

Use of Stimulation Mapping and Corticography in the Excision of Arteriovenous Malformations in Sensorimotor and Language-Related Neocortex

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The excision of an arteriovenous malformation (AVM) located within eloquent neocortex presents a formidable neurosurgical challenge. Compromise of the vascular supply to normal surrounding brain or surgical trauma to essential neighboring neocortex may result in unacceptable postoperative neurological morbidity. In addition, successful removal of these lesions without the benefit of intraoperative corticography may leave in situ areas of highly epileptogenic brain, resulting in continued epilepsy. In this report, we describe eight patients who underwent craniotomy and excision of AVMs at our institutions. Six of these lesions were located in the dominant (left) hemisphere, and two were on the right. All patients underwent preoperative testing with Amytal administered via the carotid artery (Wada test). Subsequently, the patient was placed under local anesthesia, and we performed a craniotomy. Electroocortigraphy was used to identify epileptogenic brain in the region of the AVM and to establish after-discharge thresholds to electrical stimulation. Stimulation-mapping techniques were then used to delineate critical motor, sensory, and language areas. Trial occlusion of feeding vessels was also carried out to document postocclusion neurological deterioration, if any. At a later time, a second procedure was performed under general anesthesia to excise the lesion and any epileptogenic foci, using the cortical maps derived earlier. Using these techniques, it was possible to effect complete excision of these lesions in seven of eight patients without causing additional neurological deficits. (*Neurosurgery* 24:322-327, 1989)

Key words: Arteriovenous malformation, Cortical stimulation, Electroencephalography, Language, Sensorimotor function

INTRODUCTION

We describe the technique of electrocorticography (ECoG) and mapping of the cerebral cortex in eight patients with arteriovenous malformations (AVMs). The technique is similar to the ECoG recording and stimulation mapping we perform for resection of epileptogenic cortex in patients with medically intractable epilepsy, with the exception of some minor variations dependent on the site of the AVM. In all eight cases, electrical stimulation, corticography, and mapping under local anesthesia were performed between 1 and 7 days before surgical excision of the AVM. The data obtained allowed identification of language, motor, and sensory areas. With this information, we were able to excise seven of the eight lesions completely while the patient was under general anesthesia, without causing any additional permanent neurological deficit.

METHODS

Preoperative testing with Amytal administered via the carotid artery (10) was done in patients in whom the AVM appeared to be located in or near language-related cortex, as determined by clinical presentation, examination, or computed tomographic (CT) or magnetic resonance imaging (MRI) scans.

In most patients, an initial procedure was performed under local anesthesia to determine the location of the AVM with respect to critical cortex related to language, motor, or sensory function. During this procedure, areas of epileptogenic cortex were localized by electrocorticography (ECoG) in patients with histories of epilepsy. A second procedure was considered to be necessary for the following reasons:

1. the prolonged nature of most of these operations and the impracticality of requiring patients to remain on the operating table under local anesthesia for many hours;
2. the necessity for complete control over such parameters as blood pressure, intracranial pressure, and carbon dioxide pressure during the resection;
3. the requirement for complete immobility of the head during the resection; and
4. the concern that acute blood loss in the patient under local anesthesia might lower the blood pressure, resulting in confusion that would be potentially disastrous in an awake, unrestrained patient.

The initial procedure was performed using a local anesthetic consisting of a mixture of 0.5% lidocaine, 0.25% bupivacaine, and 1:200,000 epinephrine. This mixture was injected as a field block in the scalp and intradurally along the middle meningeal artery. At the beginning of the procedure, before placement of the field block, neuroleptanalgesia was instituted with droperidol (1.25–2.5 mg) and fentanyl (50–150 µg). Supplemental analgesia was given as necessary, particularly during the closure phase of the procedure, when the patient did not need to be alert.

On exposing the cortex, a cortical electrode holder was attached to the posterosuperior edge of the skull. An array of electrodes, usually four rows of four electrodes each, provided for 12 channels of cortico-cortical linkages. A master switch on the electroencephalography machine in the operating room permitted a read-out by the encephalographer in the operating room gallery.

After ECoG recording, stimulation of the cortical surface was performed using a pair of bipolar electrodes approximately 5 mm apart. The stimuli were 2- to 8-mA (peak-to-peak) biphasic square wave pulses of 2 ms duration at 60 Hz.

Each area stimulated was denoted by a small lettered card placed on the cortex. Using this technique of cortical stimulation, ECoG, and mapping, one is able to localize functional areas of speech, language function, and sensorimotor cortex.

CASE REPORTS

Case 1

A 26-year-old, right-handed man on active duty as an Army sergeant came to the Veterans Administration Hospital with acute aphasia and a right hemisensory deficit. A CT scan revealed a contrast-enhancing lesion in the left temporoparietal region associated with an intracerebral hematoma. A cerebral angiogram revealed an AVM in the mesial postero-temporal lobe with multiple small middle cerebral artery feeders, a large arterial supply from the angular artery, and deep venous drainage through the thalamostriate vein (Fig. 1). Intracarotid testing with Amytal (Wada test) indicated complete dominance for language in the left hemisphere.

A left frontotemporoparietal craniotomy was performed under local anesthesia. Most of the feeding vessels were located deep within the sylvian fissure and were not visible on the cortical surface. Mapping of the neocortex demonstrated an area in the inferior parietal region immediately above the superior temporal gyrus that, when stimulated, resulted in speech arrest. Stimulation of the superior temporal gyrus anterior to the vein of Labbé resulted in a seizure. Stimulation immediately posterosuperior to the site of speech arrest resulted in movements of the mouth, and stimulation 1 cm posterior to the same site produced a tingling sensation in the mouth (Fig. 2).

One week after the mapping procedure, the patient was returned to the operating room, where general anesthesia was induced and the AVM was completely resected. Strict care was taken to avoid the areas previously shown to be critical for language function. Postoperatively, the patient experienced transient expressive aphasia and hemiparesis, both of which resolved completely, and returned to his previous military duty.

Case 2

A 34-year-old, right-handed male Naval officer on active duty came to the Veterans Administration Hospital with a 1-day history of weakness, clumsiness, and numbness in the left hand with ipsilateral central facial weakness. A CT scan showed a right central AVM located just anterior to the vein of Trolard, presumably in the motor strip, with an adjacent intracerebral hematoma in the parietal lobe. An angiogram revealed an AVM fed predominantly by three arterial feeders from the middle cerebral artery (Fig. 3).

A craniotomy was performed under local anesthesia, and the sensorimotor strip was mapped out (Fig. 4). Five days later, the patient was given general anesthesia, and the AVM was entirely resected. The patient had no postoperative deficits and returned to active military service.

Case 3

A 16-year-old, right-handed boy was admitted to Group Health Cooperative Hospital after a generalized seizure followed by loss of consciousness. A CT scan showed a contrast-enhancing mass lesion in the left frontoparietal region consistent with an AVM and confirmed by an angiogram (Fig. 5). The lesion was supplied by the left middle cerebral, frontopolar, and left pericallosal arteries. Wada testing determined that language function was located entirely in the left hemisphere.

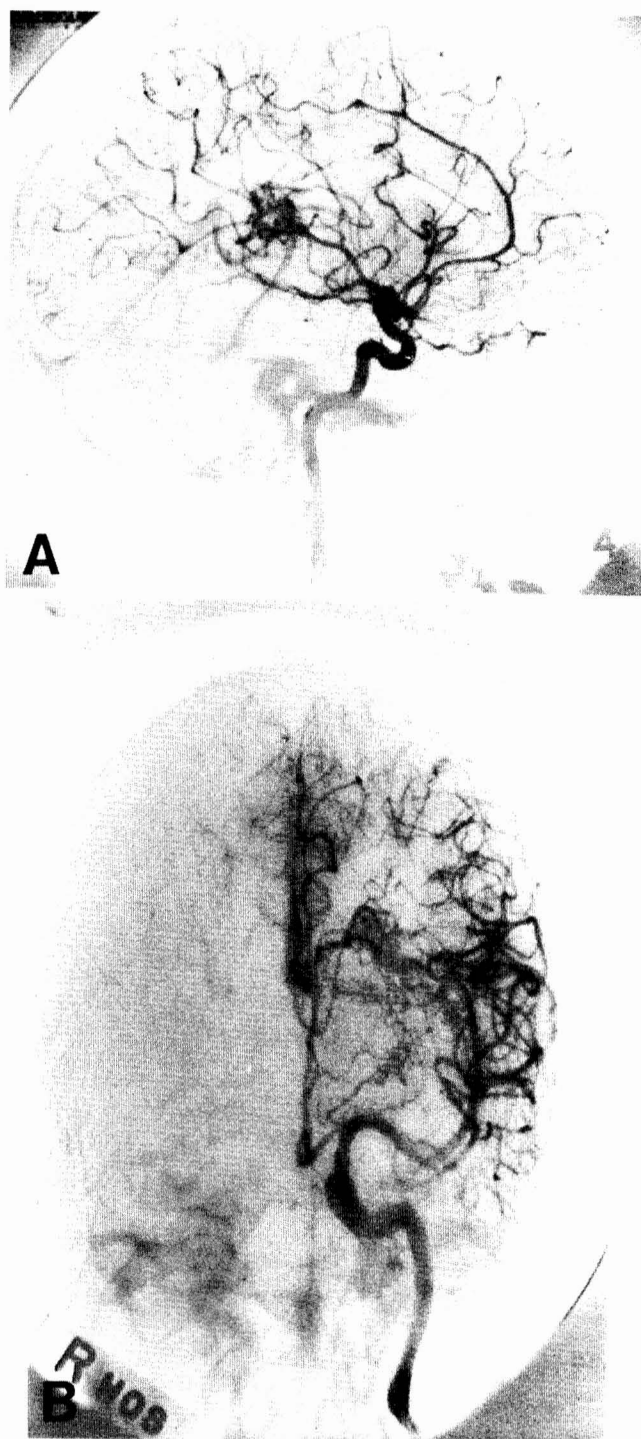


FIG. 1. Case 1. Preoperative lateral (A) and Towne (B) projection angiograms show the AVM in the left sylvian region with middle cerebral artery feeders predominating.

With the patient under local anesthesia, a craniotomy was performed and stimulation mapping of the cortex around the AVM was carried out. Stimulation immediately posterior to the AVM produced motor responses in the contralateral upper extremity and face (Fig. 6). A middle cerebral artery feeding vessel was temporarily occluded with an aneurysm clip, and no neurological deficit ensued. The clip was left in place and the craniotomy was closed.

The next day, the patient was placed under general anes-



FIG. 2. Case 1. Intraoperative photograph of the left frontotemporal cortical surface. The ear is towards the top of the photo and the nose is to the right. Numbers and letters indicate sites of cortical stimulation mapping. Cortical stimulation (1–2.5 mA) produced the following: 1) mouth and jaw movement at *A*, and mouth sensation at *C*; 2) language errors at sites *24*, *25*, *27*, *D*, and *E*; and 3) brief seizures with speech arrest from stimulation just anterior to the vein of Labbé (*arrows*). Resection of the AVM was carried out by splitting the sylvian fissure and partially sacrificing the superior temporal gyrus just anterior to the vein of Labbé, sparing the regions related to language function posterior to the vein.

thesia and a second craniotomy was performed using the cortical map from the initial procedure. The AVM was completely excised and there were no sensory or motor deficits postoperatively.

Case 4

A 30-year-old right handed man was admitted to the University Hospital with seizures and mild anomic aphasia. A cerebral angiogram revealed a large AVM involving the posterior end of the sylvian fissure of the left hemisphere (Fig. 7). Testing with Amytal administered via the carotid artery showed unilateral dominance for language in the left hemisphere.

The patient was given local anesthesia, and we performed a craniotomy. A large AVM was evident on the lateral surface of the posterior end of the sylvian fissure. Cortical mapping of the region of the AVM while the patient was under local anesthesia revealed stimulation-produced changes in language from cortex immediately posterior to the AVM. A series of temporary clips were applied to feeding arteries. However, the patient immediately became aphasic upon temporary occlusion of these vessels (Fig. 8). Because of this, and because of the high risk of postoperative aphasia if the AVM were to be removed, we elected to terminate the procedure, and no resection was done.

Cases 5 through 8

Four additional patients were operated upon for AVMs of the left temporoparietal region. In three instances, this area appeared to be dominant for language function as demonstrated by Wada testing. In the other patient, a left-handed individual, the region of the AVM was in the nondominant hemisphere. Corticography, cortical mapping and resection of the AVM were carried out in two stages, as described above. In one case, a partially thrombosed AVM was removed in one stage after cortical mapping performed under local anesthesia. All four patients recovered from surgery, with no neurological deficit or postoperative seizure activity.

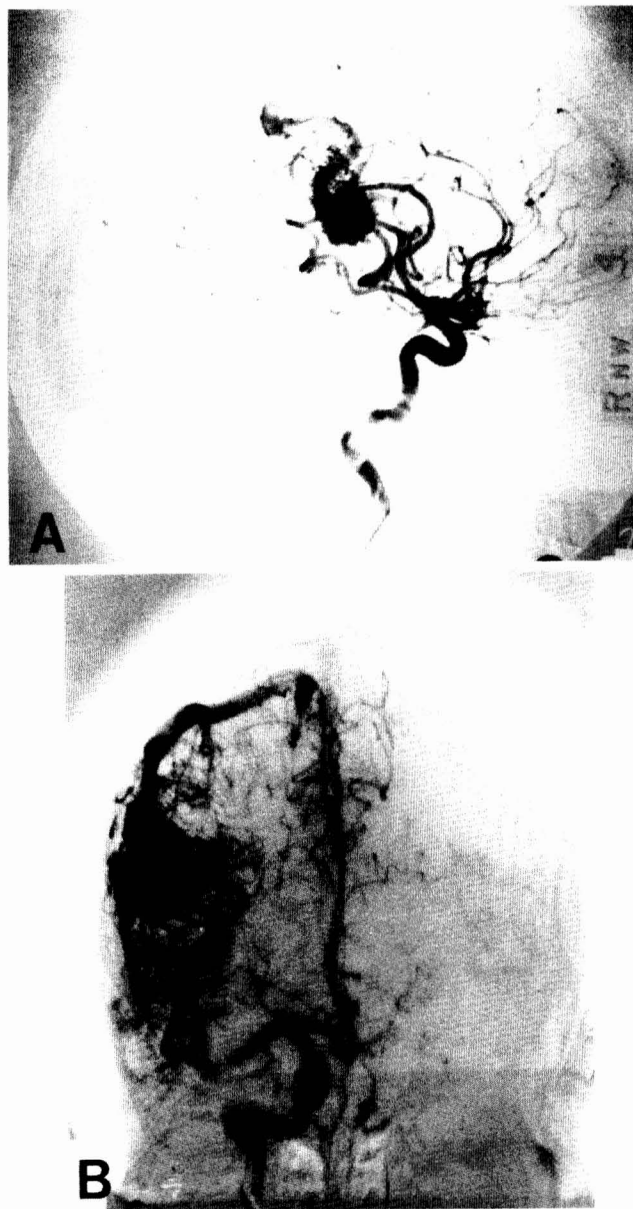


FIG. 3. Case 2. Preoperative lateral (*A*) and Towne (*B*) projection angiograms show a large AVM in the right frontal area with feeding arteries from the middle and anterior cerebral distribution.

DISCUSSION

Electrical stimulation of cerebral cortex using a weak current was first reported by Bartholow (1). Cushing, in 1909 (2), used this technique to determine the anatomic relationship of the sensory cortex strip to an adjacent tumor. Later, Penfield and Boldrey (7) used electrical stimulation to define the motor area of the cerebral cortex so that they could excise an infiltrating tumor without causing any neurological deficit. Penfield and Jasper (8) utilized ECoG in the surgical management of epilepsy, and Penfield and Roberts (9) performed stimulation ECoG and mapping in a series of 110 patients. The information obtained was invaluable in terms of left hemispheric language areas.

Electrical stimulation mapping can therefore be used to localize sensorimotor areas in either hemisphere. In the dom-



FIG. 4. Case 2. Intraoperative photograph of the frontotemporo-parietal cortical surface. The ear is at the bottom of the photo and the nose is to the right. Cortical stimulation mapping of this area produced movement of the face and arm at sites 1 through 4. The AVM and its major draining veins (arrows; compare to Fig. 5A) were located one gyrus anterior to the motor strip. The AVM was attacked through this gyrus by working along the draining veins and sparing the motor strip.

inant hemisphere, arrest of speech and errors in naming, counting, and perseveration can be produced by language-related cortex, the resection of which will leave the patient with significant postoperative language deficits (3). Use of this technique can thus provide the surgeon information concerning the route by which lesions, including AVMs that might be considered unresectable a priori, might be approached.

The application of an electrical stimulus to the cortex in these cases is not without risk. One may precipitate a generalized seizure that could result in disastrous consequences. Caution must be exercised, and the ECoG should be checked closely for any evidence of continued discharges after stimulation. Particularly, although not exclusively, in patients with a history of seizures, the surgeon should be prepared to deal with a spontaneous or induced seizure. This entails restraint of the patient's head and body and administration of short-acting anticonvulsant agents such as lorazepam (5-10 mg, IV) if necessary to control repetitive or prolonged seizures.

Most of our experience with stimulation mapping techniques has derived from cortical resection procedures performed under local anesthesia in patients with medically intractable epilepsy. A paradigm has been developed to allow precise mapping of language cortex in patients who are awake (3-6). Furthermore, Ojemann (3-5) and Ojemann and Dodrill (6) have demonstrated that if areas of cortex that produce errors on intraoperative stimulation mapping during language testing are rigorously spared, permanent postoperative aphasia can be avoided.

The techniques that have been described in this paper are simply the application of procedures that have been used successfully in patients with other disorders—most notably epileptogenic foci and intrinsic tumors—to resect cerebral lesions safely. AVMs are unique, in that often lengthy surgical procedures are required for their removal and that virtually complete physiological control over the patient is a requirement during resection procedures. Certainly, electrical stimulation of motor cortex can be used successfully under general anesthesia to localize the precentral gyrus, and somatosensory evoked potentials (SEPs) may be used in conjunction with it to confirm the location of postcentral gyrus. Thus, in a patient in whom the AVM is not located near suspected language



FIG. 5. Case 3. Preoperative lateral (A) and Towne (B) projection angiograms show a large AVM in the left midfrontal region with feeding arteries from the anterior and middle cerebral arteries.

cortex, a single procedure under general anesthesia may suffice.

If, however, the lesion involves the dominant hemisphere in the inferior frontal or parietal regions or in the temporal lobe, mapping of language cortex is only feasible under local anesthesia. In the future, modalities such as positron emission tomography (PET) or single photon emission computed tomography (SPECT) may allow preoperative localization of language cortex, although the rather poor spatial resolution of these approaches still presents a daunting limitation.

Another advantage of performing craniotomy while the patient is awake is that it allows the the surgeon to apply temporary clips to the arterial feeders and to check for any

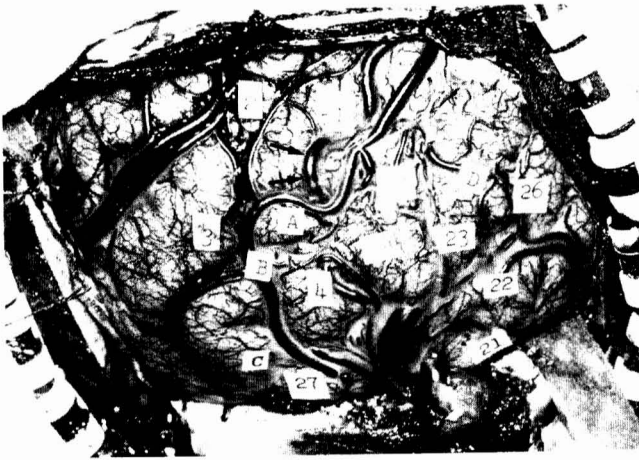


FIG. 6. Case 3. Intraoperative photograph of the frontotemporo-parietal cortical surface. The ears are toward the top of the photograph and the nose is to the right. Stimulation at site 1 arrested the patient's speech. Stimulation at sites 2 and 3 produced movements of the contralateral lip and hand, respectively. Stimulation of site 4 produced aversive turning of the head to the contralateral side. Stimulation at site 27 produced movement of the right foot. The AVM itself was anterior to all the motor responses to stimulation. There was no interference with language function from stimulation at sites 21 through 27. After stimulation mapping of the cortex, a vessel feeding the AVM from the middle cerebral artery circulation (arrow) was temporarily occluded with an aneurysm clip, and no language or motor deficit ensued. The clip was left in place and the craniotomy was closed. The next day, a second craniotomy was performed under general anesthesia, and the AVM was completely excised.

clinical evidence of neurological deterioration. Even detailed mapping of the cortex surrounding an AVM may give no hint that a vessel feeding the shunt may also contribute to normal brain in or around the lesion. Temporary occlusion of a feeding vessel may be the only way to determine whether a neurological deficit will develop after the vessel is permanently ligated. As in our Case 4, immediate signs of neurological deficit upon temporary occlusion may indicate that feeding vessels may not be sacrificed. Given this result, the surgeon may search for a site on the feeder closer to the shunt, in the hope of avoiding branches to normal brain. If this is not possible, then thoughts of performing a resection should probably be abandoned.

If no neurological deficit develops after temporary occlusion, a clip may be left on a feeding vessel at the time of the initial mapping procedure, as was done in Case 3. This clip reduces the arterial supply to the AVM and may produce actual thrombosis of part of the lesion, thus facilitating later resection.

Therefore, our conclusion is that for AVMs of the frontal, temporal, or parietal areas of the dominant hemisphere, a preresection mapping procedure to localize language cortex may allow surgical removal of lesions that otherwise would be considered unapproachable. AVMs of the nondominant hemisphere may also be mapped for sensorimotor function under local anesthesia. However, mapping restricted to the primary motor and sensory cortex may also be done under general anesthesia, making a preresection craniotomy less essential. More detailed mapping of the nondominant hemisphere will obviously require a procedure performed while the patient is awake. If epilepsy is part of the clinical presentation of the AVM, then ECoG under local anesthesia will most accurately delimit the boundary of the epileptogenic cortex, whether it is located in the dominant or nondominant hemisphere. If, in addition to removal of the AVM, cortical resection is planned in an attempt to control the seizures,

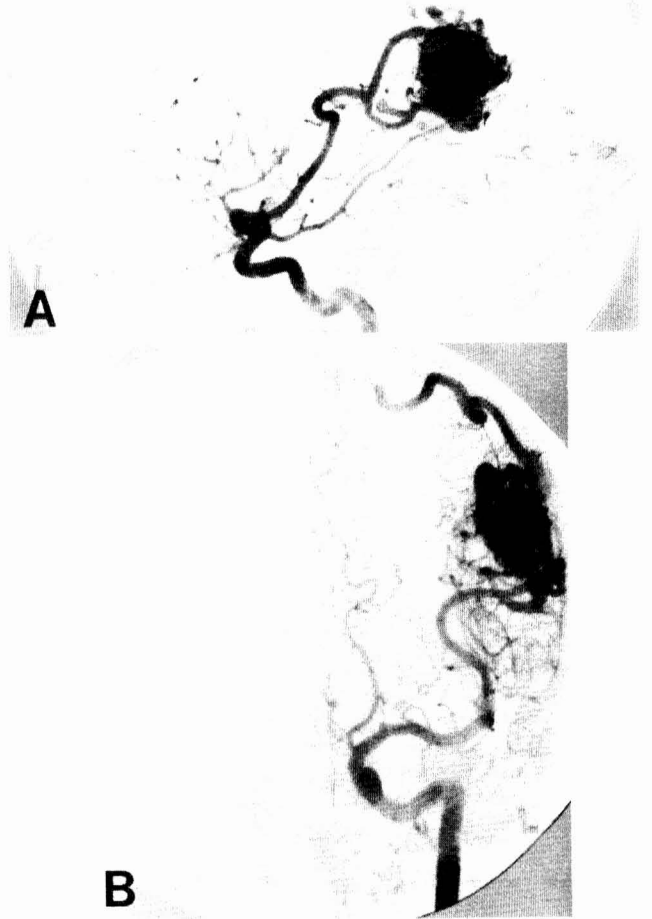


FIG. 7. Case 4. Preoperative lateral (A) and Towne (B) projection angiograms show a large AVM in the left temporoparietal region.



FIG. 8. Case 4. Surface cortical mapping of the region of the AVM under local anesthesia revealed stimulation-produced changes in language from cortex immediately posterior to the AVM (sites 23-25). A temporary aneurysm clip was placed on one of the feeding arteries and the patient immediately became aphasic. Because of this, the aneurysm clip was removed and the procedure was terminated. No subsequent resection was performed in this case.

then a mapping/corticography procedure performed with the patient awake is advisable. The surgeon may then return at a later time to perform a resection carried out under general anesthesia and planned so as to avoid essential cortex while encompassing as much of the epileptogenic focus as possible.

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COMMENTS

The efforts of Dr. Burchiel et al. to use stimulation and mapping to aid in the safe excision of arteriovenous malformations (AVMs) in eloquent cortex should be applauded. Any technique that makes surgery to remove critical AVMs safer is certainly worthwhile.

My own experience with more than 250 operations on AVMs leads me to a different approach to these patients. The patients described all had either Grade 2 or Grade 3 AVMs and, in general, low operative morbidity and mortality. AVMs of this size have the advantage of distinct, sharp planes that allow resection without damage to the surrounding critical cortex. I am not sure how corticography and corticomapping can assist in this aspect.

The authors' other claim for this technique is that it ensures that resection of adjacent epileptogenic cortex will be possible. This is bothersome, in particular since our experience with

cavernous malformations has led us to conclude that removal of the malformation, despite its separation from an epileptogenic focus, may still result in excellent seizure control. My preference would be to remove the AVM without taking any cortex. Then, should the patient have a problem with recalcitrant postoperative seizures, a separate operation for seizure control could be performed. In our entire series of AVMs, this has not been necessary. Interestingly, in the series presented by the authors, the only patient who required excision of epileptogenic cortex was Patient 5, who underwent initial surgery in which partial removal of the AVM and anterior lobectomy were performed with no subsequent improvement of the seizure disorder. An angiogram did not demonstrate an AVM; therefore, the patient was treated most appropriately with the resection of his epileptogenic cortex and, I presume, residual thrombosed AVM.

The risk of inducing a seizure in a patient under local anesthesia who may have had a recently ruptured AVM is sobering. Certainly, in the hands of an experienced team such as these authors, who perform corticography and stimulation mapping routinely, this risk is small. However, it does require an additional operation.

Finally, Patient 4 is of interest. This patient's AVM was not resected because temporary clipping of the feeding arteries resulted in immediate aphasia. Cases in which major arteries course through the periphery of an AVM and then continue to feed important cortex are not infrequent. It is incumbent upon the surgeon to maintain the integrity of these vessels and not to take all arteries that are peripheral to an AVM. Often, these arteries will dip down along with the border of the AVM, giving off many right-angled branches that can be freed relatively easily. I do not believe that Patient 4 has an unresectable AVM whose excision would result in aphasia.

None of these comments is intended as significant criticism, since the results in this series are very gratifying. The authors are to be complimented on the thoroughness of their thought processes and evaluation before the excision of these formidable lesions was undertaken.

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Burchiel et al. have provided a well-illustrated update to the neurosurgical literature regarding the use of stimulation mapping and electrocorticography performed under local anesthesia before excision of eloquently situated AVMs. The authors make the excellent point that sensorimotor cortex can be successfully mapped under general anesthesia, suggesting that putting a patient through the stress of a craniotomy while awake appears to be most valuable in planning resection of lesions adjacent to language cortex or when resection of additional cortex is planned for epilepsy management. The advantage of trial vascular occlusion performed while the patient is awake during the initial craniotomy is cited in this report in predicting tolerance of AVM resection. Many AVMs treated at our institution are preoperatively embolized by selective intracranial catheterization in the awake patient, allowing a similar provocative physiological trial balloon occlusion of many of the feeding vessels without craniotomy. Failure of a patient to tolerate such occlusions does not necessarily imply unresectability, as was assumed in Case 4 during craniotomy and temporary clipping performed while the patient was awake. Careful microdissection in the subarachnoid space and at the AVM margin in parasylvian lesions can identify vessels of passage and allow preservation of the vital efferent components.

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