Neurophysiological detection of iatrogenic C-5 nerve deficit during anterior cervical spinal surgery

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Object. The incidence of postoperative C-5 spinal nerve root palsy following decompressive cervical spinal surgery has been reported to be as high as 12% for anterior procedures and 30% for posterior procedures. The present study was conducted to document the prevalence of iatrogenic C-5 nerve root deficit during anterior cervical spinal surgery, as well as to evaluate the sensitivity and specificity of intraoperative transcranial electrical stimulation (TES)-induced motor evoked potentials (MEPs) and spontaneous electromyographic (EMG) activity for identifying evolving C-5 nerve root impairment.

Methods. The authors conducted a retrospective study of 238 consecutive anterior cervical spinal procedures performed by a single surgeon at Christiana Care Hospital within a 48-month period. Techniques used to monitor spinal nerve root function included TES-induced MEPs and spontaneous EMG activity from deltoid, biceps, triceps, wrist extensor, and hand intrinsic muscles innervated by the C5–T1 spinal nerve roots. Spinal cord function was monitored by recording TES-induced MEPs from upper- and lower-extremity muscles as well as somatosensory evoked potentials from stimulation of the ulnar and posterior tibial nerves.

Conclusions. Transcranial electrical stimulation–induced MEPs and spontaneous EMG activity offer complementary information about evolving iatrogenic C-5 spinal nerve root impairment during anterior cervical spinal surgery. The TES-induced MEPs provide prognostic information and show increased sensitivity to C-5 deficit compared with spontaneous EMG activity alone. Monitoring of spinal nerve root function using only EMG activity carries a risk of false-negative findings; without timely warning of impending neurological impairment, timely intervention to prevent permanent deficit cannot occur.

Key Words • nerve palsy • cervical spinal surgery • electromyography • neuromonitoring • transcranial electrical stimulation

The incidence of postoperative C-5 spinal nerve root palsy following decompressive cervical spinal surgery has been reported to be as high as 12% for anterior procedures and 30% for posterior procedures. Intraoperative neurophysiological monitoring that uses ulnar or median nerve SSEPs is known to be insensitive for detecting developing iatrogenic C-5 nerve root impairment. These SSEPs are mediated by pathways that enter the spinal cord through multiple (C6–T1) spinal nerve roots. Thus, it is possible for the SSEPs to miss the site of impairment, allowing evoked potentials to remain unchanged even as neurological impairment evolves.

Recently, Fan and colleagues2 reported that multimodal intraoperative neurophysiological monitoring during posterior cervical spinal surgery using TES-induced MEP and spontaneous EMG recordings from deltoid and biceps muscles was sensitive to evolving iatrogenic injury of the C-5 nerve root that innervates these muscles. The present study represents a logical follow up to the study of Fan and associates to document the prevalence of iatrogenic C-5 nerve root palsy during anterior cervical spinal surgery and to compare the relative sensitivities and specificities of intraoperative TES-induced MEPs and spontaneous EMG activity for identifying evolving nerve root impairment.

Clinical Material and Methods

Patient Population

We conducted a retrospective study of 238 consecutive anterior cervical spinal procedures performed within a 48-month period by a single neurosurgeon and monitored by a single professional-level neuromonitoring practice. Patients included in the review ranged in age from 20 to 82 years (mean 48.3 years). Forty-three percent of the patients were men. The anterior cervical spinal procedures included single-level discectomies, multilevel discectomies, corpectomies, and stabilization of odontoid fractures. The number of cervical levels treated ranged from one to four: 31% at one level, 36% at two levels, 22% at three levels, and 11% at four levels. The surgical procedures included decompression at the C4–5 and/or the C5–6 levels for 205 (86%) of 238 patients. Both C4–5 and C5–6 were involved for 74 patients treated at three or more cervical levels and for 18

Abbreviations used in this paper: EMG = electromyographic; MAP = mean arterial pressure; MEP = motor evoked potential; SSEP = somatosensory evoked potential; TES = transcranial electrical stimulation.
patients treated at two levels. Instrumentation used for fixation included the DOC Ventral Cervical Stabilization System (DePuy Acromed, Inc.) for multilevel constructs and DePuy AcroMed single-level plates for one-level fusion.

Intraoperative Neuromonitoring Procedure

Intraoperative neuromonitoring was performed using a 16-channel Axon EpochXP (Axon Systems, Inc.) or Nicolet Endeavor (Viasys Biomedical) monitoring system running proprietary software supplied by the respective manufacturer. Neurophysiological monitoring commenced at the time of anesthesia induction and ended at the time of wound closing. Spinal cord function was monitored by recording TES-induced MEPs from upper- and lower-extremity myotomes, as well as cortical and subcortical SSEPs from stimulation of the ulnar and posterior tibial nerves. Spinal nerve root function (C5–T1) was monitored by recording TES-induced MEPs and spontaneous EMG activity from deltoid (C5–6), biceps (C5–6), extensor carpi radialis (C5–8), triceps (C6–T1), first dorsal interosseous (C8–T1), and/or adductor pollicis brevis (C8–T1) muscles as appropriate for the spinal level of surgery.

When the neurophysiologist noted TES-induced MEP amplitude attenuation and/or neurotonic EMG activity during surgery, the surgeon was immediately alerted. Surgery was temporarily paused and the operative field was irrigated using saline solution. The nerve root was explored to address any obvious sources of stretching or compression. During this time, the MAP was elevated and/or maintained above 80 mm Hg to optimize perfusion. Methylprednisolone was administered intravenously to minimize possible edema of the spinal cord and/or nerve root.

Monitoring of TES-Induced MEPs

Transcranial electrical stimulation–induced MEPs were elicited using a low-output impedance electrical stimulator (Digitimer D185, Digitimer, Ltd.) that generated a high-voltage, short-duration stimulus train to activate the corticospinal tract. The constant voltage stimulus was delivered between electrodes placed at C-1 and C-2 (International 10-20 System) with the anode located over the hemisphere to be stimulated. Stimulation typically was delivered in trains of three to five pulses (50-μsec pulse width) at 500 or 1000 pulses per second, with intensity set between 300 and 700 V. A bite block was used to prevent tongue biting that might otherwise result from stimulation-induced closure of the jaw. Motor evoked potentials were recorded from pairs of stainless-steel needle electrodes inserted into at least three upper-extremity muscles whose spinal innervation patterns overlapped the level at which surgery was performed, as well as from two sites on the lower extremities, typically the tibialis anterior and abductor hallucis muscles. The recording bandwidth for MEPs was 10 to 1500 Hz. The criterion for an alert was a greater than 50% decrease in TES-induced MEP amplitude from baseline.

Monitoring of Spontaneous EMG Activity

Spontaneous EMG activity was recorded continuously from the same upper-extremity muscles used to record TES-induced MEPs. Free-running EMG signals were bandpass filtered between 10 and 1500 Hz and displayed over a 5-second recording epoch. In addition to a visual display, EMG activity was also monitored auditorily. An EMG alert was defined as sustained neurotonic discharge for longer than 3 seconds.

Monitoring of SSEPs

Cortical SSEPs that resulted from stimulation of the ulnar and posterior tibial nerves were recorded at the scalp using gold-plated disc or subdermal stainless-steel electrodes. Recording montages were Cpz-Fpz (International 10-20 System) for posterior tibial nerve stimulation, Cp4-Fpz for left ulnar nerve stimulation, and Cp3-Fpz for right ulnar nerve stimulation. Subcortical SSEPs were recorded using an electrode over the second or third cervical vertebra, referenced to Fpz. The bandpass was 30 to 300 Hz for cortical recordings and 30 to 500 Hz for subcortical recordings. Electrical stimuli were delivered at 4.7 pulses per second using a 300-μsec pulse width.

Anesthesia Management

Anesthesia was maintained using a completely intravenous propofol infusion (125–225 μg/kg/min) technique augmented with boluses of opioid (fentanyl, sufentanil, or remifentanil) and midazolam as needed. Volatile anesthetic agents and nitrous oxide were avoided entirely in order to maximize SSEP and TES-induced MEP amplitudes. Similarly, no neuromuscular blocking agent was administered following intubation to prevent compromise of TES-induced MEP and EMG recordings. Four muscle twitches were recorded from train-of-four electrical stimulation of the ulnar and/or posterior tibial nerve before the onset of decompression, to confirm adequate signal transmission across the neuromuscular junction for accurate EMG and TES-induced MEP monitoring.

Results

Twelve (5%) of 238 patients showed new-onset unilateral deltoid weakness in the immediate postoperative period following anterior cervical spinal surgery. Two of these 12 patients presented with combined deltoid and biceps weakness. For two others, weakness was noted in the deltoid, biceps, and wrist extensor myotomal distributions. All patients who showed postoperative weakness had undergone direct surgical intervention at the C4–5 and/or the C5–6 levels. Both cervical levels were involved for 10 of the 12 patients. Nine patients (75%) demonstrating new-onset weakness had undergone surgical decompression and fusion that involved three or more spinal levels (spanning both C4–5 and C5–6), two others (16.7%) had undergone a two-level procedure (C5–7 and C4–6), and the remaining patient had required only a single-level procedure (C5–6).

Six (50%) of the 12 patients who developed weakness had a history of previous cervical spinal surgery. All 12 patients recovered their full preoperative strength within 2 to 9 months (mean 5.8 months) of the surgical procedures.

Acute intraoperative changes in TES-induced MEP amplitudes (amplitude attenuation > 50%) involving the C-5 myotome on the side of postoperative deficit were noted in 10 (83%) of the 12 patients who presented postoperatively with deltoid, biceps, and/or wrist extensor weakness.
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weakness. These neurophysiological changes occurred during decompression in seven patients, following graft insertion in two patients, and following plate insertion in one patient. In eight (80%) of the 10 patients, the TES-induced MEP attenuation persisted from the time of onset through wound closing. An illustrative case that demonstrated persistent unilateral TES-induced MEP amplitude attenuation is shown in Fig. 1.

Five (50%) of the 10 patients who demonstrated TES-induced MEP amplitude attenuation also showed at least one episode of sustained neurotonic EMG activity from the C-5 myotome on the side of postoperative neurological deficit during the course of decompression. There were no intraoperative changes in the ulnar nerve SSEPs recorded for any of the 12 patients who developed postoperative C-5 palsy.

Two of the patients who demonstrated postoperative C-5 weakness did not show any significant changes in neurophysiological recordings during the course of surgery. At baseline, one of these patients had severely attenuated TES-induced MEPs from deltoid and biceps muscles, thereby precluding reliable monitoring of the C-5 nerve root with MEPs. The other patient had no remarkable changes in TES-induced MEPs from the C-5 myotome, nor was there any episode of neurotonic EMG activity during the procedure. During the procedures, neither patient had shown any SSEP changes.

Intraoperative attenuation of the TES-induced MEPs from the C-5 myotome was noted in 24 patients who did not show new-onset upper-extremity weakness postoperatively. In 19 (79%) of the 24 patients, the TES-induced MEP change resolved fully or partially following intervention during surgery. Thirteen (54%) of the 24 patients who had intraoperative attenuation of the TES-induced MEPs also had episodes of neurotonic EMG activity that prompted an alert. Twenty other patients had episodes of neurotonic EMG activity (without TES-induced MEP attenuation) but did not demonstrate C-5 palsy postoperatively.

The sensitivities of TES-induced MEPs, spontaneous EMG activity, and ulnar nerve SSEPs for postoperative C-5 palsy were 0.91, 0.42, and 0.0, respectively. The respective specificities for each monitoring modality were 0.89, 0.85, and 0.98, respectively. Frequency counts used to calculate sensitivity and specificity of TES-induced MEPs, spontaneous EMG activity, and ulnar nerve SSEPs are shown in contingency Table 1.

Discussion

Frequency of Postoperative C-5 Nerve Root Palsy

The likelihood of developing C-5 nerve root palsy following anterior cervical surgery was 5% for the present sample of 238 patients. The likelihood increased to 5.9% if one considered only those 205 patients whose surgeries included the C4–5 and/or C5–6 levels. It increased further to 10.7% if one considered only those 93 patients whose surgeries included both the C4–5 and C5–6 levels. Risk for postoperative C-5 nerve root palsy also increased with the extent and severity of spinal cord compression; for example, the incidence increased from 5.5% for 18 patients treated at C4–5 and C5–6 for two-level disease, to 12% for 75 patients treated at three or more levels, including both C4–5 and C5–6.

The prevalence of iatrogenic C-5 nerve root deficit found in this study is consistent with results of the metaanalysis by Sakaura and coworkers who found that the reported incidence of C-5 palsy after anterior decompression for cervical myelopathy ranged from 1.6 to 12.1%, with an average incidence of 4.3%. Yet the prevalence rate from the present study may somewhat overstate the incidence of iatrogenic C-5 deficit because the positioning necessary for the procedures in some patients (the use of wrist restraints with the shoulders pulled down and restrained) can potentially cause a brachial plexus stretch injury that manifests as postoperative weakness. In the present series, two of 12 patients had postoperative upper-extremity weakness that included deltoid, biceps, and wrist extensor muscles, consistent with a brachial plexus stretch injury rather than solely C-5 nerve root palsy.

The results of this study are entirely consistent with those reported by Fan and associates for posterior cervical spinal surgery which suggest that TES-induced MEPs and spontaneous EMG activity recorded from appropriate myo-

Fig. 1. Recordings of left (A) and right (B) TES-induced MEPs (tceMEPs) and SSEPs (C) from a representative patient demonstrating persistent unilateral TES-induced MEP amplitude attenuation. A: Transcranial electrical stimulation–induced MEPs recorded from upper- and lower-extremity muscles on the left side from the time of induction through wound closing. Acute attenuation of responses from left deltoid and biceps muscles (left tceMEP alert) occurred during decompression and persisted through the end of the procedure. There were no remarkable changes in the latencies or amplitudes of responses recorded from other muscles on the left side. B: Unchanged tceMEPs recorded from upper- and lower-extremity muscles on the right side at times corresponding to those in A. C: Unchanged SSEPs to interleaved stimulation of the left and right ulnar nerves from the start of surgery through wound closing. This patient demonstrated new-onset postoperative C-5 spinal nerve root palsy.
tomes are sensitive to evolving C-5 spinal nerve root injury. Data reported by Jimenez and colleagues⁵ are also consistent with the results of this study. When Jimenez et al. modified their intraoperative neuromonitoring protocol for cervical spinal surgery to include EMG recordings from the deltoid muscle, they reported a decrease in the incidence of C-5 nerve root palsy from 7.3 to 0.9%. Transcranial electrical stimulation–induced MEPs were not recorded from deltoid muscle in the study by Jimenez et al., however, which precludes comparison of the relative sensitivities of these two modalities in identifying evolving C-5 spinal nerve root deficit.

Predictive Value of Monitoring Techniques

In the present study, TES-induced MEP amplitude attenuation was predictive of postoperative C-5 palsy in 10 (91%) of 11 patients (Table 1). In this series, one of 12 patients who developed postoperative C-5 palsy was excluded from the analysis of TES-induced MEP sensitivity because of severely attenuated baseline responses that precluded TES-induced MEP monitoring during the procedure. Compared with TES-induced MEPs, neurotonic EMG activity was predictive of postoperative palsy in only five (42%) of 12 patients (Table 1).

The higher sensitivity of TES-induced MEPs compared with spontaneous EMG recordings in detecting evolving C-5 palsy may reflect the mechanism of C-5 injury. Whereas spontaneous EMG recordings are exclusively sensitive to mechanical stretch or compression of axons that innervate a target muscle, they may be insensitive to ischemic axonal injury that occurs secondary to microvascular trauma. Mechanical stretch of a nerve produces axonal depolarization and triggers sustained EMG discharges from the target muscle. Ischemic insult, on the other hand, results in EMG quiescence that is indistinguishable from the EMG signature of the healthy resting state of the nerve. In contrast, TES-induced MEPs are sensitive to both mechanical injury and ischemic insult to the nerve, which may account for their overall greater sensitivity for identifying developing C-5 neurological impairment. It is important to note that the site of vascular insult may not be the C-5 nerve itself. Chiba and associates⁴ suggest that in some cases of segmental paralysis following expansive open-door laminoplasty, the deficit may be due to rapid reperfusion of the spinal cord and hyperemia after decompression, leading to damage of alpha motor neurons and/or associated interneurons in the gray matter. Transcranial electrical stimulation–induced MEPs (but not spontaneous EMG recordings) would be sensitive to such gray matter damage. The present study further substantiates data from others⁵ showing that SSEPs from stimulation of the ulnar nerves are entirely insensitive measures for identifying evolving C-5 nerve root palsy (Table 1).

Further insight into the possible cause of iatrogenic C-5 injury may be obtained by examining the circumstances of neurophysiological change. Amplitude attenuation of TES-induced MEPs occurred during the decompressive phase of surgery for seven of the patients who developed postoperative C-5 palsy. Similarly, neurotonic EMG discharges generally occurred during decompression, if at all, for the patients who presented with neurological sequelae. Although it was not possible to determine the precise surgical maneuvers associated with injury, it is likely that aggressive decompression, including resection of the posterior longitudinal ligament in the setting of severe spinal cord compression, was a factor in some cases.

**TABLE 1**

<table>
<thead>
<tr>
<th>Neuromonitoring Technique</th>
<th>No. of Patients w/ Postop C-5 Deficit</th>
<th>No. of Patients w/o Postop C-5 Deficit</th>
<th>Total No. of Patients</th>
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<tr>
<td>TES-induced MEP change*</td>
<td>10</td>
<td>24</td>
<td>34</td>
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<tr>
<td>no TES-induced MEP change</td>
<td>1</td>
<td>202</td>
<td>203</td>
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<tr>
<td>EMG activity change†</td>
<td>5</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>no EMG activity change</td>
<td>7</td>
<td>193</td>
<td>200</td>
</tr>
<tr>
<td>SSEP change‡</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>no SSEP change</td>
<td>12</td>
<td>221</td>
<td>233</td>
</tr>
</tbody>
</table>

* Frequency counts used to calculate sensitivity (0.91) and specificity (0.89) of TES-induced MEPs for new-onset postoperative C-5 spinal nerve root deficit. One patient with postoperative C-5 deficit was excluded from the TES-induced MEP group because severely attenuated TES-induced MEPs from deltoid and biceps muscles at baseline precluded reliable monitoring of the C-5 nerve root using this modality.
† Frequency counts used to calculate sensitivity (0.42) and specificity (0.85) of spontaneous EMG activity for new-onset postoperative C-5 spinal nerve root deficit.
‡ Frequency counts used to calculate sensitivity (0.0) and specificity (0.98) of SSEPs for new-onset postoperative C-5 spinal nerve root deficit.

**Determination of False-Negative and False-Positive Results**

One of the patients who exhibited postoperative C-5 weakness in this series did not show any significant changes in spontaneous EMG activity or TES-induced MEPs during the course of surgery. This finding led us to believe that he developed delayed C-5 nerve root palsy secondary to postoperative edema. One additional patient who had severely attenuated TES-induced MEPs from deltoid and biceps muscles at baseline (thereby precluding reliable monitoring of the C-5 nerve root with TES-induced MEPs) did not show TES-induced MEP changes, but this was to be expected given his baseline measures; this should not be considered a false-negative result for TES-induced MEP monitoring. This same patient did not show any sustained EMG activity that was suggestive of mechanical irritation of the nerve root either, which represents a false-negative result of EMG monitoring.

In this series, 10.1% of the patients experienced an episode of intraoperative TES-induced MEP attenuation for the C-5 myotome, but did not show postoperative C-5 palsy. We do not consider the results in these cases to be false positives because intervention (as described in Clinical Material and Methods) may have reversed the evolving neurological deficit. Partial or full recovery of attenuated TES-induced MEPs occurred in 79% of these patients. This high rate of recovery suggests that early detection of an evolving deficit can prevent it or reduce its severity. Similarly, 13.8% of patients generated alerts for neurotonic EMG activity from the C-5 myotome, but did not show postoperative neurological sequelae. In each patient, the neurotonic discharges resolved with intervention.
Conclusions

The risk of new-onset C-5 palsy following anterior cervical spinal surgery is greatest for those patients who require aggressive treatment of severe spinal cord compression at three or more levels spanning C4–5 and C5–6. Transcranial electrical stimulation–induced MEPs and spontaneous EMG activity recorded from the C-5 myotome are sensitive to evolving iatrogenic C-5 spinal nerve root deficit during anterior cervical spinal surgery. Spontaneous EMG activity recordings provide instantaneous feedback about stretching and/or compression of the nerve, but are insensitive to other forms of injury that produce EMG quiescence, such as ischemia. Transcranial electrical stimulation–induced MEPs appear particularly sensitive both to stretching and/or compression and ischemia, providing increased sensitivity to evolving neurological deficit compared with EMG activity recordings alone. We suggest that the combined use of TES-induced MEPs and spontaneous EMG activity from deltoid muscle be considered to optimize monitoring of C-5 nerve root function during cervical spinal surgery. The use of SSEPs from ulnar nerve stimulation is unsuitable for identifying evolving C-5 nerve root palsy.

References


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