Threshold-level repetitive transcranial electrical stimulation for intraoperative monitoring of central motor conduction

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Object. The authors conducted a study to evaluate repetitive transcranial electrical stimulation (TES) to assess spinal cord motor tract function in individuals undergoing spine surgery, with emphasis on safety and efficacy.

Methods. Somatosensory evoked potentials (SSEPs) were elicited using standard technique. Muscle electromyographic values were measured in response to a three- or four-pulse train of stimulation delivered to the motor cortex via subdermal electrodes. They also evaluated whether changes in the minimum stimulus intensity (that is, threshold level) needed to elicit a response from a given muscle predict motor status immediately postoperatively, as well as whether changes in SSEP response amplitude and latency predict sensory status immediately postoperatively. Anesthesia was routinely induced with intravenous propofol and remifentanil, supplemented with inhaled nitrous oxide. Use of neuromuscular block was avoided after intubation.

Satisfactory monitoring of muscle response to threshold-level repetitive TES was achieved in all but nine of the 194 patients studied. In contrast, cortical SSEP responses could not be elicited in 42 of 194 individuals. In cases in which responses were present, TES-based evoked responses proved to be extremely accurate for predicting postoperative motor status. Somatosensory evoked potential monitoring was nearly as accurate for predicting postoperative sensory status. There were frequent instances of postoperative motor or sensory deficit that were not predicted by SSEP- and TES-based monitoring, respectively. There were no adverse events attributable to TES-based monitoring, although since this study ended we have had a single adverse event attributable to threshold-level repetitive TES.

Conclusions. Intraoperative threshold-level repetitive TES–based monitoring of central motor conduction has proven to be a simple, safe, and highly accurate technique for the prevention or minimization of inadvertent motor deficit during surgery involving the spine or spinal cord.

Key Words • intraoperative monitoring • evoked potential • electromyography • repetitive transcranial electrical stimulation
Clinical Material and Methods

All patients in whom intraoperative threshold-level repetitive TES monitoring was performed underwent surgery in which the cauda equina, spinal cord, and/or brainstem were considered, based on the opinion of the attending surgeon, to be at risk. A total of 194 procedures were performed in which threshold-level repetitive TES monitoring was used. There were 110 male patients who ranged in age from 9 to 83 years (average age 50.1 ± 17.2 years; average age ± standard deviation) and 84 female patients who ranged in age from 9 to 89 years (50.7 ± 19.6 years). Reasons for surgery included tumor resection (103 cases), spinal cord untethering (46 cases), correction of orthopedic abnormality (37 cases), and correction of vascular abnormality (eight cases).

All patients gave their informed consent to participate in this research protocol, which was approved by the University of Miami’s Institutional Review Board. Approval from the United States Food and Drug Administration to use the Digitimer D185 stimulator (Digitimer Ltd., Hertfordshire, UK) was granted to Dr. Calancie (Investigational Device Exemption #G890040/S12). As part of the informed consent procedure, we warned potential patients that risks of their participation included: 1) seizure; 2) skin burn from stimulating electrodes; 3) infection from needle recording or stimulating electrodes; and 4) inadvertent neural injury caused by TES-induced patient movement at a time when a surgical instrument was being used within or against the brainstem, spinal cord, or nerve roots.

Anesthesia Induction Protocol

Following a preliminary administration of 2 to 3 mg midazolam in the average patient, general anesthesia was induced with 1.4 to 2.5 mg/kg propofol, 0.95 to 1 μg/kg remifentanil, and an intermediate-duration nondepolarizing muscle relaxant. After laryngoscopy and insertion of an endotracheal tube, anesthesia was maintained with nitrous oxide (60–65%) and infusions of 0.124 to 0.375 μg/kg/min remifentanil and 25 to 200 μg/kg/min propofol. No additional muscle relaxants were given, and isoflurane, if used at all, was discontinued. The patients were positioned following application of the Mayfield head holder. Anesthesia was deepened for the positioning by adjusting the propofol and remifentanil infusion rates.

Recording and Stimulation

Eight-channel muscle EMG was typically performed in all cases, with pairs of 0.5-in stainless steel electroencephalographic-type electrodes placed subcutaneously approximately 2 to 4 cm apart, which were positioned over (or in, depending on the amount of adipose tissue present) the target muscle. The one exception to this placement method was in the case of hand intrinsic muscles, in which one needle electrode was placed over/in the thenar group (that is, at the base of the thumb) and the second needle electrode was positioned over/in the hypothenar muscle group (that is, alongside metacarpal V). Hand intrinsic EMG monitoring was always performed, regardless of the site of surgery. For surgical procedures in the spine inferior to the T-1 level, monitoring of hand intrinsicss was used to confirm proper stimulator function and anesthesia compatibility. Determination of which other muscles to monitor was based on the site of surgery. In cases of the brainstem or cervical spine, biceps, wrist flexors, and foot intrinsicus (abductor hallucis muscle) were typically monitored; in cases of the thoracic or thoracolumbar spine, quadriceps, tibialis anterior, and foot inferences were typically monitored. An additional factor that helped determine which muscles were monitored was whether nerve roots of the cervical or thoracolumbar enlargements might be at risk of mechanical irritation by the surgical procedure (for example, during foraminotomies), such that monitoring of spontaneous EMG would be advantageous during nerve root decompression. Filtering of EMG signals was typically 100 to 3000 Hz, and gain (“sensitivity”) was adjusted from 50 to 1000 μV/division.

Somatosensory evoked responses were recorded from needle electrodes positioned 1 cm posterior to C-3 and C-4 (for median nerve stimulation) or at central midline (for posterior tibial nerve stimulation), with all sites referenced to a needle electrode at frontoparietal midline. Filtering was typically 10 to 1000 Hz, and stimulus intensities were approximately 45 mA and 85 mA for median and posterior tibial nerves, respectively. Stimulus pulse durations for SSEP monitoring were always 200 μsec.

Transcranial stimulation was delivered through corkscrew-type needle electrodes placed under the scalp at C-3 and C-4 (surface electrodes were used in preliminary studies, as described previously). A constant-voltage stimulator (Digitimer D185) was used at all times for threshold-level repetitive TES monitoring. In early studies we used a D185 with a single-turn knob for adjusting output voltage, whereas in later cases we used a D185 modified with a 10-turn voltage knob, making it easy to preset stimulus intensity to within plus or minus 2-V values. Stimulus intensity and the number of pulses in the pulse train varied (see next section), but all stimulus pulse durations were fixed at 50 μsec.

An eight-channel evoked potential device (Excel; Cadwell Laboratories Inc., Kennewick, WA) was used for all SSEP monitoring, and for all but the most preliminary cases of TES monitoring as well. The Digitimer D185 output was triggered by the Excel device for synchronizing stimulus delivery with the Excel’s data-capture and display functions.

Determination of TES-Evoked Thresholds

The stimulus intensity (measured in volts) needed to elicit a minimum evoked EMG response (that is, the threshold response) from each of the muscles being monitored served as the primary outcome measure of this approach. During initial studies, all threshold determinations were made with a stimulus pattern of three pulses, separated from one another by a 2-msec interval. Over time, we revised this strategy slightly; if the patient had preexisting weakness, we used four pulses delivered at 2-msec or four pulses delivered at 3-msec intervals to establish initial (baseline) threshold values.

For determination of baseline thresholds, the initial voltage used was typically 100 V. A single stimulus train (that is, three pulses at 2-msec intervals) was delivered be-
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between C-3 and C-4, the records saved, the stimulator polarity reversed and the stimulus repeated. Because we did not use signal averaging to resolve EMG responses, this process required as little as 2 seconds. Unless all eight muscles being monitored responded at this weak intensity (which occurred rarely, in practice), the voltage was increased in increments until all muscles responded to TES. An initial increment of 25 V (to 125 V total) was used, stimuli were delivered, and the process repeated for stimuli of 150 V intensities, beyond which voltages were increased in increments of 50 V, to a maximum of 500 V.

When a muscle response was first elicited, the voltage necessary to elicit that response was noted on a worksheet, and it served as the value against which subsequent threshold determinations for that particular muscle were compared. In cases in which the threshold for all muscles placed at risk by the surgical procedure (that is, the “target” muscles) were within 50 V of one another, we simply set the voltage to the highest threshold and monitored all muscles simultaneously with that stimulus intensity. That is, we only repeated the systematic determination of thresholds on a limited basis, in the absence of a fundamental change in the evoked waveform appearances, such as a pronounced reduction in amplitude. Under these circumstances, bilateral testing and interpretation of central motor conduction to multiple upper and lower limb motor neuron pools was, for all practical purposes, immediate.

Criteria for Intraoperative Warnings

For SSEP monitoring, we warned the surgical team when the averaged SSEP response amplitude declined by 50% or more from baseline value or when the latency to the initial major deflection in waveform (N19 and P37 for stimulation of median and posterior tibial nerves, respectively) increased by more than 10% from baseline latency. For TES monitoring, we warned the surgical team in the event that a given muscle’s threshold increased by 100 V or more (provided the number of pulses in a train was unchanged). For both SSEP and TES monitoring, substantive alterations in anesthetic delivery or mean arterial blood pressure, which might account for deviations from intraoperative baselines, were ruled out prior to warning the surgical team.

Follow-Up Course

Detailed sensory and motor clinical follow-up examination was performed in the initial 34 patients in this study by physical therapists blinded to the surgical procedure or intraoperative findings.3 Emphasis was placed on the patient’s clinical condition within the first 24 hours of surgery. In the next 49 consecutive subjects, postoperative clinical outcome was assessed within 24 hours by: 1) a combination of interview and physical examination (31 patients); and 2) by interview and chart review when assessment was not possible within 24 hours of surgery (18 patients). Values of sensitivity and specificity of the two intraoperative monitoring techniques are based on these combined populations. The technician who performed the TES monitoring was responsible for noting the nature and severity of any adverse events caused by this technique during the surgical procedure.

Results

Of the 194 surgical procedures in which threshold-level repetitive TES was performed, responses from at least one of the target muscles were obtained in 185 of the patients at some point during monitoring. No responses from any of the target muscles (that is, those muscles innervated by central motor tracts at risk from the surgical procedure) were evident at any time during the surgical procedure in nine patients, although responses to TES were seen in muscles innervated at levels cranial to the spinal cord region in which surgery was being performed in eight of these nine cases.

The success rate for obtaining motor responses to TES. Somatosensory evoked potentials could not be resolved for either side of stimulation in 42 of the 194 patients. It is unlikely that anesthetic considerations could account for more than a fraction of these cases in which SSEPs were absent because the TES protocol called for the avoidance of halogenated agents such as isoflurane altogether. We did not routinely monitor noncerebral evoked potentials because many of the procedures involved the cervical spine (86 cases) or brainstem (four cases); available amplifier channels were instead dedicated to EMG monitoring.

There were eight cases in which baseline TES-evoked responses were absent in all target muscles but then emerged as the surgical procedure progressed; all involved thoracic or thoracolumbar surgical procedures. Improvement in SSEP responses (from absent at baseline to present by the conclusion of surgery) was noted in two cases.

There were 145 cases in which both SSEPs and TES-evoked responses in target muscles were demonstrated at baseline monitoring. Table I provides a summary of these cases in which significant alterations were seen in either SSEP records, target muscle TES-evoked stimulus thresholds, or both. In the majority of cases, these two parameters paralleled each other, either both remaining unchanged (87 cases), or both deteriorating (23 cases).

Of particular interest were those cases in which one parameter changed by a significant amount while the other remained within baseline limits. Such a deterioration was more common for SSEP values. Significant deterioration in SSEP parameters in the absence of target muscle threshold changes was observed in 22 patients, whereas the converse was true in 13 patients (target muscle threshold increased despite stable SSEP parameters) (Table 1). This probably reflects the relatively high number of surgeries performed for tumor resection, in which a common

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tbody>
<tr>
<td>Number of cases in which there was either no significant change or deterioration in intraoperative SSEP waveforms and thresholds for TES-evoked muscle responses*</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>TES</td>
</tr>
<tr>
<td>no change</td>
</tr>
<tr>
<td>worse</td>
</tr>
</tbody>
</table>

* Values reflect a comparison with baseline status.
TABLE 2
Comparisons of intraoperative SSEP or TES findings with postoperative clinical findings*

<table>
<thead>
<tr>
<th>Type of Monitoring</th>
<th>True Positive</th>
<th>True Negative</th>
<th>False Positive</th>
<th>False Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSEP (sensory)</td>
<td>20</td>
<td>36</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>TES (motor)</td>
<td>29</td>
<td>51</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* True positive = significant deterioration in intraoperative records, combined with new (or worsened) postoperative clinical deficit specific to modality; False negative = no significant change in intraoperative records, combined with no detectable worsening of postoperative clinical status specific to modality; False positive = significant deterioration in intraoperative records but no detectable worsening of postoperative clinical status specific to modality; True negative = no significant change in intraoperative records, combined with new (or worsened) postoperative clinical deficit specific to modality.

surgical strategy called for midline myelotomy of the dorsal column fibers to expose the intramedullary mass; we often found that the SSEP parameters deteriorated significantly immediately following this stage in the resection.

Sensitivity and Specificity
We compared intraoperative electrophysiology findings using both SSEP and threshold-level repetitive TES techniques with postoperative clinical outcome in 83 consecutively studied patients. Table 2 provides a summary of the relationships between the number of cases in which an intraoperative test outcome (sensory or motor) matched or differed from the clinical outcome. Based on these data, the results of sensitivity and specificity calculations were 0.87 and 0.9, respectively, for SSEP monitoring relative to postoperative sensory deficit, and 1 and 1, respectively, for TES monitoring relative to postoperative motor deficit. We did not compare intraoperative SSEP findings with postoperative motor deficit, nor did we compare intraoperative TES findings with postoperative sensory deficit. In other words, our comparisons between intra- and postoperative findings were modality specific.

Illustrative Case

History and Presentation. This patient was a 44-year-old left-handed caucasian man with a history of surgery for a cervicothoracic meningioma. When he was 40 years of age, the original tumor was observed to be an extensive mass along the right side of the spinal canal from C-5 to T-1. Cervicothoracic laminectomy/laminoplasty and subtotal resection of tumor were performed and a lyophilized cadaver dura graft was placed, and his symptoms completely resolved. Four years later, repeated magnetic resonance imaging revealed expansion of the residual tumor in the lower cervical region including the right C-8 nerve root area. Occasional episodes of paresthesia in the right C-8 distribution were the only symptoms. The patient underwent an aggressive attempt at complete or near-complete resection of the tumor. The plan was to repeat the posterior approach and then turn the patient supine for an anterior approach to further resection.

Operation. Figure 1 illustrates cortical SSEPs and TES-evoked motor responses in each of the biceps brachii, FCR, hand intrinsics, and TA muscles on the patient’s left side and right side. The SSEP and TES-evoked responses were obtained within 10 minutes of each other for each image, at the times described in each figure’s legend. Each SSEP trace represents the average of two independently gathered averages of 200 responses each. For TES responses, waveforms following stimulation of C3–4 (anode–cathode) and C4–3 (anode–cathode) are superimposed. The stimulus parameters for TES are shown above each of the muscle records in each figure.

Figure 1 (upper left) shows responses evoked during soft-tissue dissection to expose the cervical laminae. Somatosensory evoked potential waveforms were well defined, with comparable latency and amplitude values from side to side. Muscle response amplitudes in the biceps brachii bilaterally to the 300-V stimulus train (2-msec interpulse interval in this and all waveforms) were small relative to the other muscles being monitored but were present nevertheless. Other muscle groups showed large amplitude responses, which saturated some of the amplifier channels.

Several hours later during tumor resection, changes in responses to TES were evident, as shown in Fig. 1 (upper right). The right TA muscle was no longer responding to the stronger, 400-V stimulus train, which had become the new, higher threshold value for the biceps (bilaterally) and the right hand muscles. Based on these findings, the decision was made to limit the extent of the posterior tumor resection and to abandon the presurgical plan in which corpectomy and continued resection via an anterior approach were to be performed. At the end stages of this resection, the 400-V, three-pulse stimulus train was no longer adequate for evoking responses in the patient’s TA muscles (bilaterally) or the right hand muscles (Fig. 1 lower left). The response amplitude from the left hand was considerably lower than that seen up to this point (note the sensitivity change in motor responses in Fig. 1 lower left and right). Following closure of the dura, responses to a three-pulse, 500-V stimulus train were absent in the right hand, the left and right TA, and the left and right quadriceps muscles (quadriceps was substituted for biceps to provide a more comprehensive evaluation of lower limb responsiveness to TES) (Fig. 1 lower right). Although still responding, amplitudes from the bilateral FCR muscles and left hand muscles were barely discernable above background noise. Immediately after closing the dura, a final trial using a four-pulse train at 500-V intensity was delivered and low-amplitude responses were observed in the left FCR, hand, and TA muscles, as well as in the right-side FCR muscle. At this time the patient’s core temperature was noted to be 2.1°C cooler than it had been at the beginning of the surgical procedure (approximately 9.5 hours before). Blood pressure values were maintained at approximately 105/65 mm Hg (systolic/diastolic; mean arterial approximately 80 mm Hg), although some fluctuations in these values inevitably occurred during this procedure. There was no obvious relationship between periods of hypotension and thresholds to TES in this particular case, although such a relationship was observed in other cases.

Throughout all of the records shown in Fig. 1 and in many others not provided, posterior tibial muscle SSEP responses were within baseline limits. That is, there was a
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FIG. 1. Waveforms. Upper Left: Intraoperative evoked responses obtained during soft-tissue dissection (at approximately 09:45 hours) for resection of intradural spinal meningioma. The SSEP responses (A) are averages of two successive trials in which 200 stimuli were used in each. Latency of the “P37” trough is indicated on this and subsequent images. Evoked motor responses to TES in each muscle are shown below B. Waveforms are single, unprocessed EMG responses to anodal stimulation at either C-4 or C-3 of the stimulus pattern and intensity shown. Stimulus artifacts toward the left side of each EMG trace denote the onset of cortical stimulation. The horizontal calibration bar (10 msec) is the same for both SSEP and TES records; the vertical calibration bars differ between SSEP (A) and evoked motor responses (B), as indicated.

Upper Right: Responses elicited during tumor resection (at approximately 13:50 hours). Note in B that the stimulus intensity was 400 V. Lower Left: Responses elicited nearing completion of resection (at approximately 15:20 hours). In B, the vertical calibration bar now represents a 0.5-mV amplitude. Lower Right: Responses evoked following dura closure (at approximately 16:50 hours). In B, the stimulus intensity was increased to 500 V. The top waveforms in B now show EMG records from quadriceps muscles bilaterally, instead of biceps as was shown in the previous three images. APB = abductor pollicis brevis muscle; L PT = left-side posterior tibial nerve; R PT = right-side posterior tibial nerve.
modest increase in response latency between the records shown in Fig. 1 (2.8 msec and 1.9 msec for left and right responses, respectively), but this change was within the 10% criteria denoting significance. Moreover, there was no substantive change in SSEP waveform morphology.

During this procedure, threshold intensities for TES-evoked muscle responses in all four limbs were elevated in this patient by 100 V or more, and this elevation persisted for more than 1 hour. Given these findings, we predicted immediate postoperative motor weakness in all four limbs. Because of the complete absence of response in the right hand, TA, and quadriceps muscles to the final stimulus pattern (four pulses of 500 V at 2-msec intervals), we predicted a more severe motor deficit in the right muscles distal to wrist flexors compared with the left-sided muscles.

Postoperative Course. Postoperatively, the decision was made to treat the patient with a period of hypothermia. He remained intubated, was given a sedative agent, pharmacological paralysis was induced, and his body temperature was cooled to 33 to 34°C for 3 days. After gradual warming and extubation, his neurological status was evaluated. Motor function on the left side seemed approximately normal. Right lower-extremity strength was 3/5. Right deltoid and biceps brachii were of normal strength. Right wrist extensors and right triceps muscles were each 3/5, and right wrist flexors was 2/5. Right finger flexors and extensors and right hand intrinsic muscle groups were objectively 0/5. Pain–temperature sensation was reduced in the left lower extremity, and vibration–proprioception sense was markedly reduced in the right lower extremity. Touch sensation was reduced in both lower extremities. Three weeks after surgery, right lower-extremity strength had improved sufficiently to allow ambulation with a walker.

Discussion

Success Rate

This study expands on our initial report of using threshold-level repetitive TES of motor cortex for monitoring central motor pathway function during spine surgery.3 In our experience, the success rate for evoking motor responses in target muscles to TES was considerably higher than for eliciting cortical SSEPs during surgery. Failures reflected, in nearly all cases, each patient’s preexisting clinical condition and were not related to technical difficulties such as inadequate stimulus intensity, equipment malfunction, or anesthesia incompatibility. We believe this higher level of agreement for TES-based monitoring compared with SSEP-based monitoring reflects the physiology of the anatomical pathways being studied. We often had difficulty, for example, eliciting cortical SSEPs in patients with preexisting sensory neuropathy (particularly Type 1 diabetes mellitus), a condition that would lead to a temporal dispersion of theafferent volley with subsequent attenuation (or loss) of the cortically evoked SEP. In contrast, eliciting TES responses in target muscles in these same patients was usually possible. In these circumstances, TES monitoring provided the sole means of evaluating spinal cord conduction.

Accuracy of TES Monitoring

As in our preliminary report, the threshold-level repetitive TES method was again found to be highly accurate for predicting postoperative motor deficits, this time in a larger sample size. There were no cases in which clinical motor outcome was at odds with intraoperative TES-based findings (that is, either false negative or false positive). The sensitivity and specificity values of this technique were 1 and 1, respectively, as was found in our earlier study of a smaller population.3 The accuracy of the SSEP test for anticipating postoperative sensory deficits was also high, with sensitivity and specificity values in the current study (0.87 and 0.9, respectively) similar to those reported earlier (0.92 and 0.85, respectively).3 In a representative case (see Case Illustration) the results serve to emphasize, though, that marked discrepancies can exist between intraoperative TES- and SSEP-based records, and postoperative findings. In those few cases in which intraoperative SSEP findings (unchanged) were at odds with postoperative sensory loss (that is, false-negative result, as was true for the case study provided), reliance on SSEP findings alone for surgical decision making could have been disastrous. Therefore we believe that testing of both modalities—the motor systems with the TES method and the sensory systems with the SSEP—is essential for providing an accurate overview of intraoperative spinal cord long tract function. This view is shared by other investigators.1,15

We found TES monitoring to be useful in recognizing conduction loss caused by positioning-related issues: threshold elevation caused by excess pressure at the axilla (two cases), threshold elevation following hyperextension of the patient’s neck during an anterior discectomy (one case), and threshold elevation attributed to hyperextension of the patient’s hips during surgery to correct L5–S1 spondylolisthesis (one case). In three of these cases, the neural elements affected were almost certainly peripheral nerves, which underscores one of the advantages of monitoring muscle EMG as the output signal, rather than relying on waveforms from the spinal cord as the primary indicator of central motor conduction.14,22

Relevance of TES

One indication of the perceived value of any intraoperative monitoring technique is the extent to which the surgical team bases clinical decision making on its feedback. In our initial description of the threshold-level repetitive TES technique, we reported that in six (17.7%) of the 34 cases technique-related feedback influenced decision making intraoperatively. The course of the procedure performed in our Case Illustration was also clearly influenced by feedback, however, we are not able to present overall statistics about the frequency with which TES-based feedback influenced surgical decision making in the present study. This is because as experience with the TES technique has been gained, many of our surgeons now respond to this feedback in their moment-to-moment approach, and a defining moment when surgical strategy shifts has not emerged.

Safety of TES

Transcranial electrical stimulation with either single- or multipulse inputs is now used extensively in some centers, and serious adverse events have been avoided, even when
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charge deliveries considerably stronger than those report-
ed herein were used.2,11,20 Based on these studies, the crite-
ria for adverse event included skin complications, sei-
zuers, infection, and intraoperative recall. To our knowledge, the only published adverse events associated with intraop-
erative TES have been tongue laceration (three cases) caused by contraction in the masseter and/or temporalis muscles.9,11

Since we ceased enrolling patients in this particular study we have used this technique as a standard of care in an additional 367 surgical cases. Recently, our first case of an intraoperative monitoring–related adverse event occurred. Fracture of the mandible and anterior displace-
ment of three teeth, presumably due to biting movements onto the tracheal tube occurred in a 33-year-old man un-
dergoing laminectomy and laminoplasty in the prone posi-
tion for cervical stenosis. A bite-block was not used in this patient and likely would have prevented this complication, as reported elsewhere.9,11

Application in Young Adults

There were seven children and young adults (<18 years of age) in the present series. Using the TES tech-
nique, there were no appreciable differences in threshold voltages needed to elicit responses in this cohort of sub-
jects compared with adults. In the subset of children aged 13 years or younger (three cases), the mean stimulus intensities needed to elicit threshold-level responses were 132 ± 37 V and 165 ± 24 V for muscles of the hand and feet, respectively. Anesthesia was also induced in a man-
ner comparable with that used in adults, without complic-
ation or obvious difficulty.

Implementation of the Monitoring Technique

Provided that routine intraoperative monitoring equip-
ment is available and personnel are trained to provide such monitoring, the costs associated with adding threshold-
level repetitive TES–based monitoring of central motor tracts are modest. The Digitimer D185 stimulator retails for approximately $6000, and it interfaces with standard EMG monitoring is already in place is relatively straight-
forward, and it adds little additional cost (financially, or in time required to do the monitoring) to the procedure.

Anesthesia Monitoring

Careful monitoring of the level of anesthesia was nec-

essary to keep the patient between too “light” a level of anesthesia and too deep a level, with resultant depression of evoked responses.6 The constant infusion of remifentanil, with its rapid offset and its 90-second response time, permitted precise control of the depth of anesthesia. Remifentanil is a synthetic opioid recently approved for use in anesthesia protocols. Its ester structure renders it susceptible to hydrolysis by nonspecific tissue and blood esterases. It is rapidly metabolized and is the first ultra-
short–acting opioid available as a supplement to general anesthesia. In balance, we believe the ability to monitor central motor conduction during the surgical procedure, combined with the fact that the patient rapidly emerges from anesthesia, thus permitting a postoperative neurological motor assessment while still in the operating room, justifies the use of remifentanil and propofol.

Conclusions

The threshold-level repetitive TES technique developed in our center for monitoring central motor conduction has, in our experience, satisfied all of the criteria described in the Introduction. It is suitable for all levels of surgery in the neuraxis; the presence or absence of intraoperative respons-
eses in a given target muscle agrees closely with the patient’s pre- and postoperative motor status; feedback to the surgical team is essentially immediate; parallel monitoring of nerve root function can be conducted using stimulus-
evoked EMG; and adverse events are rare. Its implementa-
tion into a setting in which intraoperative (SSEP and/or EMG) monitoring is already in place is relatively straight-
forward, and it adds little additional cost (financially, or in time required to do the monitoring) to the procedure.

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