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Intraoperative changes in transcranial motor evoked potentials and somatosensory evoked potentials predicting outcome in children with intramedullary spinal cord tumors

Clinical article

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Object. Intraoperative dorsal column mapping, transcranial motor evoked potentials (TcMEPs), and somatosensory evoked potentials (SSEPs) have been used in adults to assist with the resection of intramedullary spinal cord tumors (IMSCTs) and to predict postoperative motor deficits. The authors sought to determine whether changes in MEP and SSEP waveforms would similarly predict postoperative motor deficits in children.

Methods. The authors reviewed charts and intraoperative records for children who had undergone resection for IMSCTs as well as dorsal column mapping and TcMEP and SSEP monitoring. Motor evoked potential data were supplemented with electromyography data obtained using a Kartush microstimulator (Medtronic Inc.). Motor strength was graded using the Medical Research Council (MRC) scale during the preoperative, immediate postoperative, and follow-up periods. Reductions in SSEPs were documented after mechanical traction, in response to maneuvers with the cavitation ultrasonic surgical aspirator (CUSA), or both.

Results. Data from 12 patients were analyzed. Three lesions were encountered in the cervical and 7 in the thoracic spinal cord. Two patients had lesions of the cervicomedullary junction and upper spinal cord. Intraoperative MEP changes were noted in half of the patients. In these cases, normal polyphasic signals converted to biphasic signals, and these changes correlated with a loss of 1–2 grades in motor strength. One patient lost MEP signals completely and recovered strength to MRC Grade 4/5. The 2 patients with high cervical lesions showed neither intraoperative MEP changes nor motor deficits postoperatively. Dorsal columns were mapped in 7 patients, and the midline was determined accurately in all 7. Somatosensory evoked potentials were decreased in 7 patients. Two patients each had 2 SSEP decreases in response to traction intraoperatively but had no new sensory findings postoperatively. Another 2 patients had 3 traction-related SSEP decreases intraoperatively, and both had new postoperative sensory deficits that resolved. One additional patient had a CUSA-related SSEP decrease intraoperatively, which resolved postoperatively, and the last patient had 3 traction-related sensory deficits and a CUSA-related sensory deficit postoperatively, none of which resolved.

Conclusions. Intraoperative TcMEPs and SSEPs can predict the degree of postoperative motor deficit in pediatric patients undergoing IMSCt resection. This technique, combined with dorsal column mapping, is particularly useful in resecting lesions of the upper cervical cord, which are generally considered to be high risk in this population. Furthermore, the spinal cord appears to be less tolerant of repeated intraoperative SSEP decreases, with 3 successive insults most likely to yield postoperative sensory deficits. Changes in TcMEPs and SSEP waveforms can signal the need to guard against excessive manipulation thereby increasing the safety of tumor resection.

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KEY WORDS • pediatric • spinal cord tumor • neuromonitoring • transcranial motor evoked potential • dorsal column mapping • spine

INTRAMEDULLARY spinal cord tumors (IMSCTs) account for 4%–6% of all pediatric CNS tumors, with an incidence of less than 1 case in 100,000 persons.^{5,8,13} Symptom onset is insidious and commonly includes weakness,

paresthesias, and bowel and bladder dysfunction.^{5,13,44} Most commonly, these tumors involve the cervical and thoracic cord.^{13,19} Low-grade astrocytomas are the most common pathological type, accounting for 60% of cases.^{10,14,45} Resection is the initial step in the management for IMSCTs followed by adjuvant therapy in some cases.^{5,13,15,16,18,33}

Abbreviations used in this paper: CUSA = cavitation ultrasonic surgical aspirator; IMSCt = intramedullary spinal cord tumor; MRC = Medical Research Council; SSEP = somatosensory evoked potential; TcMEP = transcranial motor evoked potential.

This article contains some figures that are displayed in color online but in black-and-white in the print edition.

The most significant risk associated with surgery for IM SCTs is spinal cord injury and a resulting neurological deficit. Electrophysiological monitoring is an important tool intended to eliminate or reduce this surgical risk.^{12,21,36} To date, both somatosensory evoked potential (SSEP) and transcranial motor evoked potential (TcMEP) monitoring techniques have been used.^{5,10,36,43} Somatosensory evoked potentials provide information regarding the function of sensory pathways, whereas TcMEPs provide a direct means of monitoring the descending motor pathways. However, motor and sensory pathways may be affected differently depending on tumor location, and other studies have shown significant postoperative motor deficits despite normal SSEPs throughout a case.^{2,31,41,55} Not surprisingly, TcMEPs are less reliable at predicting postoperative paresthesias and sensory disturbances.^{4,9,22,36} While both motor and sensory systems affect postoperative outcome, several studies have shown that motor function predicts quality-of-life measures more reliably than sensory function.^{23,24,30,33,37,42}

Transcranial MEP monitoring begins with multiple transcranial stimulations of the motor cortex and recording the signal either in the epidural space at the surgical site or from needle electrodes placed in the extremities. These recordings are then analyzed throughout the case for changes in amplitude, baseline threshold, or waveform to determine possible spinal cord injury.^{4,22,32,35,43}

Prior studies have shown significant correlations between TcMEP waveform changes and postoperative motor deficits.^{29,43} As described in another study, TcMEP signals recorded from muscle can be separated into 3 categories: polyphasic, biphasic, and absent. Degradation from polyphasic to biphasic signals reliably predicted a decrease of 1–2 points in the motor score. This signal change correlated with an increase in the average voltage threshold of 175 mV. Other studies have examined the use of TcMEP amplitude changes to guide intraoperative decisions during both intracranial and spinal surgery.^{43,50,51} Using a threshold of an 80% amplitude decrease based on the average amplitude of multiple stimulations, Lang et al.²⁸ did not find this decrement to be predictive of postoperative deficits. Other studies utilizing an “all or none” threshold could not reliably predict motor deficits either.^{7,17,20,21,26–28,36,43,46,50} A related technique, D-wave monitoring, uses 1 stimulation instead of a short train and specifically records from fast conducting fibers in the corticospinal tract. A more than 50% decrease in amplitude is reported to correlate with postoperative motor deficits.⁵² When used in combination with TcMEP recording, D-wave monitoring is a robust measure of motor function. However, D-wave monitoring is less reliable in the upper cervical cord, where the complexity of hand and arm intrinsic fibers complicates monitoring.

Given these findings, we wanted to investigate whether TcMEPs and SSEPs would similarly predict postoperative motor function in a pediatric population. We also sought to assess the utility of dorsal column mapping in children.

Methods

Patient Characteristics

From our pediatric database we obtained records on

all consecutive patients who had undergone surgery between 1995 and 2003 at a single institution (University of California, San Francisco) and in whom TcMEP and SSEP monitoring methods had been used. The medical records were retrospectively reviewed and abstracted to identify the following data: demographic information, clinical evaluations, operative details, and final pathological diagnosis. A qualified electrophysiologist blinded to the clinical data independently reviewed the intraoperative SSEP and TcMEP recording data. Physical examinations with motor grade evaluations (0–5) were performed preoperatively, on postoperative Day 1, at the time of discharge, and on all subsequent follow-up visits. All data were collected after we had obtained approval from the Committee for Human Research at the University of California, San Francisco.

Anesthesia

Desflurane (2.5%–3.5%) was maintained at less than one-half the minimum alveolar concentration with a continuous infusion of propofol (50–75 µg/kg/min). Additionally, bolus infusions of remifentanyl or fentanyl were used as needed, guided by blood pressure and heart rate. After inducing anesthesia and intubating the patient, we allowed the paralytic agents to wear off and ceased their use. Just prior to myelotomy, the propofol infusion was increased to 75–120 µg/kg/min and the desflurane concentration was reduced to below 2%. The goal mean arterial pressure was greater than 80 mm Hg and aided with the use of pressors (most commonly phenylephrine) if required.

Dorsal Column Mapping

Dorsal column mapping was performed to determine the midline and to guide a safe myelotomy. Microstimulation was performed at the following settings: pulse rate 9.1 Hz, duration 200 µsec, initial current 3 mA, constant current ≤ 8 mA. Somatosensory evoked potential recordings during stimulation aided in determining the site for the myelotomy (Fig. 1).

Motor Grading

Motor strength was assessed using the standardized Medical Research Council (MRC) scale: Grade 5, muscle contracts normally against full resistance; Grade 4, muscle strength reduced but still moves joint against resistance; Grade 3, muscle contracts against gravity only; Grade 2, muscle contracts only with gravity removed; Grade 1, tracer or flicker movement observed in the muscle; and Grade 0, no muscle movement observed.

Recording SSEPs and TcMEPs

All patients underwent neuromonitoring of both SSEPs and TcMEPs during surgery. Monitoring was performed using the standardized techniques previously described.^{38–40,43} Briefly, a Digitimer D185 constant-voltage stimulator (Digitimer Ltd.) generated fixed-duration pulses of 50 µsec at an interval of 0.1–9.9 msec. Stimulating electrodes (Nicolet Biomedical Inc.) were placed overlying the primary motor cortex, and recording electrodes were placed intramuscularly in the extremities. Leads were placed in the thenar and hypothenar, tibialis

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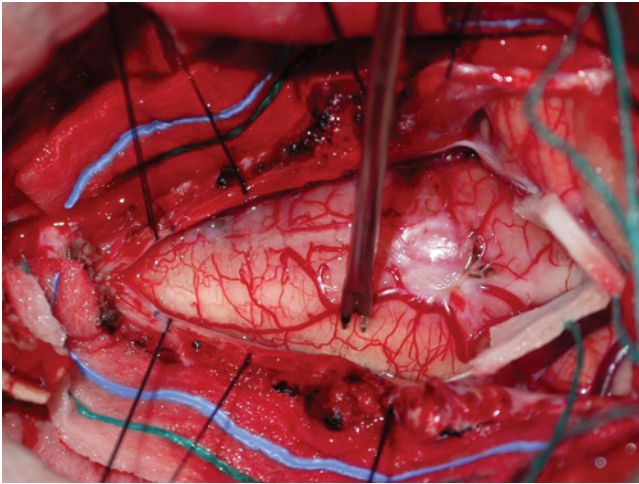


Fig. 1. Intraoperative photograph of dorsal column mapping with a microstimulator.

anterior, foot flexor, and extensor hallucis longus muscle groups. Initial stimulation to establish a recording baseline and threshold was performed after proper patient positioning. Somatosensory evoked potentials aided in identifying the myelotomy site and were continuously recorded throughout the procedure.

During the course of surgery, TcMEPs were obtained every 30 minutes prior to tumor resection and more frequently during tumor manipulation and resection. Intraoperative TcMEP testing was triggered after prolonged traction on the tumor, after ultrasonic aspiration, or after significant manipulation of the tumor capsule or spinal cord. A certified neuro-electrophysiologist continuously analyzed the electrophysiology data. Agreed-upon criteria for notifying the surgeon included an increase in baseline voltage of more than 100 mV or a significant change in the morphology and duration of the waveform. Waveforms were defined as polyphasic if they had more than 2 phases, biphasic if they had 1–2 phases, and absent if they had 0 phases (Fig. 2).

Results

Clinical Information

Twelve patients were included in our study, with an equal number of male and female patients and an average age of 8 years (range 2–14 years). Tumor locations included thoracic (7), cervical (3), and cervicomedullary junction (2). Final pathology included astrocytoma (6), ependymoma (2), ganglioglioma (2), oligoastrocytoma (1), and glioblastoma multiforme (1) (Table 1). The follow-up averaged 17 months (range 3–72 months).

Dorsal Column Mapping for Accurate Identification of the Midline

Dorsal column mapping was performed in 7 patients (28 extremities), 3 of whom had existing preoperative sensory deficits. Among these 3 were 1 patient with right hand paresthesias and proprioceptive sensory loss and 2 patients with just proprioceptive sensory loss. The midline of the spinal cord was accurately mapped in all 7 pa-

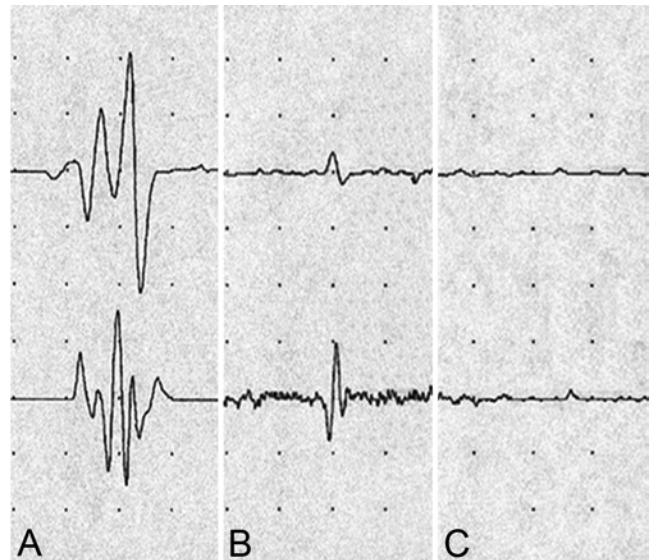


Fig. 2. Representative illustration of the 3 waveforms observed during tumor resection. Transition from polyphasic (A) to biphasic (B) or no signal (C) predicted postoperative motor deficits in all cases.

tients, and each of them had some form of SSEP change during tumor resection. The average time between the end of mapping and the appearance of SSEP changes was approximately 34 minutes.

Predicting Postoperative Motor Deficits With TcMEP Recordings

All 12 study patients underwent TcMEP recordings, and 6 of them had intraoperative changes. Among those with TcMEP changes, 4 had preoperative weakness (MRC Grade 3–4/5), while the remaining 2 had full strength (MRC Grade 5/5). The average baseline voltage was 330 ± 103 mV. Five of the 6 patients underwent transformation to biphasic waveforms, with an average reduction in MEP duration of $41\% \pm 11\%$ and an average increase in voltage of 156 ± 56 mV. Changes were observed in a unilateral lower extremity (3 patients), bilateral lower extremity (1 patient), and unilateral upper extremity (2 patients). Data in 1 patient with a ganglioglioma who had polyphasic to biphasic waveform changes are featured in Fig. 3. Additionally, 1 patient had complete loss of waveform in both lower extremities. In all cases, these intraoperative changes correlated with postoperative motor deficits (Table 2).

Specifically, TcMEP signal changes in all patients corresponded to immediate postoperative motor deficits assessed on postoperative Day 1 (Fig. 4). The patient in Case 4 with complete loss of TcMEP signal began with a preoperative MRC motor score of 3/5 and had an immediate postoperative score of 0/5. This grade improved to 1/5 at discharge and 2/5 at the last follow-up (8 months). The remaining 5 patients (Cases 1–3, 5, and 6) with biphasic waveforms all experienced a 1-point decrease in the motor score on postoperative examination. At the time of discharge, 2 of these patients (Cases 1 and 2) had improved motor function and 3 (Cases 3, 5, and 6) had no change. At the last follow-up, 2 patients (Cases 2 and 3) recovered to full strength, 1 (Case 1) had 4/5 strength,

TABLE 1: Summary of patient demographics and tumor type and location*

Case No.	Age (yrs), Sex	Level of Lesion	Pathological Diagnosis	Duration of FU (mos)
1	14, F	CMJ-C2	ganglioglioma	12
2	12, F	C1-3	astrocytoma	24
3	6, M	C2-4	astrocytoma	3
4	10, M	C4-7	ganglioglioma	8
5	11, M	C5-T4	astrocytoma	14
6	9, M	T1-3	GBM	6
7	9, F	T-2	ependymoma	6
8	2, M	T3-7	oligoastrocytoma	3
9	3, F	T3-7	astrocytoma	48
10	10, F	T5-8	astrocytoma	72
11	2, F	T7-9	astrocytoma	3
12	13, M	T7-L3	ependymoma	7

* CMJ = cervicomedullary junction; FU = follow-up; GBM = glioblastoma multiforme.

and 2 (Cases 5 and 6) had residual deficits similar to those at their discharge examination. Comparing follow-up exams, we noted a trend toward improvement in motor grade, but the comparison was not statistically significant. The 6 patients who demonstrated no signal changes intraoperatively also had no change in motor scores at the postoperative evaluation and follow-up (data not shown).

Postoperative Sensory Deficits Predicted by Frequency and Cause of SSEP Changes

Transcranial MEP and SSEP monitoring was performed simultaneously. Of the 12 study patients, 7 experienced intraoperative decreases in SSEPs (Table 3). In these instances, we attempted to attribute the cause to traction

or cavitation ultrasonic surgical aspirator (CUSA)-related events. In 5 patients, SSEP changes occurred because of traction. After the preliminary decrease in SSEPs, the signals returned completely to baseline after traction was released. Following a second episode of traction with SSEP changes, the SSEPs returned to 75%–80% of baseline over minutes once traction was released. Two patients had 3 traction-induced SSEP decreases intraoperatively, and signals returned to approximately 25%–35% of baseline over minutes to hours. These patients had new sensory deficits postoperatively, which ultimately resolved (3 and 8 months, respectively). One patient had diminished SSEPs with the use of the CUSA, which returned to 75% of baseline over minutes. This patient had worsening of a preoperative par-

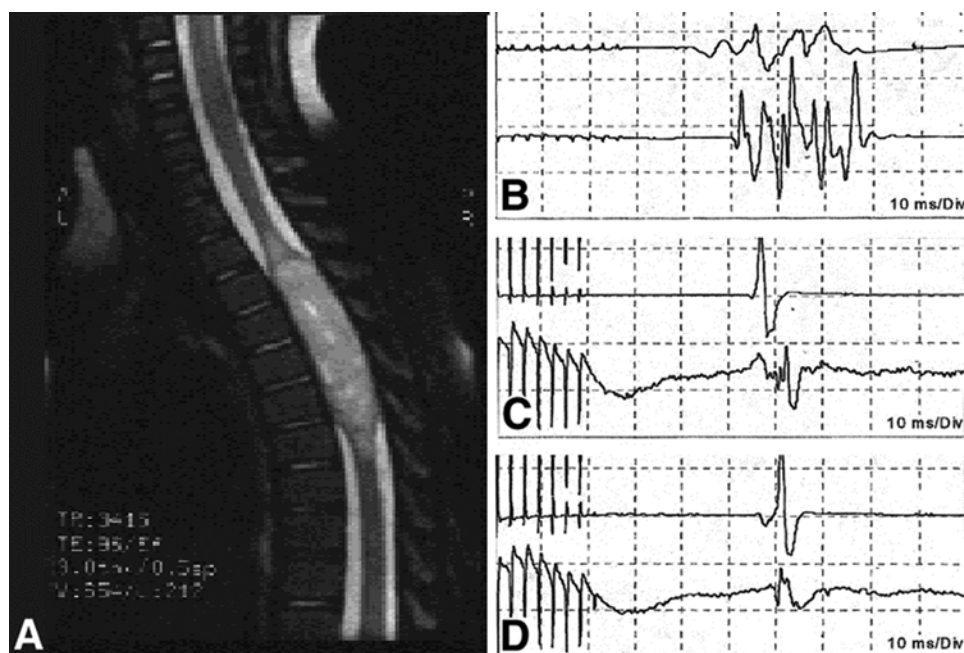


FIG. 3. Representative case of an intramedullary thoracic tumor (A) with intraoperative TcMEP waveform degradation from polyphasic (B) to biphasic signal (C and D). Linear correlation of the percent change in MEP signal versus the change in motor grade on postoperative Day 1 ($p < 0.001$, $R^2 = 0.8533$).

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TABLE 2: Patients with TcMEP waveform changes intraoperatively along with corresponding voltage changes (V) and motor grades as assessed postoperatively, at discharge, and at follow-up*

Case No.	Extremity	MEP Final Waveform	Percent Reduction in MEP Duration	Voltage (mV)		MRC Motor Grade (0–5)			
				Baseline	Increase	Preop	Postop	Discharge	FU
1	RUE	biphasic	36	300	125	3	2	4	4
2	LLE	biphasic	33	400	125	5	4	5	5
	RLE	biphasic	58	400	150	5	1P; 4D	4	5
3	LUE	biphasic	27	175	100	5	4+	4+	5
4	LLE	loss	100	475	150	3	0	1	2
	RLE	loss	100	475	125	3	0	1	2
5	LLE	biphasic	55	250	275	4	3	3	4P; 2–3D
	RLE	biphasic	48	250	225	4	3	3	4P; 2–3D
6	RLE	biphasic	31	250	125	4	3	3	4P; 3D

* D = distal extremity; LLE = left lower extremity; LUE = left upper extremity; P = proximal extremity; RLE = right lower extremity; RUE = right upper extremity.

esthesia, which resolved over 24 months. One patient had 1 CUSA-related and 3 traction-related decreases in SSEPs intraoperatively. This patient had new postoperative paresthesias that did not resolve.

Postoperative surgical outcomes included gross-total resection in 3 (25%) of 12 patients and subtotal resection in the 9 (75%) of 12. Three patients went on to have combined radiation and chemotherapy, and 1 each had radiation or chemotherapy alone. Four patients had preoperative paresthesias that were unchanged after surgery, 2 had resolution, and 2 had new paresthesias (Table 4).

Discussion

Our study consists of a small cohort of 12 patients who underwent resection of an IMSCT. All patients underwent monitoring of both TcMEPs and SSEPs, and intraoperative changes were correlated with postoperative and follow-up neurological examinations. Moreover, 7 patients also underwent dorsal column mapping, a technique well described in adults but not in children.

Historically, SSEPs preceded TcMEPs as a means of monitoring and were initially used to monitor both sensory and motor pathways. Not surprisingly, SSEP changes were not effective in predicting postoperative motor deficits. Transcranial MEPs were developed to directly measure the integrity of the corticospinal tract by stimulating primary motor cortex and recording distally with either an epidural electrode or needle electrodes embedded in target muscles. The stimulation parameters vary, but most often involve multipulse stimulations 4 msec apart. Unlike with SSEPs, TcMEP stimulation trains are not averaged and provide a more rapid feedback. Efforts to reliably correlate signal loss with postoperative deficits using epidural electrodes have been met with limited success primarily because of the variability in placing and locating the distal electrode.^{1,26,36,49}

To avoid the limitations of epidural recording, peripheral electrodes can be placed in the target muscles of interest.^{25,26} This technique allows for direct recording at the neuromuscular junction, the end point of the corticospinal circuit. In addition to its improved signal

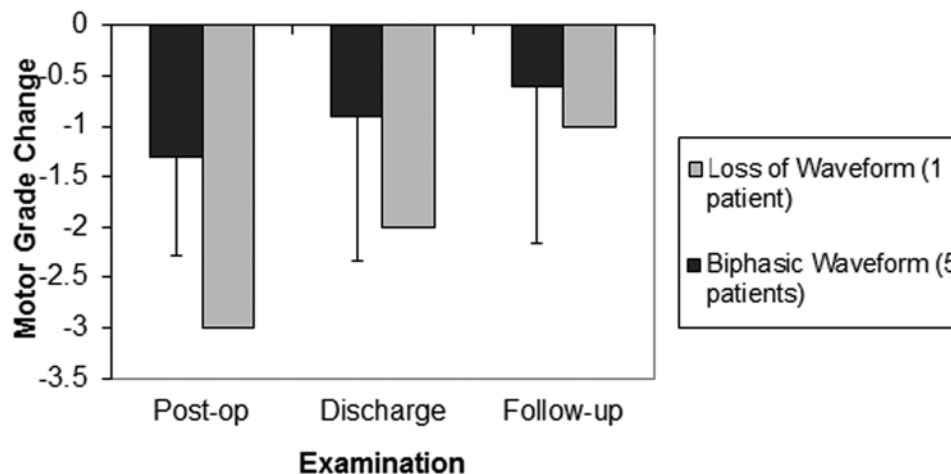


Fig. 4. Six patients demonstrated TcMEP signal changes intraoperatively. Among these patients, 1 had complete loss of waveform, whereas 5 changed to biphasic signals. Changes in motor grade are depicted at the postoperative, discharge, and last follow-up evaluation.

TABLE 3: Decreases in somatosensory evoked potentials as a result of traction or dissection with CUSA*

Insult	No. of Pts	Outcome
1 or 2 SSEP changes: traction	3	3 pts w/o new sensory findings
3 SSEP changes: traction	2	1 pt w/ new paresthesia, resolved (8 mos) 1 pt w/ new paresthesia, resolved (3 mos)
≥1 CUSA injury	1	1 pt whose preop paresthesia worsened, resolved (24 mos)
CUSA injury + 3 SSEP changes	1	1 pt w/ new paresthesia, no resolution

* pt(s) = patient(s).

acquisition, this technique also allows for the visual assessment of muscle and limb twitches during stimulation. While this makes it necessary to temporarily suspend resection, the results are unambiguous. Additional advantages of muscle TcMEPs include the ability to monitor all 4 extremities and individual muscle groups. This is particularly useful when a patient has preoperative deficits, as those muscle groups are the most likely to be affected during resection. However, muscle recordings are not without limitations, and the importance of preoperatively communicating with the pediatric anesthesia team to select the correct anesthetic agents without the use of paralytics is paramount to successful monitoring.

In this study, 6 (50%) of 12 patients experienced TcMEP changes intraoperatively, which correlated with motor deficits in the immediate postoperative period. A change from polyphasic to biphasic waveforms predicted, on average, a 1-point decrease in motor grade. The one patient with a complete loss of signal had a 3-point drop to 0, which improved to a score of 2/5 at the last follow-up. These waveform changes guided the resection strategy by favoring a less aggressive approach after such changes occurred. Most patients recovered some or all of their motor function during the follow-up evaluation.

D-wave recordings, which are closely related to TcMEPs, also rely on cortical stimulation but only through a single stimulus event. The amplitude of the muscle re-

sponse (D-wave) is measured.^{52,53} Previous studies have specifically examined D-wave amplitude changes and have shown that a 50% decrease reliably predicts postoperative motor deficit.³⁶ While informative, D-waves are not perfect. In some patients with preexisting deficits, D-waves are not recordable, and signal responses are only captured after multitrain stimulation—in essence, after multiple D-waves. Furthermore, amplitude changes alone do not test the full length of the corticospinal tract, and circuits distal to the recording can be disrupted but not detected during monitoring. Lastly, early plasticity of neural pathways in children has been considered an additional explanation for unreliable signal reproducibility.³⁶ In our small study, D-wave monitoring was not performed.

To better understand postoperative sensory deficits as they relate to intraoperative events, we recorded SSEPs in all of the patients. Somatosensory evoked potential events—related to traction, to dissection with an ultrasonic aspirator, or to both—occurred in 7 patients. Previous larger studies in adults have demonstrated significant correlations between incremental decreases in SSEPs related to traction and postoperative paresthesias.⁴³ Changes in SSEPs related to traction followed a predictable pattern of three changes, or “strikes,” in our series. Each strike appeared to result in an increased recovery time. The first decrease showed complete resolution with the release of traction. The second decrease to 75%–80% of baseline

TABLE 4: Operative characteristics, including extent of resection and adjuvant therapy, and postoperative sensory findings*

Case No.	Extent of Resection	Radiation Treatment	Chemotherapy Treatment	Change in Motor Grade	Sensory Findings
1	GTR	N	N	-1	NA
2	STR	N	N	0	NA
3	STR	Y	Y	0	unchanged paresthesia
4	STR	N	N	-1	resolved paresthesia
5	GTR	Y	N	-2	unchanged paresthesia
6	STR	Y	Y	0	NA
7	GTR	N	N	0	unchanged paresthesia
8	STR	N	Y	0	unchanged paresthesia
9	STR	Y	Y	0	new paresthesia
10	STR	N	N	0	new paresthesia
11	STR	N	N	+1	NA
12	STR	N	N	+1	resolved paresthesia

* GTR = gross-total resection; N = no; NA = not available; STR = subtotal resection; Y = yes.

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showed a slower recovery over minutes. The third decrease showed an even slower recovery (minutes to hours) and returned to only 25%–35% of baseline. Intraoperatively increasing blood pressure did not speed recovery time or slow SSEP changes. In cases of hypotension, however, the restoration of blood pressure did aid in recovery. In our experience, the release of traction most reliably improved SSEP changes.

In contrast, an SSEP decrease directly attributable to tumor aspiration typically resulted in a 75% loss of signal and slow recovery. A combination of both 3 strikes and a CUSA injury produced the worst outcome with a new, persistent sensory deficit that did not resolve. Taken together, these findings suggested that traction-related SSEP changes could be tolerated in children up to a point of 3 strikes. This is a useful guideline given that some degree of traction is necessary for tumor removal and that surgeons frequently arrive at a crossroads of overly aggressive resection and preservation of neurological function at the expense of leaving residual tumor. Furthermore, given the choice between blunt dissection plus traction and dissection with an aspirator for tumor removal, data in the present study suggested that the latter is less forgiving.

To aid in the myelotomy, we successfully performed dorsal column mapping in 7 patients. While well documented and shown to improve outcomes in adults, dorsal column mapping in children, to our knowledge, has not been described, and the present study is the first to describe as much in the pediatric population.³⁴ In our series, the column maps provided valuable intraoperative confirmation of the midline and the location for a safe myelotomy. No column maps yielded erroneous information, and mapping appears to be as worthwhile and informative an adjunct in children as in adults. The time to an SSEP change after myelotomy was, on average, 34 minutes in children, which may represent increased accuracy of the midline by using this technique in children, although times in adults are not well studied.^{34,54} It is also possible that the SSEP changes ultimately noted are in fact attributable to tumor traction or resection and not to excessive lateralization of the myelotomy. Additionally, a new technique of SSEP phase-reversal monitoring after gracile tract stimulation may provide additional utility in dorsal column mapping and further refine the location and technique.⁴⁸

Predictors of good outcome after IMSCT resection remain elusive even in adults. Factors associated with improved outcomes in adults include the presence of a tumor plane, tumor size, the use of neuromonitoring, and postoperative radiation therapy.^{6,11,12} However, significant differences in tumor histology, presentation, and character of neurological deficits in children, as compared with adults, makes extrapolation from adult studies difficult.^{12,16,47} In our small study, it was notable that all children with significant postoperative neurological deficits had tumors in the cervical cord (Table 3). While a larger study would be required to conclusively determine the relationship among tumor location, size, histology, and outcome, these variables may play important roles in determining outcomes.

Successfully differentiating true intraoperative TcMEP and SSEP changes from false-positives remains an

art for the skilled practitioner. In the absence of technical or physiological explanations for signal change, we posit that all signal changes should be treated as true events. In our study, we did not encounter any false-positive TcMEP waveform changes, and all patients in the study with a change from polyphasic to biphasic or loss of signal all had postoperative motor deficits. In these instances, we err toward preserving motor function at the expense of achieving gross-total resection. With regard to SSEPs, our findings remain consistent with those in adults. Up to 2 discrete SSEP signal changes attributable to traction appear to be well tolerated, but a third traction event or a CUSA-related event will probably precipitate postoperative sensory deficits. Our approach to SSEP changes remains unchanged from our strategy in adults: after the first strike, proceed with caution; and after the second strike, consider resecting only accessible tumor or aborting the procedure altogether. However, there are instances, most notably with hemangioblastomas, in which leaving residual tumor may pose an even greater risk to the patient than continuing with resection. In such instances, the risks and benefits must be weighed carefully and ideally discussed with the patient and family prior to surgery.

The major limitations of our study are its retrospective nature and small sample size. Several patients received adjuvant therapy, which may have altered the motor examination on follow-up clinic visits. An additional weakness of our study is that D-waves were not directly measured. D-waves represent the direct activation of axons in the corticospinal tract and are the initial sequence of MEP responses after stimulation. Decreases in D-wave amplitude of more than 50% have been shown to predict postoperative motor deficits.^{3,36,52} When used in conjunction with muscle MEPs, D-waves may change independently of MEPs, and it has been postulated that D-wave changes correspond to potentially permanent motor deficits, whereas MEP changes correlate more with temporary deficits. A situation in which MEP changes occurred without D-wave alterations might represent a threshold at which decreased surgical manipulation and resection would be prudent before the onset of irreversible injury.²⁶ In future studies we intend to combine D-wave analysis with muscle MEPs to better guide intraoperative resection and functional preservation.

Conclusions

In this study we examined the relationship between intraoperative neurophysiological signal changes and postoperative motor and sensory examinations. We demonstrated that all patients with decreased waveform complexity experienced at least a 1-point decrease in motor score in the immediate postoperative period, with good recovery on subsequent follow-up. We also determined a possible threshold for traction during tumor resection, as evidenced by somatosensory recordings. Finally, we illustrated how dorsal column stimulation can assist in mapping the pediatric spinal cord with accuracy. These findings suggest that intraoperative neurophysiology is a useful tool to guide surgical approaches and tumor resection in children.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Cheng, Stapleton, Quinones-Hinojosa, Gupta, Auguste. Acquisition of data: Cheng, Stapleton, Auguste. Analysis and interpretation of data: Cheng, Stapleton, Auguste. Drafting the article: Cheng. 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: Cheng. Statistical analysis: Cheng. Study supervision: Gupta, Auguste.

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