

INTRAOPERATIVE MOTOR MAPPING OF THE CEREBRAL PEDUNCLE DURING RESECTION OF A MIDBRAIN CAVERNOUS MALFORMATION: TECHNICAL CASE REPORT

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OBJECTIVE AND IMPORTANCE: Brainstem cavernous malformations that seem to come to a pial or ependymal surface on preoperative magnetic resonance imaging studies may, in fact, be covered by an intact layer of neural tissue. For cavernous malformations in the cerebral peduncle, intraoperative stimulation mapping with a miniaturized probe can determine whether this overlying tissue harbors fibers in the corticospinal tract. In addition, intermittent monitoring with transcranial motor evoked potentials (TcMEPs) helps to protect this vital pathway during resection of the lesion.

CLINICAL PRESENTATION: A 20-year-old woman collapsed after a cavernous malformation in the left cerebral peduncle hemorrhaged into the pons, midbrain, and thalamus. She presented with right hemiparesis and left oculomotor palsy.

INTERVENTION: The cavernous malformation was completely resected through a left orbitozygomatic craniotomy and transylvian approach. Stimulation mapping of the cerebral peduncle with a Kartush probe (Medtronic Xomed, Inc., Jacksonville, FL) identified the corticospinal tract lateral to the lesion, and a layer of tissue over the lesion harbored no motor fibers. TcMEP monitoring helped to guide the resection, with increased voltage thresholds and altered waveform morphologies indicating transient impaired motor conduction. All TcMEP changes returned to baseline by the end of the procedure, and the patient's hemiparesis improved after surgery.

CONCLUSION: Stimulation mapping of the corticospinal tract and intermittent TcMEPs is a safe and simple surgical adjunct. Expanded monitoring of the motor pathway during the resection of cerebral peduncle cavernous malformations may improve the safety of these operations.

KEY WORDS: Cavernous malformation, Intraoperative stimulation, Motor evoked potential, Neuromonitoring, Subarachnoid hemorrhage

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Cavernous malformations are vascular anomalies with cavernous spaces lined by endothelial cells and collagen, lacking smooth muscle or intervening neural tissue, filled with blood at various stages of degradation, and surrounded by gliotic brain. Most cavernous malformations are supratentorial, but 10 to 23% are located in the posterior fossa with a predilection for the pons (12). Asymptomatic patients with incidentally detected brainstem cavernous malformations are usually managed conservatively, whereas symptomatic patients with lesions that come to a pial or ependymal surface are candidates for microsurgical resection. Past reluctance to operate on these lesions in densely eloquent brainstem has largely been overcome as a result of advances in microsurgical and cranial

base surgical techniques, neuroanesthesia, neurophysiological monitoring, and frameless stereotactic navigation (5, 9, 13, 16, 19–21, 25, 27). Still, appropriate patient selection depends on a careful assessment of whether or not the cavernous malformation comes to a surgically accessible surface. T1-weighted magnetic resonance imaging (MRI) in axial, coronal, and sagittal sections remains the best measure of a lesion's surface accessibility, and even this modality is unclear in some cases. Ideally, MRI demonstrates a lesion bulging into the subarachnoid or ventricular space, leaving little doubt as to its accessibility. However, even T1-weighted MRI may overestimate surface representation. An embedded lesion at the surface of the brainstem without apparent overlying neural tissue may, in fact,

be covered by a thin intact layer. This situation raises an intraoperative dilemma: does this layer contain functional tissue such that the operation should be aborted, or can this layer be traversed safely to expose and remove the lesion?

We report the intraoperative use of a miniaturized stimulating probe to map the corticospinal tract as it coursed through the cerebral peduncle and around a cavernous malformation. In this case, motor mapping helped to resolve the dilemma regarding overlying neural tissue and the proximity of functional tissue to the lesion. Intraoperative neurophysiological monitoring with somatosensory evoked potentials and cranial nerve monitoring (21) has been reported with similar cases, providing feedback during manipulation and resection of cavernous malformations. However, somatosensory evoked potentials measure conduction along the dorsal columns in the spinal cord, medial lemniscus in the brainstem and thalamus, and primary sensory cortex in the cerebral hemispheres, but they do not monitor motor pathways, whose injury can be even more debilitating. To our knowledge, this case details the first reported use of cerebral peduncle mapping in the resection of a brainstem cavernous malformation. In addition, transcranial motor evoked potentials (TcMEPs) were used to monitor the integrity of motor pathways during the resection.

CASE REPORT

A 20-year-old previously healthy woman collapsed in August 2003. Her urine was positive for amphetamines. Computed tomographic scans of the head revealed hemorrhage in the left pons, midbrain, and thalamus. Brain MRI revealed multiple cavernous malformations in the left midbrain, bilateral posterior temporal lobes, and left cerebellar hemisphere. The patient was initially stuporous with dense right hemiparesis, but she improved with rehabilitation during the next 2 months. She was referred to the senior author (MTL) at that time for definitive treatment.

Before surgery, the patient was alert and obeying commands but nonverbal. She communicated by blinking her eyes. She had left oculomotor nerve palsy and right abducens nerve palsy. Her corneal, cough, and gag reflexes were intact. She had a right facial droop. Her left upper and lower extremities had normal strength, but her right upper extremity had 2/5 strength and her right lower extremity had 4/5 strength. Her sensation was intact to light touch throughout. Her follow-up MRI scan (Fig. 1) demonstrated resolution of blood around the cavernous malformation and an embedded lesion that seemed to come to the surface of the left cerebral peduncle. The lesion extended posteriorly to the inferior colliculus.

Surgical Intervention

The patient was taken to the operating room, where she was anesthetized with desflurane at 2 to 3% (<0.5 maximum allowable concentration) and continuous propofol infusion (50–125 µg/kg/min). Narcotic administration included remifen-

til or fentanyl boluses. No paralytic agents were used after induction and intubation.

Multipulse transcranial electrical stimulation was generated with a CV-2 constant-voltage stimulator (Cadwell Laboratories, Inc., Kennewick, WA). An investigational device exemption was granted by the United States Food and Drug Administration for clinical application of this equipment. TcMEP stimulation parameters included one to nine pulses at an adjustable duration of 50 to 500 microseconds, with a pulse generation interval (interstimulus interval) that was adjusted between 0.1 and 9.9 milliseconds. Stimuli were delivered through two “corkscrew” scalp stimulating electrodes (Nicolet Biomedical, Inc., Madison, WI) placed by the neuromonitoring team at the standardized 10 to 20 electrode positions of C1 and C2 overlying motor cortex. Stimulation was conducted during pauses in the dissection, with clear communication between the neurosurgeon and neurophysiologist. TcMEPs were quickly assessed within 15 seconds, without interrupting the flow of the surgical procedure. TcMEP responses were used to monitor the effects of the dissection and traction on the malformation.

A left orbitozygomatic craniotomy was performed with a wide sylvian fissure split, lateral retraction of the temporal lobe, and opening of the tentorial incisura. When the cerebral peduncle was fully exposed, a thin layer of hemosiderin-stained neural tissue was encountered overlying the cavernous malformation. Frameless stereotaxy with the Stealth Navigation system (Medtronic Sofamor Danek, Inc., Memphis, TN) confirmed the location of the lesion.

Motor mapping of the cerebral peduncle was performed using the Ojemann stimulator (Model OCS-1; Radionics, Inc., Burlington, MA), and electromyographic monitoring of specific muscles was performed according to Yingling et al. (24). The stimulator delivered 60-Hz pulses with a 1-millisecond pulse length. Instead of the Ojemann bipolar stimulator probe, a Kartush side-by-side bipolar stimulator probe (Medtronic Xomed, Inc., Jacksonville, FL) was used (Fig. 2). A custom-made banana plug/protected din adapter connected the Kartush probe to the Ojemann stimulator.

Electromyographic (EMG) activity recorded from TcMEP stimulation and functional mapping of the cerebral peduncle was recorded using subdermal needle electrodes (29 gauge, 1.5 cm in length; Medtronic Xomed), which were placed ap-

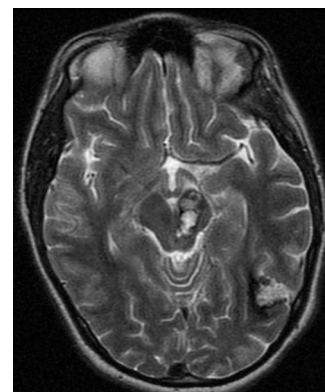


FIGURE 1. Preoperative MRI scan (axial T2-weighted image) showing the cavernous malformation in the cerebral peduncle. The hematoma cavity seemed to come to the surface of the cerebral peduncle without any overlying neural tissue. Other cavernous malformations were also observed in the left cerebellum and bilateral temporal lobes.

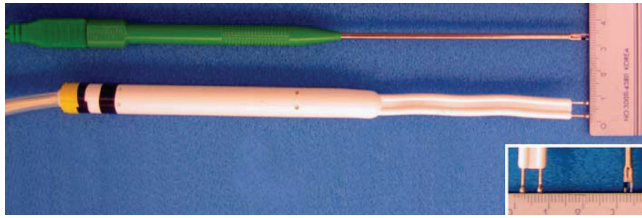


FIGURE 2. Photograph comparing the Ojemann stimulator (Model OCS-1) (bottom) with the Kartush stimulator (top). Inset, the tips of Ojemann stimulator (left) are spaced 5 mm apart, whereas the finer tips of the Kartush stimulator (right) are spaced less than 2 mm apart.

proximately 4 cm apart in the thenar-hypothenar eminences bilaterally as well as in the tibialis anterior, extensor hallucis longus, and foot flexors bilaterally. All electrophysiological responses were recorded using a 16-channel Cascade system (Cadwell Laboratories, Inc.). Recording and filtering parameters for functional mapping were used in a “free-run” EMG mode with a bandpass of 30 to 500 Hz and a display gain of 100 V per division. These traces were displayed at a time base of 500 milliseconds per division to allow better discrimination of individual motor unit potentials. TcMEPs were set at 30 to 1000 Hz, a time base of 100 milliseconds, and a display gain of 50 to 100 mV per division.

RESULTS

Direct stimulation mapping of the neural tissue overlying the cavernous malformation did not elicit any motor activity (Fig. 3A). As the stimulator was moved laterally from the cavernous malformation, activity was observed grossly in the right arm biceps muscle. No EMG activity was elicited in the right hand muscles. With progressively more lateral stimulation, EMG activity was observed first in the anterior tibialis, then in the extensor hallucis longus, and finally in the foot flexors (Fig. 3, B–D). Muscle activity correlated with the expected somatotopic organization of the cerebral peduncle. Thus, motor mapping revealed that the corticospinal tract was lateral to the cavernous malformation and that no functional tract resided in the thin layer between the surface of the peduncle and the lesion. The fibers of the cerebral peduncle were then separated, the hemorrhage cavity was accessed, and the cavernous malformation was completely resected.

TcMEPs were obtained after sustained manipulation of the lesion. Acute changes were detected in the TcMEPs, consisting of an increased voltage threshold (125 V) and an altered waveform (Fig. 4). After a pause of 1 to 2 minutes in the dissection, the TcMEP waveform returned to baseline. Repeated motor mapping of the peduncle with the Kartush probe confirmed the functional integrity of the cortical spinal tract. These TcMEP changes occurred three separate times, each one correlating with mild traction on the lesion and resolving shortly after the lesion was released. TcMEPs were unchanged from their baseline at the completion of the resection.

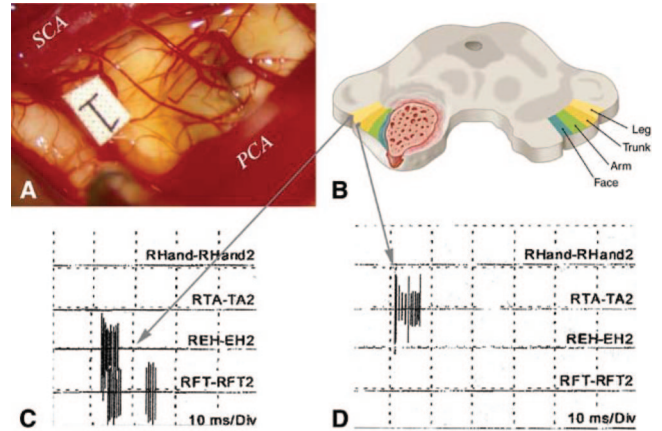


FIGURE 3. A, intraoperative photograph (surgeon’s view from a left-sided orbitozygomatic approach) showing the appearance of the left cerebral peduncle. A thin layer of hemosiderin-stained tissue covers the cavernous malformation. The number “1” lies on the corticospinal tract, lateral to the cavernous malformation, as determined by direct stimulation mapping with the Kartush stimulator. PCA, posterior cerebral artery; SCA, superior cerebellar artery. B, drawing showing the relationship between the corticospinal tract and a right-sided cavernous malformation in the cerebral peduncle. C and D, tracings showing that stimulation of the corticospinal tract produced positive EMG recordings in the right extensor hallucis longus (REH) (C) and the right tibialis anterior (RTA) (D). RHand, right hand; RFT, right foot.

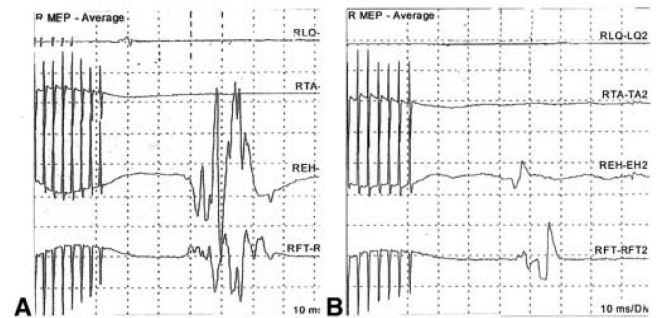


FIGURE 4. Tracings showing TcMEPs during resection of the cavernous malformation. A, baseline TcMEPs demonstrated a robust polyphasic response. B, TcMEPs obtained after the cavernous malformation was manipulated with a micropituitary were noted to have an increase in the voltage threshold (125 V), a change in the waveform morphology from polyphasic to biphasic, and a decrease in amplitude and duration of the response. The waveform returned to baseline a few minutes after release of the cavernous malformation. RTA, right tibialis anterior; REH, right extensor hallucis longus; RFT, right foot.

After surgery, the patient’s right hemiparesis was worse temporarily but gradually improved beyond her preoperative strength. At the time of discharge to an acute rehabilitation center 2 weeks after surgery, her right upper extremity strength was 4+ /5 proximally and 2/5 distally, and her right lower extremity strength was 4+ /5 proximally and 5/5 distally. Her left upper and lower extremities remained at a strength of 5/5. She was able to ambulate with assistance. Her

sensation remained intact to light touch. Postoperative MRI revealed complete resection of the cavernous malformation (Fig. 5).

DISCUSSION

During the resection of cavernous malformations involving the midbrain and cerebral peduncle, protection of the corticospinal tract and preservation of motor function are the neurosurgeon's primary concerns. In this report, we demonstrate that direct stimulation mapping and intermittent monitoring with TcMEPs can be useful in addressing these concerns. We demonstrated that a motor potential can be obtained by stimulating the peduncle directly and that TcMEP recordings can be transiently altered during the resection of a brainstem cavernous malformation. Each can be added to the neuromonitoring regimen easily and safely; together, they may have contributed to this patient's favorable outcome. Detailed mapping and monitoring of the motor pathway seem to be justified in select neurosurgical cases such as this one.

Cerebral Peduncle Mapping

One could argue that if a cavernous malformation was properly selected for microsurgical resection, the lesion would always be at the pial or ependymal surface, functional tissue would be pushed aside by the lesion and/or its hematoma, and mapping would be unnecessary because there would be no violation of intact brain. However, this case demonstrates that a thin layer of overlying tissue can be missed by preoperative MRI. Furthermore, even when a lesion in the cerebral peduncle clearly extends through the pial surface, knowing exactly where the corticospinal tract is can help the neurosurgeon to protect it during the dissection around and mobilization of the lesion. Most of all, the information derived from mapping eliminates the unsettling uncertainty that comes from not knowing exactly where this vital tract lies.

In this case, the tissue overlying the cavernous malformation did not contain functional corticospinal tract, informing the neurosurgeon that the obvious trajectory to the lesion would be safe. In other cases in which the overlying tissue

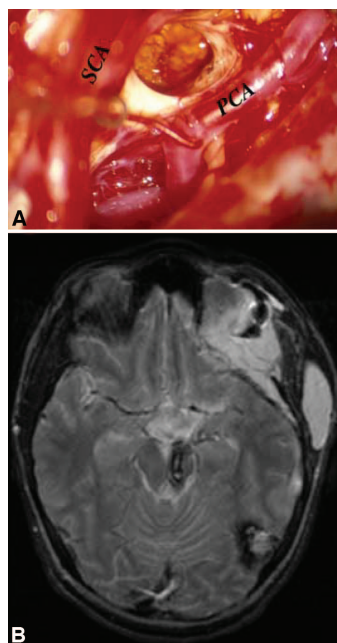


FIGURE 5. A, intraoperative photograph demonstrating the resection cavity after removal of the cavernous malformation. PCA, posterior cerebral artery; SCA, superior cerebellar artery. B, postoperative T2-weighted MRI scan documenting complete resection of the cavernous malformation.

contains functional corticospinal tract, the surgical plan can be modified to avoid a postoperative motor deficit by finding an alternative route to the cavernous malformation through non-eloquent tissue or by aborting the procedure. Although “negative” peduncle mapping in our case did not alter the surgical plan, “positive” mapping in these other cases may be even more beneficial.

The Kartush stimulator probe is a significant improvement over the standard Ojemann stimulator probe and is essential for this technique application. The tips of the Ojemann probe are nearly 2 mm in diameter, with 5-mm spacing between the cathode and anode tips. These dimensions make it bulky and dangerous for such a narrow surgical corridor and not discriminating enough for such a small tract. In contrast, the Kartush probe has less than 2-mm spacing between the tips and an overall width of approximately 2.5 mm, making it more maneuverable and accurate. It has been used for dorsal sulcus mapping and intramedullary mapping during the resection of intrinsic spinal cord tumors (18). It requires a banana plug/protected din adapter to connect to the Ojemann stimulus generator, but this adapter was easily made by our bioengineering staff.

There are other miniaturized stimulation probes that might also work, namely, a bayoneted probe described by Duffau and Sichez (7). These authors initially described a bipolar probe with 3-mm spacing between the tips used for tectal mapping during the resection of a midbrain cavernous malformation. This device was, by their own account, “not precise enough” (8, p 61) and “without good ergonomics under the microscope” (8, p 61), prompting a modification to 2-mm spacing between the tips. At this time, the device used by Duffau and his colleagues is commercially available in Europe. The Kartush probe is readily available in the United States and is approved by the United States Food and Drug Administration for intracranial procedures.

EMG monitoring is an important element of our mapping technique. Others have relied solely on observation of gross motor responses during stimulation, but monitoring of EMG responses has been demonstrated to increase sensitivity in localizing primary motor cortex and subcortical pathways with electrical stimulation (24). In our case, EMG activity was occasionally observed after stimulation mapping that had no associated gross movement. Therefore, the sensitivity of mapping was enhanced by careful observation of EMG responses in this patient and, generally, in patients whose gross motor responses may already be diminished by hemorrhage from a cavernous malformation.

TcMEP Monitoring

Although stimulation mapping identifies where the corticospinal tract is located in the cerebral peduncle, TcMEPs provide an easier method of intermittently monitoring conduction along the tract, and thus the integrity of the tract, during the procedure. TcMEPs are compound action potentials recorded in muscles after cortical stimulation, reflecting

conduction along the corticospinal tract, anterior horn cells, and peripheral nerves. TcMEP monitoring has been used during brain and spinal cord tumor resections (4, 6, 14, 18, 23, 26), during spinal reconstructions (1–3, 10, 11, 15, 26), and during aneurysm surgery (17, 22). The technique adds little time to the operation (less than 30 min, most of which is spent placing additional electrodes initially during anesthesia preparations) and can be easily incorporated into the electrophysiological monitoring routine. TcMEPs elicit some patient movement that can be dangerous if performed during microsurgical dissection, making communication between the neurosurgeon and electrophysiologist essential to coordinate pauses in the dissection for TcMEPs. The advantage of monitoring the motor pathway with TcMEPs rather than with stimulation mapping is that it is quicker and easier, requiring only a pause in the dissection rather than moving the Kartush probe in and out of the surgical field. In addition, TcMEPs seem to be more sensitive to deleterious effects from manipulation of the cavernous malformation or surrounding brain. Changes in voltage thresholds and waveform morphology are harbingers of a compromised tract that are not apparent with stimulation mapping. Therefore, TcMEPs are better suited to detect evolving changes in motor conduction. Frequent TcMEP checks are needed to identify these evolving trends before motor responses are lost completely. A definite correlation between TcMEP changes and clinical symptoms cannot be verified from this single case but may emerge in future studies.

These techniques of mapping and monitoring the motor pathway have applications other than for cavernous malformations in the cerebral peduncle. Microsurgical resection of cavernous malformations along the corticospinal tract in the internal capsule, pons, and anterior medulla might also benefit from these techniques. Location aside, they may play a role whenever there is shadow of a doubt about a lesion's surface accessibility, particularly when the lesion seems to be embedded in the brain rather than protruding from it. In these cases, monitoring the motor pathway may supplement other techniques like somatosensory evoked potentials, brainstem auditory evoked potentials, and cranial nerve monitoring (21).

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COMMENTS

Cavernous malformations of the brainstem are among the most challenging lesions to treat surgically. First, one must decide when to intervene surgically. We recommend operative resection if the lesion reaches the surface and the patient has experienced multiple hemorrhages associated with progressive neurological decline.

Once the decision to operate has been made, a surgical approach must be selected. To do so, we use the two-point method (1). One point is placed in the center of the lesion, and a second point is placed at the surface of the lesion. A straight line is drawn connecting the points to the external surface of the skull. This trajectory dictates the most direct surgical approach, and the appropriate craniotomy can be chosen.

If the two-point method dictates a trajectory that traverses functional brainstem tissue, intraoperative neurophysiological monitoring can be an invaluable tool. The facial colliculus, for example, can be stimulated on the floor of the fourth ventricle when a suboccipital approach is contemplated. The authors describe a modification of a Kartush stimulator used after a banana plug adapter is connected to the Ojemann stimulus generator. This probe has a narrow profile, has a thin shaft, and is amenable for use in deep areas of the brainstem. Despite stimulation at the entry point, no corresponding electromyographic response was obtained. The probe was invaluable for reassuring the surgeons that the entry point was safe. As in electrocorticography, however, this probe primarily stimulates the surface. Deep within the brainstem, there is no guarantee that eloquent tissue involving cranial nerve nuclei will not be disrupted.

The authors also indicate that magnetic resonance imaging might be subject to misinterpretation in terms of the location of the lesion with respect to the surface. We agree. Preoperatively, we also use T1- rather than T2-weighted imaging to determine whether a lesion reaches the surface and is therefore safe to resect. This nice case report demonstrates the use of intraoperative motor mapping of the cerebral peduncle during resection of a midbrain cavernous malformation. We

thank the authors for reminding us that the Kartush stimulator can be used in this application.

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The authors have described an elegant technique for mapping the cerebral peduncle during resection of a midbrain cavernous malformation. This technique assisted the surgeon in precisely localizing the corticospinal tracts, which had been displaced posteriorly and laterally by the hematoma and cavernous malformation, and in achieving a complete resection without incurring any new permanent neurological deficit.

Successful removal of brainstem cavernous malformations requires a precise and delicate microsurgical technique and, very importantly, appropriate patient selection. To successfully remove these challenging lesions, the malformation and/or associated hematoma must come to an approachable surface of the brainstem. If any significant functional brainstem tissue lies between the surgeon and the lesion, new and potentially devastating neurological deficits can be expected. As the authors have clearly stated, the appearance of these lesions on magnetic resonance imaging can be misleading. In most instances, surgical exposure will clearly demonstrate gross discoloration at the site at which the lesion comes closest to the brainstem surface. Not infrequently, however, the surgeon must make a judgment as to where the initial incision into the brainstem must be made. This report clearly demonstrates the usefulness of this elegant technique not only in selecting the precise site for entering the hematoma cavity but also in aiding the surgeon during microsurgical resection of the malformation.

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