High-resolution direct microstimulation mapping of spinal cord motor pathways during resection of an intramedullary tumor

Ravi Gandhi, MD,¹ Corinne M. Curtis, BSBME, REEG/EP T, CNIM,²
and Aaron A. Cohen-Gadol, MD, MSc¹

¹Goodman Campbell Brain and Spine and Department of Neurological Surgery, Indiana University; and ²Indiana University Health, Indianapolis, Indiana

Despite the use of advanced microsurgical techniques, resection of intramedullary tumors may result in significant postoperative deficits because of the vicinity or invasion of important functional tracts. Intraoperative monitoring of somatosensory evoked potentials and transcranial electrical motor evoked potentials has been used previously to limit such complications. Electromyography offers an opportunity for the surgeon to map the eloquent tissue associated with the tumor using intraoperative motor fiber stimulation. Similar to the use of cortical simulation in the resection of supratentorial gliomas, this technique can potentially advance the safety of intramedullary spinal cord tumor resection. The authors describe the use of intraoperative motor fiber tract stimulation to map the corticospinal tracts associated with an intramedullary tumor. This technique led to protection of these tracts during resection of the tumor.

<http://thejns.org/doi/abs/10.3171/2014.10.SPINE1474>

KEY WORDS spinal cord tumor; brain mapping; electrical stimulation; microsurgical resection; oncology

INTRAMEDULLARY spinal cord tumors often present with neurological symptoms based on compression, displacement, or invasion of surrounding fiber tracts. Although microsurgery is usually the best treatment modality, invasion of these tracts by the tumor may increase the risk of postoperative deficits. This risk has been reduced by intraoperative monitoring of somatosensory evoked potentials (SSEPs) and/or motor evoked potentials (MEPs).³ However, these techniques may not always allow for prevention of injury to the corticospinal tracts and often indicate such injury only after it occurred.

We describe our technique of using a Kartush concentric bipolar probe (Medtronic Xomed) to perform high-resolution microstimulation motor mapping of corticospinal tracts responsible for individual muscle groups during resection of a cervicomedullary junction cystic ependymoma. This maneuver allowed identification and avoidance of these functional tracts throughout the procedure. High-resolution microstimulation motor mapping, in

conjunction with monitoring of transcranial electrical motor evoked potentials (TceMEPs), served as a potentially invaluable technique in planning our operative trajectory and guiding the extent of resection while avoiding a neurological deficit.

Illustrative Case

A 52-year-old otherwise healthy man presented with a 3-year history of progressive bilateral hand weakness. Magnetic resonance imaging revealed an intramedullary cystic mass at the level of the cervicomedullary junction (Fig. 1). He underwent surgery under using total intravenous anesthesia; paralytic medications were avoided after intubation. The patient was positioned in the lateral decubitus position, and his head was fixed in a skull clamp.

Electrophysiological Monitoring and Stimulation Mapping

Compound muscle action potentials obtained from

ABBREVIATIONS EMG = electromyogram; MEP = motor evoked potential; SSEP = somatosensory evoked potential; TceMEP = transcranial MEP.

SUBMITTED January 21, 2014. **ACCEPTED** October 23, 2014.

INCLUDE WHEN CITING Published online November 28, 2014; DOI: 10.3171/2014.10.SPINE1474.

DISCLOSURE None of the authors has any conflict of interest regarding the information presented in this report. No funding was received for this study.

FIG. 1. Preoperative MRI reveals a cystic cervicomedullary tumor with an enhancing nodule at the level of the upper cervical spinal cord. **A:** Sagittal contrast-enhanced MR image showing tumor (*arrow*). **B:** Axial contrast-enhanced MR image delineating the location of the nodule (*arrow*). **C:** Axial T2-weighted MR image demonstrating the large cyst associated with the tumor.

TceMEP stimulation and electromyogram (EMG) were recorded using paired subdermal needle electrodes (13 mm long, 0.4 mm in diameter; Rhythmlink International). These needles were placed bilaterally in the thenar-hypothenar (TH, hand), tibialis anterior, medial gastrocnemius, and abductor hallucis and extensor hallucis longus (AE, foot) muscles. All electrophysiological responses were recorded using a Cadwell Cascade Elite 32-channel amplifier (Cadwell Laboratories).

Recording and filtering parameters for direct spinal cord stimulation motor mapping were used in “free-run” and “triggered” EMG modes. This maneuver was conducted with a bandpass of 30 to 500 Hz and a display gain of 200 μ V per division, with a time base of 10 msec per division. High-resolution motor mapping was performed using a Kartush concentric bipolar stimulating probe with a biphasic waveform. This biphasic waveform consists of a 60.11-Hz repetition rate and a 1.0-msec pulse width, with stimulation intensities ranging from 0.1 to 1.0 mA.

Multipulse TceMEPs were generated with a TCS-4 constant-voltage stimulator (Cadwell Laboratories). TceMEP stimulation parameters included a train of 7 pulses with a pulse width of 75 μ sec, a pulse generation interval

(interstimulus interval) of 3 msec, and a stimulation intensity of 126 V. TceMEPs were used at a bandpass of 30 to 1000 Hz, a time base of 10 milliseconds per division, and a display gain of 100 to 2000 μ V per division.

TceMEP stimuli were delivered through 2 subdermal needle scalp stimulating electrodes placed by the neuro-monitorist at the standardized 10–20 electrode positions of C1 and C2, overlying the motor cortex. Stimulation was conducted during pauses in dissection at the surgeon’s request. This was done while microdissection was stopped because the stimulation caused jerky body movements.

Mapping Results and Microsurgical Resection

We completed a suboccipital craniotomy and C-1 laminectomy followed by a midline myelotomy and cyst drainage. Pial retraction sutures were placed to keep the cystic cavity open. The solid component or the tumor nodule infiltrating the anterior spinal cord or corticospinal tracts was identified. To avoid injury to these tracts, we performed motor mapping of the anterior spinal cord over and along the periphery of the nodule to evaluate whether the margin of the tumor had infiltrated motor pathways (Fig. 2). The Kartush probe was used to map the surrounding fibers and construct the map illustrated in Fig. 3. We stimulated the area of interest for 1–2 seconds and repeated this maneuver for confirmation with a second stimulation at each area (Fig. 3).

Using these mapping data, we established that there was infiltration of motor pathways immediately adjacent to the tumor. Motor tracts were especially close to the margin of the tumor along the tumor’s left upper quadrant (Fig. 3). We completed dissection of the nodule around its margins, disconnecting it at its most immediate border to avoid injury to the functionally mapped areas. Stimulation of the tumor–spinal cord border was intermittently performed before bipolar coagulation to confirm absence of highly functional tissue. We continued dissection of the nodule in a counterclockwise fashion. Intermittent TceMEP stimulation was also used to ensure integrity of the motor system. Upon elevation of the nodule, stimulation mapping along the resection bed was also performed to ensure tract integrity (Fig. 4). Stimulation of the tumor along its left upper quadrant attachments revealed intense left foot responses (Fig. 5). This area was therefore deemed too risky to resect, and a small portion of the tumor was left behind to avoid injury to the tracts corresponding to the left foot area. (Please see Video 1 for the details of this technique.)

VIDEO 1. Video clip showing the operative nuances involved in performance of the described procedure. Copyright Aaron A. Cohen-Gadol. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

Results

During surgery, we were able to stimulate the tumor surface and confirm an absence of functional fibers overlying the tumor. Mapping data confirm that the tumor had mainly displaced the corticospinal tracts. Once we reached the end of our resection, stimulation data informed us that a small portion of the tumor might have invaded corticospinal fibers responsible for left foot control, and this por-

FIG. 2. A midline myelotomy exposed the nodule of the tumor. **Upper:** Intraoperative photograph showing the tumor nodule (N) and use of the probe to map the spinal cord at the periphery of the tumor. **Lower:** Sketch illustrating the anatomy of the nodule. Copyright *The Neurosurgical Atlas*, Aaron A. Cohen-Gadol. Used with permission. Figure is available in color online only.

tion of the tumor was thus left behind to avoid the risk of postoperative deficits.

Immediately after surgery, detailed neurological examination demonstrated slightly decreased proprioception and pinprick perception in both of the patient's lower

extremities and subtle weakness in his left plantar extensors. He was discharged home without any need for rehabilitation. At the 3-month follow-up examination, his left foot strength was found to have returned to normal and his sensory deficits to have completely resolved.

Discussion

Preservation of functional tracts during microsurgery of intramedullary spinal cord tumors is of the utmost importance. We demonstrate that direct microsurgical stimulation and mapping may prove to be an invaluable tool in the neurosurgeon's armamentarium. In conjunction with traditional TceMEPs, this tool can advance the safety of the operation. More specifically, this mapping technique can help the surgeon decide when to stop resection in order to avoid neurological morbidity. In the case of our patient, the postoperative presence of slight left foot weakness in conjunction with the intraoperative finding of left foot responses to stimulation over the small piece of residual tumor may support the hypothesis that aggressive tumor resection may have left the patient with a permanent foot weakness.

Other monitoring modalities, such as epidural motor evoked potentials and SSEPs have been employed to advance the safety of resection for intramedullary spinal cord lesions.²⁻⁵ Epidural MEPs allow D-wave monitoring. This technique is a relative measure of the number of fast conducting fibers within the corticospinal tract. A 50% loss of amplitude suggests damage to approximately 50% of the fibers. This method, in conjunction with EMG-based TceMEPs, prevents unsafe maneuvers, including aggressive retraction during spinal cord surgery. The loss of MEPs in the presence of D-wave preservation is a predictor of transient weakness.² These findings suggest that further tumor resection is feasible; however, a change in surgical strategy may be necessary. Although this technique has been shown to be effective in increasing the safety of surgery,² it may be ineffective in the upper cervical spinal cord, as the density of critical fibers is much greater in that region.

An alternative form of our technique for spinal cord motor pathway stimulation has been previously described in 2 other publications^{1,5} reporting on a total of 3 cases (Table 1). Although Duffau and colleagues¹ report the use of a modified bipolar probe, they did not describe the anatomical resolution of individual tracts or the components of the pyramidal tracts in detail, as described in our report. The stimulating surfaces of their bipolar probe were 4 mm apart. The Kartush probe has an overall width of 2 mm, adequate for finer microstimulation motor fiber mapping. As described above, direct fiber stimulation mapping has the added benefit of preemptively identifying critical fibers and allowing proactive adjustments to the surgical strategy.

Quiñones-Hinojosa and colleagues⁶ used the Kartush probe to map the corticospinal tracts in the cerebral peduncle during resection of a midbrain cavernous malformation, and they were able to map the location of individual motor tracts that were lateral to the planned entry site. During resection, they were able to confirm the functional integrity of these tracts. This mapping strategy was

FIG. 3. The results of stimulation mapping demonstrate the location of functional tracts in the close vicinity of tumor margins. **A:** Stimulation at 0.1 mA, triggered EMG response seen in left (L) thenar-hypothenar (TH, hand). **B:** Stimulation at 1.0 mA, triggered EMG response seen in left abductor hallucis (AH, foot flexors). **C:** Stimulation at 1.0 mA, triggered EMG response seen in right (R) thenar-hypothenar (TH, hand). **D:** Stimulation at 1.0 mA, triggered EMG response seen in right extensor hallucis longus (EHL-AE). AE = abductor hallucis and extensor hallucis longus; MG = medial gastrocnemius; TA = tibialis anterior. Copyright *The Neurosurgical Atlas*, Aaron A. Cohen-Gadol. Used with permission. Figure is available in color online only.

used for brainstem and not spinal cord and therefore may not be comparable to our technique. Another report by Quiñones-Hinojosa and colleagues⁵ described resection of 2 intramedullary spinal cord tumors using the Ojemann cortical stimulator (Model OCS-1) for intraoperative corticospinal tract stimulation. The authors did not comment on whether they were able to map pathways to the indi-

vidual muscle groups. In one of their cases, they limited their resection based on stimulation findings. Notably, the stimulating tips of the Ojemann stimulator are spaced 5 mm apart, whereas the finer and closely spaced concentric tips of the Kartush stimulator allow for higher-resolution mapping of motor pathways corresponding to muscle groups in our report.

TABLE 1. Results of spinal cord mapping using direct stimulation previously reported in the literature

Authors & Year	Technique	Location/Pathology	Findings	Results
Duffau et al., 2003	Bayonet, bipolar microprobe w/ 2 mm btwn 1-mm tips; observation of motor response	Not reported/glioma	Inferior limb movement	Gross-total resection; no increased neurological deficit
Quiñones-Hinojosa et al., 2002				
Case 1	Model OCS-1 Ojemann cortical stimulator; EMG response recorded	T3–7/juvenile pilocytic astrocytoma	No change in resection based on stimulation	Gross-total resection; transiently diminished proprioception
Case 2	Model OCS-1 Ojemann cortical stimulator; EMG response recorded	Cervicomedullary junction to C-4/juvenile pilocytic astrocytoma	Stimulation led to right upper-extremity EMG activity, which led to less aggressive resection	Persistent right upper-extremity weakness

FIG. 4. Artist's illustration of resection bed. Upon elevation of the nodule, stimulation mapping along the resection bed was also performed to ensure tract integrity. Copyright *The Neurosurgical Atlas*, Aaron A. Cohen-Gadol. Used with permission. Figure is available in color online only.

To our knowledge, the present report is the first description of mapping the spinal cord motor pathways in fine detail to allow identification of fiber components responsible for individual muscle groups. This increased resolution of mapping technique allows more precise identification of functional pathways controlling smaller but functionally as important muscle groups. Although not evaluated in our report, direct spinal cord microstimulation can potentially be used to further assess the integrity of motor pathways if deterioration in TceMEPs is noted intraoperatively. These 2 monitoring modalities can synergistically provide valuable information regarding the status of corticospinal tracts.

Conclusions

High-resolution mapping of the spinal cord motor path-

FIG. 5. **Upper:** Artist's illustration showing the areas where stimulation of the tumor along its left upper quadrant attachments resulted in intense left foot responses. **Lower:** Intraoperative photograph demonstrating the small piece of the tumor (T) left behind. Copyright *The Neurosurgical Atlas*, Aaron A. Cohen-Gadol. Used with permission. Figure is available in color online only.

ways using direct fiber stimulation may improve the safety of intramedullary tumor resection.

Acknowledgments

We sincerely appreciate the assistance of Bryan Faust, BSEE/AMT, REP T, CNIM, and James Leuck, BA, REEG/EP T, CNIM, in preparation of this manuscript.

References

1. Duffau H, Lopes M, Sichez JP, Bitar A, Capelle L: A new device for electrical stimulation mapping of the brainstem and spinal cord. **Minim Invasive Neurosurg** **46**:61–64, 2003
2. Jallo GI, Kothbauer KF, Epstein FJ: Intrinsic spinal cord tumor resection. **Neurosurgery** **49**:1124–1128, 2001
3. Kothbauer KF: Intraoperative neurophysiologic monitoring for intramedullary spinal-cord tumor surgery. **Neurophysiol Clin** **37**:407–414, 2007
4. Morota N, Deletis V: The importance of brainstem mapping in brainstem surgical anatomy before the fourth ventricle and implication for intraoperative neurophysiological mapping. **Acta Neurochir (Wien)** **148**:499–509, 2006
5. Quiñones-Hinojosa A, Gulati M, Lyon R, Gupta N, Yingling C: Spinal cord mapping as an adjunct for resection of intramedullary tumors: surgical technique with case illustrations. **Neurosurgery** **51**:1199–1207, 2002
6. Quiñones-Hinojosa A, Lyon R, Du R, Lawton MT: Intraop-

erative motor mapping of the cerebral peduncle during resection of a midbrain cavernous malformation: technical case report. **Neurosurgery** **56** (2 Suppl):E439, 2005

Author Contributions

Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Cohen-Gadol. Study supervision: Cohen-Gadol.

Supplemental Information

Video

Video 1, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-national/spine14-74_video_1.asx.

Video 1, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/spine14-74_video_1.mov.

Correspondence

Aaron A. Cohen-Gadol, Goodman Campbell Brain and Spine, Indiana University Department of Neurosurgery, 355 W. 16th St., Ste. 5100, Indianapolis, IN 46202. email: acohenmd@gmail.com.