A diffuse AVM forces the surgeon to create a dissection plane. If that plane is too close to the core of the nidus, the fringe is truncated and can be a source of bleeding that is difficult to control. If the dissection plane veers too far from the core of the nidus, then normal brain in eloquent areas might be affected. The neurosurgeon must balance these opposing influences in establishing dissection planes, which can be particularly difficult with diffuse AVMs in eloquent territories.

Deep feeding arteries that traverse white matter tracts, such as lenticulostriate and thalamoperforating arteries, are thin-walled, fragile, and notoriously difficult to coagulate. Their bleeding can draw the surgeon deep into critical areas. They are often left unembolized, reside at the depths of the nidus where they are difficult to fully visualize, and can bleed with surprising ferocity. Preoperatively, these arteries are readily identified on the angiogram. Intraoperatively, they should be anticipated and saved until the very end, when the overlying nidus can be mobilized or removed, if necessary, to improve their exposure. AVM clips allow these arteries to first be occluded, which facilitates their coagulation. AVM clips are also useful in controlling an escaped artery that is already bleeding.

Although radiation facilitates most AVM resections by sclerosing feeding arteries to make them more coagulable and producing a gliotic margin around the nidus, it can be detrimental. Radiation can make the nidus seem smaller and more compact on the preoperative angiogram than it actually is, drawing the dissection into the nidus. The initial angiogram, performed before radiosurgery, better represents the true AVM border and should be the primary angiogram used for surgical planning despite its being years old. In other cases, feeding arteries are recruited after incomplete embolization and radiation, and similar to the thin-wall lenticulostriates or thalamoperforators discussed above, can be difficult to control.

The degree of eloquence must also be considered when assessing surgical risk. AVMs in highly eloquent areas, such as speech and Rolandic cortex, basal ganglia, brainstem, and thalamus, have elevated surgical risks that are not differentiated from less eloquent areas by the Spetzler-Martin grading scale (41). Resection of highly eloquent AVMs may require special neurophysiological monitoring or a more conservative approach.

Hemorrhagic Presentation

Hemorrhagic presentation is an under-appreciated factor in predicting patient outcome after microsurgical AVM resection, and is not a part of other predictive tools, such as the Spetzler-Martin grading scale. Patients presenting with a ruptured AVM often have neurological deficits that impact surgical results and outcomes. A lowered preoperative baseline is produced by hemorrhagic brain injury and its secondary effects, such as intracerebral hematoma, cerebral edema, elevated ICP, and hydrocephalus from intraventricular hemorrhage. In addition, hemorrhage can create surgical advantages that facilitate resection, such as an adjacent hematoma cavity, gliosis, encephalomalacia, or a nonanatomic route of access. These byproducts of AVM rupture can improve outcomes, when good outcomes are defined as neurological improvement relative to preoperative baseline. In contrast, unruptured AVM patients typically present as neurologically intact, making them more vulnerable to deterioration after elective AVM resection.

In a consecutive series of 224 patients treated microsurgically by the senior author (MTL) during 6.4 years, hemorrhagic presentation was associated with improved outcomes, with a mean change in MRS score of +0.89 in patients with a ruptured AVM and −0.38 in patients with an unruptured AVM ($P < 0.001$). The final mean MRS scores in patients with unruptured AVMs were better than those in patients with ruptured AVMs (1.44 versus 1.90, $P = 0.048$). Presentation with an unruptured AVM was a predictor of worsening MRS score (odds ratio, 2.33; 95% confidence interval, 1.3–4.3; $P = 0.006$), but not of worsening GOS score.

This study demonstrated two distinctly different clinical courses, depending on whether an AVM hemorrhaged or not. Patients with ruptured AVMs tended to have deficits at presentation and, generally, improved after surgery. In contrast, patients with unruptured AVMs tended to have normal or nearly normal neurological function at presentation and were susceptible to worsening with surgery, albeit slight, as measured by MRS scores. Therefore, changes in neurological condition trended in a negative direction with unruptured AVMs and in a positive direction with ruptured AVMs, with final outcomes converging between MRS scores of 1 (no significant disability despite symptoms) and 2 (slight disability). These findings are intuitive and support the hypothesis that patients with unruptured AVMs are at greater risk of worsening after surgery than patients with ruptured AVMs. A small price in neurological outcome is paid for the prevention of more costly and potentially devastating hemorrhage that typically compromises the final outcome. However, when significant surgical morbidity is likely or expected in a neurologically normal patient with an unruptured AVM, conservative management is often recommended until the AVM hemorrhages, thereby maximizing the duration of normal function. This cautious approach embodies sound judgment and experienced patient selection, but it also exposes a patient to hemorrhagic risk, if not outright hemorrhage.

CONCLUSIONS

AVMs challenge the neurosurgeon in all aspects of care. Preoperatively, the neurosurgeon must synthesize the many variables that impact the decision to treat. A coordinated strategy must be designed to optimize the different therapeutic modalities of embolization, microsurgery, and radiosurgery. Intraoperatively, the technical challenges and dangers associated with AVMs are extreme. Postoperatively, there are difficult recovery and rehabilitation challenges to be met. A multidisciplinary team approach, such as the one at UCSF involving neurosurgeons, neurointerventional radiologists, neurologists, neuroanesthesiologists, radiation oncologists, research scientists, and clinical nurses, is essential. Cooperative synergy at critical clinical crossroads optimizes patient outcomes, answers important clinical research questions, and leads to the development of innovative therapies for brain AVMs.

References

1. Aoyama H, Shirato H, Nishioka T, Kagei K, Onimaru R, Suzuki K, Ushikoshi S, Houkin K, Kuroda S, Abe H, Miyasaka K: Treatment outcome of single or hypofractionated single-isocentric stereotactic irradiation (STI) using a linear accelerator for intracranial arteriovenous malformation. Radiother Oncol 59:323–328, 2001.

2. Baciu M, Le Bas JF, Segebarth C, Benabid AL: Presurgical fMRI evaluation of cerebral reorganization and motor deficit in patients with tumors and vascular malformations. Eur J Radiol 46:139–146, 2003.

3. Barker FG 2nd, Butler WE, Lyons S, Cascio E, Ogilvy CS, Loeffler JS, Chapman PH: Dose-volume prediction of radiation-related complications after proton beam radiosurgery for cerebral arteriovenous malformations. J Neurosurg 99:254–263, 2003.

4. Berger MS, Kincaid J, Ojemann GA: Brain mapping techniques to maximize resection, safety, seizure control in children with brain tumors. Neurosurgery 25:786–792, 1989.

5. Berthelsen B, Lofgren J, Svendsen P: Embolization of cerebral arteriovenous malformations with bucrylate: Experience in a first series of 29 patients. Acta Radiol 31:13–21, 1990.

6. Burchiel KJ, Clarke H, Ojemann GA, Dacey RG, Winn HR: Use of stimulation mapping and corticography in the excision of arteriovenous malformations in sensorimotor and language-related neocortex. Neurosurgery 24:322–327, 1989.

7. Du R, Young WL, Lawton MT: "Tangential" resection of medial temporal lobe arteriovenous malformations with the orbitozygomatic approach. Neurosurgery 54:645–651; discussion 651–642, 2004.

8. Fleetwood IG, Steinberg GK: Arteriovenous malformations. Lancet 359:863–873, 2002.

9. Flickinger JC, Kondziolka D, Lunsford LD, Kassam A, Phuong LK, Liscak R, Pollock B: Development of a model to predict permanent symptomatic postradiosurgery injury for arteriovenous malformation patients. Arteriovenous Malformation Radiosurgery Study Group. Int J Radiat Oncol Biol Phys 46:1143–1148, 2000.

10. Flickinger JC, Kondziolka D, Lunsford LD, Pollock BE, Yamamoto M, Gorman DA, Schomberg PJ, Sneed P, Larson D, Smith V, McDermott MW, Miyawaki L, Chilton J, Morantz RA, Young B, Jokura H, Liscak R: A multi-institutional analysis of complication outcomes after arteriovenous malformation radiosurgery. Int J Radiat Oncol Biol

Phys 44:67–74, 1999.

11. Flickinger JC, Kondziolka D, Pollock BE, Maitz AH, Lunsford LD: Complications from arteriovenous malformation radiosurgery: Multivariate analysis and risk modeling. Int J Radiat Oncol Biol Phys 38:485–490, 1997.

12. Gobin YP, Laurent A, Merienne L, Schlienger M, Aymard A, Houdart E, Casasco A, Lefkopoulos D, George B, Merland JJ: Treatment of brain arteriovenous malformations by embolization and radiosurgery. J Neurosurg 85:19–28, 1996.

13. Graf CJ, Perret GE, Torner JC: Bleeding from cerebral arteriovenous malformations as part of their natural history. J Neurosurg 58:331–337, 1983.

14. Hamilton MG, Spetzler RF: The prospective application of a grading system for arteriovenous malformations. Neurosurgery 34:2–7, 1994.

15. Han PP, Ponce FA, Spetzler RF: Intention-to-treat analysis of Spetzler-Martin grades IV and V arteriovenous malformations: Natural history and treatment paradigm. J Neurosurg 98:3–7, 2003.

16. Henkes H, Nahser HC, Berg-Dammer E, Weber W, Lange S, Kuhne D: Endovascular therapy of brain AVMs prior to radiosurgery. Neurol Res 20:479–492, 1998.

17. Heros RC, Korosue K, Diebold PM: Surgical excision of cerebral arteriovenous malformations: Late results. Neurosurgery 26:570–577, 1990.

18. Hillman J: Population-based analysis of arteriovenous malformation treatment. J Neurosurg 95:633–637, 2001.

19. Hoh BL, Ogilvy CS, Butler WE, Loeffler JS, Putman CM, Chapman PH: Multimodality treatment of nongalenic arteriovenous malformations in pediatric patients. Neurosurgery 47:346–357; discussion 357–348, 2000.

20. Hongo K, Koike T, Isobe M, Watabe T, Morota N, Nakagawa K: Surgical resection of cerebral arteriovenous malformation combined with pre-operative embolisation. J Clin Neurosci 7(Suppl 1):88–91, 2000.

21. Itoyama Y, Uemura S, Ushio Y, Kuratsu J, Nonaka N, Wada H, Sano Y, Fukumura A, Yoshida K, Yano T: Natural course of unoperated intracranial arteriovenous malformations: Study of 50 cases. J Neurosurg 71:805–809, 1989.

22. Jahan R, Murayama Y, Gobin YP, Duckwiler GR, Vinters HV, Vinuela F: Embolization of arteriovenous malformations with Onyx: Clinicopathological experience in 23 patients. Neurosurgery 48:984–995; discussion 995–987, 2001.

23. Jennett B, Bond M: Assessment of outcome after severe brain damage. Lancet 1:480–484, 1975.

24. Jomin M, Lesoin F, Lozes G: Prognosis for arteriovenous malformations of the brain in adults based on 150 cases. Surg Neurol 23:362–366, 1985.

25. Kjellberg RN: Stereotactic Bragg peak proton beam radiosurgery for cerebral arteriovenous malformations. Ann Clin Res 18(Suppl 47):17–19, 1986.

26. Kwon OK, Han DH, Han MH, Chung YS: Palliatively treated cerebral arteriovenous malformations: Follow-up results. J Clin Neurosci 7(Suppl 1):69–72, 2000.

27. Kwon Y, Jeon SR, Kim JH, Lee JK, Ra DS, Lee DJ, Kwun BD: Analysis of the causes of treatment failure in gamma knife radiosurgery for intracranial arteriovenous malformations. J Neurosurg 93(Suppl 3):104–106, 2000.

28. Lawton MT: Spetzler-Martin Grade III arteriovenous malformations: Surgical results and a modification of the grading scale. Neurosurgery 52:740–748; discussion 748–749, 2003.

29. Lawton MT, Daspit CP, Spetzler RF: Transpetrosal and combination approaches to skull base lesions. Clin Neurosurg 43:91–112, 1996.

30. Lawton MT, Hamilton MG, Spetzler RF: Multimodality treatment of deep arteriovenous malformations: Thalamus, basal ganglia, and brain stem. Neurosurgery 37:29–35; discussion 35–26, 1995.

31. Lunsford LD, Kondziolka D, Flickinger JC, Bissonette DJ, Jungreis CA, Maitz AH, Horton JA, Coffey RJ: Stereotactic radiosurgery for arteriovenous malformations of the brain. J Neurosurg 75:512–524, 1991.

32. Mast H, Young WL, Koennecke HC, Sciacca RR, Osipov A, Pile-Spellman J, Hacein-Bey L, Duong H, Stein BM, Mohr JP: Risk of spontaneous haemorrhage after diagnosis of cerebral arteriovenous malformation. Lancet 350:1065–1068, 1997.

33. Miyachi S, Negoro M, Okamoto T, Kobayashi T, Kida Y, Tanaka T, Yoshida J: Embolisation of cerebral

arteriovenous malformations to assure successful subsequent radiosurgery. J Clin Neurosci 7(Suppl 1):82–85, 2000.

34. Miyamoto S, Hashimoto N, Nagata I, Nozaki K, Morimoto M, Taki W, Kikuchi H: Posttreatment sequelae of palliatively treated cerebral arteriovenous malformations. Neurosurgery 46:589–594; discussion 594–585, 2000.

35. Nornes H, Lundar T, Wikeby P: Cerebral arteriovenous malformations; results of microsurgical management. Acta Neurochir (Wien) 50:243–257, 1979.

36. Pollock BE, Flickinger JC, Lunsford LD, Maitz A, Kondziolka D: Factors associated with successful arteriovenous malformation radiosurgery. Neurosurgery 42:1239–1244; discussion 1244–1237, 1998.

37. Pollock BE, Gorman DA, Brown PD: Radiosurgery for arteriovenous malformations of the basal ganglia, thalamus, and brainstem. J Neurosurg 100:210–214, 2004.

38. Quinones-Hinojosa A, Alam M, Lyon R, Yingling CD, Lawton MT: Transcranial motor evoked potentials during basilar artery aneurysm surgery: Technique application for 30 consecutive patients. Neurosurgery 54:916–924, 2004.

39. Richling B, Killer M: Endovascular management of patients with cerebral arteriovenous malformations. Neurosurg Clin N Am 11:123–145, ix, 2000.

40. Sasaki T, Kurita H, Saito I, Kawamoto S, Nemoto S, Terahara A, Kirino T, Takakura K: Arteriovenous malformations in the basal ganglia and thalamus: Management and results in 101 cases. J Neurosurg 88:285–292, 1998.

41. Schaller C, Schramm J, Haun D: Significance of factors contributing to surgical complications and to late outcome after elective surgery of cerebral arteriovenous malformations. J Neurol Neurosurg Psychiatry 65:547–554, 1998.

42. Shin M, Maruyama K, Kurita H, Kawamoto S, Tago M, Terahara A, Morita A, Ueki K, Takakura K, Kirino T: Analysis of nidus obliteration rates after gamma knife surgery for arteriovenous malformations based on long-term follow-up data: The University of Tokyo experience. J Neurosurg 101:18–24, 2004.

43. Sisti MB, Kader A, Stein BM: Microsurgery for 67 intracranial arteriovenous malformations less than 3 cm in diameter. J Neurosurg 79:653–660, 1993.

44. Smith KA, Shetter A, Speiser B, Spetzler RF: Angiographic follow-up in 37 patients after radiosurgery for cerebral

arteriovenous malformations as part of a multimodality treatment approach. Stereotact Funct Neurosurg 69:136–142, 1997.

45. Spetzler RF, Martin NA: A proposed grading system for arteriovenous malformations. J Neurosurg 65:476–483, 1986.

46. Steinberg GK, Chang SD, Levy RP, Marks MP, Frankel K, Marcellus M: Surgical resection of large incompletely treated intracranial arteriovenous malformations following stereotactic radiosurgery. J Neurosurg 84:920–928, 1996.

47. Taylor CL, Dutton K, Rappard G, Pride GL, Replogle R, Purdy PD, White J, Giller C, Kopitnik TAJ, Samson DS: Complications of preoperative embolization of cerebral arteriovenous malformations. J Neurosurg 100:810–812, 2004.

48. U HS, Kerber CW, Todd MM: Multimodality treatment of deep periventricular cerebral arteriovenous malformations. Surg Neurol 38:192–203, 1992.

49. van Swieten JC, Koudstaal PJ, Visser MC, Schouten HJ, van Gijn J: Interobserver agreement for the assessment of handicap in stroke patients. Stroke 19:604–607, 1988.

50. Vates GE, Lawton MT, Wilson CB, McDermott MW, Halbach VV, Roberts TP, Rowley HA: Magnetic source imaging demonstrates altered cortical distribution of function in patients with arteriovenous malformations. Neurosurgery 51:614–623, 2002.

51. Wikholm G, Lundqvist C, Svendsen P: Embolization of cerebral arteriovenous malformations: Part I. Technique, morphology, and complications. Neurosurgery 3:448–459, 1996.

<DFIG>

Fig. 22.1 Algorithm for the multimodality management of brain AVMs.

Fig. 22.2 Orbitozygomatic approach to a medial temporal lobe AVM. This 22-year-old man presented with a seizure and no evidence of hemorrhage. A, anteroposterior and B, lateral views of a right internal carotid artery angiogram demonstrated a Spetzler-Martin Grade II AVM (S1E0V1) fed by the anterior choroidal artery (AChA) and posterior cerebral artery (PCA), and drained by the basal vein of Rosenthal and vein of Galen. The AVM was embolized preoperatively. The orbitozygomatic approach with wide splitting of the Sylvian fissure accessed these feeding

arteries along the medial border of the AVM. The anterior choroidal artery was exposed, C; and its branches supplying the nidus were coagulated and cut, D. More posteriorly, the feeding arteries from the posterior cerebral artery were exposed and divided, E (CN III, Cranial Nerve III). The AVM was completely resected, F; and after the operation, the patient remained neurologically intact.

Fig. 22.3 Anterior interhemispheric, contralateral transcallosal approach to a lateral ventricular/choroidal AVM. This 33-year-old man presented with sudden, severe headache and confusion. A, axial T1-weighted MRI with contrast revealed a lateral ventricular AVM. B, lateral and C, anteroposterior views of a left vertebral artery angiogram revealed a Spetzler-Martin Grade III AVM (S2E0V1) fed by the left medial and lateral posterior choroidal arteries, and drained by the internal cerebral vein and the vein of Galen. The AVM was embolized preoperatively. A bifrontal craniotomy was performed with an anterior interhemispheric, contralateral transcallosal approach. The AVM was resected completely and the patient was neurologically intact 2 months after surgery.

Fig. 22.4 Posterior interhemispheric approach to a vein of Galen region AVM. This 27-year-old woman presented with headaches. A, axial T2-weighted MRI of the brain revealed marked hydrocephalus and a Spetzler-Martin Grade III (S1E1V1) AVM. B, oblique view of the left vertebral artery angiogram revealed that the AVM was fed by posterior cerebral artery branches bilaterally, and drained into the vein of Galen. The AVM was embolized preoperatively in two stages. The posterior interhemispheric approach opened the interhemispheric fissure, with gravity retracting the right occipital lobe when the patient’s head was positioned laterally, C. The tentorium was divided to widen exposure of the Galenic region, D; and enable the dissection to reach around the entire nidus, E. Postoperatively, the patient remained neurologically intact.

Fig. 22.5 Far lateral approach to a medullary AVM. This 20-year-old man presented with cerebellar hemorrhage. A, sagittal T1-weighted MRI with contrast; and B, anteroposterior and C, lateral views of a left vertebral artery angiogram demonstrated a Spetzler-Martin Grade III (S1E1V1) AVM fed by left posterior inferior cerebellar artery and left anterior inferior cerebellar artery, and draining to the transverse sinus. The patient underwent preoperative embolization and complete resection of the AVM. The far lateral approach provided complete exposure to the cisterna magna, D; posteroinferior cerebellar artery feeding arteries, E; and all margins of the nidus, F. Postoperatively, the patient remained neurologically intact.

Fig. 22.6 Extended retrosigmoid approach to a pontine AVM. This 28-year-old pregnant woman presented in coma with a ruptured AVM. A, head computed tomography scan revealed cerebellar hemorrhage with extension into the fourth ventricle. She underwent an emergent posterior fossa decompressive craniectomy. B, oblique view of right

vertebral artery angiogram and C, lateral view of selective left posterior cerebral artery angiogram show a Spetzler-Martin Grade III (S1E1V1) AVM located in the left middle cerebellar peduncle, fed by the left superior cerebellar artery, anteroinferior cerebellar artery, and a perforator from the basilar artery. The AVM drained into the transverse sinus. The patient underwent preoperative embolization. The extended retrosigmoid approach accessed the anteroinferior cerebellar artery feeding arteries, D; and the dominant draining vein, E. The nidus was circumferentially dissected and removed completely, F. The patient completed her pregnancy and recovered to live at home in a dependent condition.