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Transcranial Electrical Motor-Evoked Potential Monitoring During Surgery for Spinal Deformity

A Study of 145 Patients

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Robert Slappendel, MD, PhD,‡ and Marinus de Kleuver, MD, PhD*

Study Design. A descriptive historic cohort study was conducted.

Objectives. To determine intraoperative response amplitude criteria for transcranial electrical motor-evoked potential monitoring that warn of neurologic damage, and to determine the additional value of monitoring six instead of two muscle sites.

Summary of Background Data. Transcranial electrical motor-evoked potential monitoring provides immediate and reliable information about the integrity of the motor pathways during spine surgery. Although this monitoring technique is more frequently used, criteria for interpretation of the amplitude responses have not been defined.

Methods. The intraoperative monitoring outcomes were compared with the patient’s clinical outcomes. The sensitivity, specificity, positive predictive value, and negative predictive value were determined for four different monitoring criteria.

Results. Transcranial electrical motor-evoked potential monitoring was possible 142 of 145 patients undergoing corrective surgery. In this study, 16 patients had a neurologic event, and 11 patients showed recovery of response amplitude after a second surgical maneuver, whereas the remaining 5 patients had permanent partial neurologic damage. The criterion that at least one of six recordings must show an amplitude decrease of more than 80% was sufficiently strict to achieve a sensitivity of 1.0 and a specificity of 0.91. Less strict criteria, including recording at two instead of six sites, resulted in lower sensitivity, with the lower bound of the 95% confidence interval at 0.62.

Conclusions. Transcranial electrical motor-evoked potential monitoring allowed successful intraoperative monitoring. The criterion of one recording showing a response amplitude decrease of more than 80% during a surgical action can be considered a valuable warning criterion for neurologic damage. The authors also consider that monitoring at six instead of two muscles improves the value of neuromonitoring. [Key words: intraoperative monitoring, motor-evoked potentials, spinal surgery, TCE–MEP] Spine 2003;28:1043–1050

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A surgically induced postoperative neurologic deficit is an important complication of deformity spine surgery. Reliable information about the impact of surgical action on spinal cord function is needed because corrective intraoperative maneuvers, such as reducing the achieved correction or removal of implants, may prevent or diminish permanent neurologic damage.

The Stagnara wake-up test is the oldest intraoperative monitoring method, but its use is limited. It monitors global motor deficits only and does not allow repeated application.

Somatosensory-evoked potentials monitoring (SSEP) is the technique most commonly used to monitor the integrity of the spinal cord, but with this method, motor tract lesions may go undetected. Furthermore, SSEP monitoring requires time-consuming averaging procedures, and thus provides only a limited number of timedelayed monitoring events.

During the past decade, transcranial electrical motor-evoked potential monitoring (TCE–MEP) has been proved capable of providing instantaneous information about the integrity of the motor pathways that may not be shown by SSEP monitoring. Successful intraoperative use of TCE–MEP has been reported in several studies. During surgery, TCE–MEPs are elicited by transcranial electrical stimulation of the motor cortex. The resulting EMG responses are recorded at peripheral muscles below the level of surgery. Usually, the bilateral anterior tibial muscle is chosen, but various limb muscles below the level of surgery can be used simultaneously for recording. Most commonly, decrease of amplitude is used to detect impending neurologic damage, but sometimes increased response latencies or signal disturbances also are registered.

Response criteria that should warn the surgeon of impending neurologic damage, similar to those available for SSEP, have not been defined. Clinicians have interpreted TCE–MEP monitoring outcomes on the basis of surgical and clinical information without using strict criteria for amplitude decreases. Because TCE–MEP monitoring is becoming more popular, the development of explicit response warning criteria is desirable. In 1999, Padberg and Bridwell stated: “Further research is definitely needed from the clinical sector to more fully define parameters for determining the significance of response decrement.”

In this study, the use of TCE–MEP monitoring in 145 patients who underwent deformity spinal surgery is evalu-
The first purpose of this study was to determine the actual amplitudes recorded at the time of impending neurologic damage, and to derive adequate criteria that could be used to warn the surgeon about spinal cord injuries at an early stage. The second purpose was to assess the supplementary value of monitoring six instead of two muscles for the early detection of surgically induced neurologic damage.

Materials and Methods

TCE–MEP Technique. The motor responses were elicited by transcranial electrical stimulation using a custom-made stimulator, the Neuro-guard (JS-Center, Bedum, the Netherlands). This is a voltage stimulator with a low-output impedance (22 Ω) and a current limit of 1 A.

Two needle electrodes were inserted subcutaneously at Cz (the anode). The cathode, a Velcro ground strip electrode, was immersed in saline and placed on the forehead. Electrode impedance calibration was performed before surgery. The evoked muscle responses were recorded in four bilateral muscle groups with surface electrodes.

Multipulse stimulation was used at a supramaximal level in a train of four pulses with a pulse width of 2 ms. The supramaximal level was determined before surgery and generally measured between 150 and 250 V.

During all the surgical procedures, one bilateral muscle group above the spinal level of surgery was used as a control site. The combined activity of the abductor pollicis brevis muscle (APB) and the abductor digitus V muscle (ADV) of the hand was used as a control condition in thoracolumbar spine surgery. During eight cervical procedures, the trapezius muscle was selected instead of the hand muscle as a control site.

In thoracolumbar surgery, the other six recording electrodes were placed symmetrically: three on each of the lower limbs. Any three of the following four sites were used: the anterior tibial muscle (L4–L5), the hamstrings (L5–S1), the quadriceps (L2–L4) and the calf muscle (S1–S2). The bilateral lower limb muscle groups with the largest elicited MEP amplitude were selected for monitoring. During cervical procedures, the bilateral extensor muscles of the forearm (C6–C7), the abductor digitus V muscle (C6–C8), and the anterior tibial muscle (L4–L5) were used for monitoring. Reference values of all muscle sites were obtained just before the surgical incision. Figure 1 shows time plots of TCE–MEP amplitudes during an undisturbed monitoring procedure of a patient undergoing corrective spine surgery.

As a rule, monitoring was performed every 10 minutes, and additional stimulation was applied during the instrumentation of each hook or screw throughout the correction procedure, and whenever the surgeon requested another measurement.

Three-Step Protocol. The TCE–MEP technique together with an incident protocol is designed only to warn the surgeon of surgically induced neurologic deficits. The protocol checklist was used whenever a decrease in amplitude occurred. First, equipment was checked for technical malfunctions that could cause amplitude disturbance, and any such problems were solved. For instance, loosening of electrodes or impedance changes by drying out of the saline Velcro ground strip could
change the amplitude outcome. Second, systemic and anesthetic circumstances were checked and normalized when possible. Systemic and anesthetic problems were identified such as a drop in mean arterial pressure (MAP) below 60 mm Hg, major blood loss, or a decrease in body temperature. After technical failure and systemic or anesthetic problems had been ruled out as a cause for the decreased amplitude, the most recent surgical action was considered to be the probable cause of the amplitude decrease.

Anesthetic Protocol. Patients were orally premedicated with midazolam (0.1 mg/kg) 1 hour before general anesthesia. No muscle relaxants were given because these would influence the muscle responses. General anesthesia was induced with a bolus dose of propofol (2 mg/kg) and remifentanil (1 μg/kg). If relaxation was necessary for smooth intubation, atracurium (0.4 mg/kg) was given once (t1/2, 15–30 minutes). During the first 30 minutes, anesthesia was maintained by propofol (4 mg/kg/hour) using continuous infusion. Thereafter, the dose was lowered to 2 mg/kg/hour. Continuous infusion of remifentanil began at 15 μg/kg/hour and was titrated according to pain responses. Bolus application of remifentanil and propofol was avoided because it could lead to disappearance or marked decrease of TCE-MEP responses. Morphine was given (0.15 mg/kg) 30 minutes before the end of the operation, and remifentanil was stopped 20 minutes thereafter. Patients were ventilated with a gas mixture of O2 and N2O in the ratio 1:2. For postoperative pain control, 0.1–0.2 mg intrathecal morphine was given to some patients.

Of these 145 patients, 106 were neurologically normal, 17 had cerebral palsy, 9 had neuromuscular weakness (Duchenne dystrophy, spinal dysraphism, spinal muscular atrophy), and 13 patients had a secondarily compromised cord.

Surgery. Posterior fusion and correction were performed in 82 patients with scoliotic deformity or thoracic kyphosis deformity. Anterior fusion and correction were performed in 32 patients with scoliotic deformity. Lumbar closing wedge osteotomy and posterior instrumentation were performed in 20 patients with kyphotic deformity caused by ankylosing spondylitis. Cervical osteotomy and posterior instrumentation were performed in seven patients with cervical kyphotic deformity caused by ankylosing spondylitis. The remaining four patients underwent other spinal procedures.

Definitions. The clinical outcome was defined as the presence or absence of a neurologic event. For the purpose of this study a “neurologic event” was defined as the occurrence of a postoperative neurologic deficit or a marked decrease of TCE-MEP amplitude caused by surgical maneuvers that recovers after further surgical intervention. Patients in the latter category were assumed to have experienced neurologic events, but this cannot be verified because no alternative intraoperative testing was performed, and the patients had no postoperative neurologic deficit. The term surgical maneuvers indicates all actions that were performed in the latter category, except for the postoperative neurologic deficit or a marked decrease of TCE-MEP amplitude caused by surgical maneuvers that recovers after further surgical intervention. A negative clinical outcome is defined when no neurologic event results from surgical maneuvers. A positive clinical outcome is defined when a neurologic event results from surgical maneuvers.

Patients. Intraoperative TCE-MEP data for 145 patients (83 females and 62 males) who underwent corrective spine surgery in the years 1999 and 2000 were analyzed. The average age of the patients was 29.4 years (range, 4–82 years).

<table>
<thead>
<tr>
<th>N</th>
<th>Diagnosis</th>
<th>Comorbidity</th>
<th>NR of Sites With Amplitude Decrease</th>
<th>Surgical Approach</th>
<th>Surgical Cause of Amplitude Decrease</th>
<th>Subsequent Surgical Action</th>
<th>Recovery</th>
<th>Deficit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cervical kyphosis</td>
<td>AS</td>
<td>2</td>
<td>P</td>
<td>Slowly progressive kyphosis while preparing the osteotomy</td>
<td>Correction</td>
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<td>No</td>
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<tr>
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<td>I</td>
<td>2</td>
<td>P</td>
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<td>Correction reduction</td>
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<td>No</td>
</tr>
<tr>
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<td>Scoliosis</td>
<td>CP</td>
<td>4</td>
<td>P</td>
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<td>Removal of hook</td>
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<td>No</td>
</tr>
<tr>
<td>4</td>
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<td>AS</td>
<td>4</td>
<td>P</td>
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<tr>
<td>5</td>
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<td>No</td>
</tr>
<tr>
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<td>CP</td>
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<td>A</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Scoliosis</td>
<td>I</td>
<td>1</td>
<td>P</td>
<td>Slip of instrument in spinal canal</td>
<td>Removal of instrument</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
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<td>RA, myelopathy</td>
<td>4</td>
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<td>Resection of vertebral body</td>
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<td>I</td>
<td>6</td>
<td>P</td>
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<td>I</td>
<td>2</td>
<td>P</td>
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<td>No</td>
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<tr>
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<tr>
<td>12</td>
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<td>3</td>
<td>P</td>
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<td>Removal of hook, laminectomy and wake-up test</td>
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<tr>
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<td>P</td>
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<td>AS</td>
<td>2</td>
<td>P</td>
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<td>No</td>
</tr>
<tr>
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<td>CP</td>
<td>6</td>
<td>P</td>
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<td>Removal of bone graft</td>
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<td>No</td>
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<tr>
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<td>3</td>
<td>P</td>
<td>Kyphosis correction 50°</td>
<td>Correction reduced by 10°</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

All 16 patients had surgical-induced neurologic events.

i = idiopathic scoliosis; CP = cerebral palsy; AS = ankylosing spondylitis; RA = rheumatoid arthritis; P = posterior; A = anterior.

Table 1. Positive Monitoring Outcomes
The monitoring outcome is the outcome registered by the neuromonitoring system. In contrast to the clinical outcome, it is not fixed. It is influenced by the criteria (see later discussion) applied during monitoring.

A negative monitoring outcome is identified when no amplitude decreases result from the surgical maneuvers meeting the warning criteria. A positive monitoring outcome is identified when an amplitude decrease results from surgical maneuvers meeting the warning criteria. The success of neuromonitoring in detecting surgically induced neurologic deficit can be expressed in terms of true or false-positive and true or false-negative monitoring outcomes.

**Criteria.** To determine which amplitude decrease was most useful in detecting neurologic deficit, the complete patient data set was analyzed three times, each time using a new criterion to define the positive monitoring outcomes. Criterion A allowed registration of a positive monitoring outcome if one of six recordings had more than an 80% decrease in amplitude. Criterion B allowed registration of a positive monitoring outcome if two of six recordings had more than an 80% decrease in amplitude. Criterion C allowed registration of a positive monitoring outcome if one of the two anterior tibial muscle recordings had more than an 80% decrease in amplitude.

**Outcome Parameters.** To determine the success of the three criteria, the sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated for each of the criteria with the corresponding 95% confidence intervals.

Sensitivity is the percentage of positive outcomes correctly indicated by the monitoring procedure. Specificity is the percentage of negative outcomes correctly indicated by the monitoring procedure. The PPV is the chance of a “neurologic event,” given a positive monitoring outcome. The NPV is the chance of no neurologic event occurring, given an undisturbed monitoring procedure.

**Nonsurgically Induced Neurologic Deficits.** The purpose of this study was to define explicit criteria that warn of surgically induced neurologic damage. These criteria can be defined only if there are no anesthetic or systemic problems. Therefore, in the attempt to determine these criteria, patients with intraoperative systemic or anesthetic problems causing TCE–MEP amplitude decreases were excluded.

**Results**

For this study, TCE–MEP monitoring was started in 145 patients undergoing corrective deformity surgery. There were no side effects or complications of the transcranial electrical stimulation monitoring technique during or after surgery.

In two patients, monitoring was not continued after measurement of the reference values. These patients showed virtually no clinical neurologic functions. Consequently, reference EMG amplitudes were measured be-

![Figure 2](image-url)
low background noise (<10 μV). The monitoring of one patient was not completed because of technical malfunction that could not be repaired during surgery.

Severe amplitude decreases, as indicated in the three-step protocol, occurred as a result of systemic or anesthetic changes in 10 of the 142 patients monitored. These patients were therefore excluded, leaving 132 patients for the analysis.

All 10 monitoring procedures were continued successfully with measurable low amplitudes. No increased postoperative neurologic deficit was diagnosed. Among this group of excluded patients, five patients had pre-existing neurologic deficits.

*Positive Clinical Outcomes*
A positive clinical outcome was identified in 16 patients (Table 1). Corrective surgical maneuvers were performed in 13 of these patients, resulting in amplitude recovery without postoperative neurologic deficits in 11 of the 13 patients. Figure 2 illustrates the recovery of amplitude after subsequent intervention in 1 of the 11 patients (patient 9) (Table 1). In the two patients for whom no amplitude recovery was obtained by additional surgical intervention, postoperative neurologic function had deteriorated. In both patients, the sensibility was intact. One patient, who underwent a scoliosis correction experienced persistent muscle weakness of the right leg. In the other patient, who had cervical osteotomy in ankylosing spondylitis, a complete loss of motor function in both arms and legs was diagnosed directly after surgery, for which additional surgical procedures followed. During the follow-up period, the muscle weakness persisted, with partial motor function of both hands and one leg and a complete paresis of the other leg.

In 3 of 16 patients with a positive clinical outcome, additional surgical maneuvers were not, or could not, be performed intraoperatively. Two of these patients showed no recovery of amplitude, and neurologic deficits were found postoperatively. The sensibility of both patients was intact. One patient showed weakness in the muscles of the quadriceps. Muscle weakness of the right leg was diagnosed in the other patient, which improved during the follow-up period.

In the remaining patient, a spontaneous intraoperative amplitude recovery took place 45 minutes after the amplitude decrease. This patient had a transient ataxic gait problem, but had fully recovered after 3 months.

*Evaluation of Warning Criteria*
The results after application of the three warning criteria are listed in Figures 3, 4, and 5. If Criterion A had been used, all 16 positive outcomes would have been detected, so no neurologic event would have occurred unnoticed. Hence Criterion A yields a sensitivity of 1.0 (95% CI lower bound, 0.97) and a negative predictive value of 1.0 (95% CI lower bound, 0.97). However, 10 of the 126 negative clinical outcomes would have been misclassified as positive, yielding a specificity of 0.91 and a positive predictive value of 0.61 (95% CI, 0.41–0.80). This criterion, that at least one recording must show an amplitude decrease of at least 80%, is sufficiently stringent to prevent the occurrence of false-negatives in this group of patients.

If Criterion B had been used, more false-negatives would have occurred (3 patients) than with criterion A, yielding a lower sensitivity (0.81; 95% CI, 0.54–0.96) and a negative predictive value (0.97; 95% CI, 0.91–0.99). The number of false-positives would have been 3,
resulting in a slight increase in specificity (0.97; 95% CI, 0.91–0.99) and a slightly higher positive predictive value (0.76; 95% CI, 0.50–0.93).

If Criterion C had been used, two false-negative and six false-positive outcomes would have been obtained, yielding in comparison with Criterion A, a decreased sensitivity (0.88; 95% CI, 0.62–0.98) and a decreased negative predictive value (0.98; 95% CI, 0.94–0.99), whereas the specificity (0.95; 95% CI, 0.89–0.98) and positive predictive value (0.7; 95% CI, 0.46–0.88) would have increased.

Patients With Preoperative Neurologic Deficits

In this study, 39 of 145 patients had preoperative neurologic deficits. The findings showed TCE–MEP amplitude decreases in 26% of these neurologic compromised patients: in 5 patients because of neurologic damage and in 5 patients because of systemic or anesthetic changes. This is more than in the group of neurologically intact patients before surgery (11%), but the differences are not significant.

Discussion

Transcranial motor-evoked potentials are used increasingly for intraoperative neuromonitoring during corrective spinal surgery. In contrast to SSEP, this technique monitors the more vulnerable and clinically more relevant motor pathways, and averaging procedures are not required. However, monitoring guidelines are available for SSEP: A decrease in amplitude of 50% or an increased latency of more than 10% is considered a warning criterion. For TCE–MEP, the threshold values that warn of imminent neurologic damage have not yet been established. Methodologically, it is difficult to determine warning criteria because it is ethically unacceptable to ignore neuromonitoring outcomes while waiting for postoperative evaluation to determine whether these signal changes were indeed true-positives of false-positives. Accepting the limitations of evaluating monitoring outcome criteria in a clinical setting, the authors attempted to evaluate three different sets of criteria related to well-defined clinical outcomes.

In this study, TCE–MEP monitoring allowed short-interval monitoring of the motor tracts in 142 of 145 consecutive patients who underwent corrective spinal surgery, including 39 patients with preexisting neurologic deficits. The high rate of successful application was obtained by using a custom-made stimulator.

Of the 16 neurologic events (11%) identified, recovery of response amplitude was obtained in 11 after subsequent surgical maneuvers. It is assumed that the subsequent surgical intervention prevented postoperative neurologic deficit in these 11 patients (7% of the study population). It is exactly for this reason that neuromonitoring is performed.

The number of positive clinical outcomes (neurologic events) in this study is relatively high, as compared with those in reports. There are three possible explanations for this relatively high incidence.

First, this may reflect the patient population. Patients with preexisting neurologic deficits and congenital scoliosis are considered more vulnerable to intraoperative neurologic damage. In this study, patients with preexistent neurologic deficits had a higher incidence of positive monitoring outcomes, more positive clinical outcomes, and more intraoperative systemic problems, but these differences were not statistically significant.

Second, the high incidence of positive clinical outcomes may result from the sensitivity of motor-evoked potential monitoring. As a consequence of this increased sensitivity, harmful situations may have been registered that otherwise would not have been noticed.

Third, the authors considered both the occurrence of postoperative neurologic deficit and the severe amplitude decreases that recovered after additional surgical intervention as positive outcomes. In the latter case, it was assumed that the neurologic event would have led to a postoperative neurologic deficit if there had been no surgical intervention. However, the amplitudes may have recovered spontaneously without the subsequent surgical intervention. In such an event, this definition may have led to more diagnoses of neurologic events than actually occurred.

When three different warning criteria were applied retrospectively to the TCE–MEP recordings of 142 patients, it appeared that at least one amplitude decrease of at least 80% (Criterion A) would be a sufficiently stringent warning criterion to ensure that no neurologic events go undetected. Application of less strict
criteria, in terms of how many muscles recordings must decrease, leads to a loss in sensitivity. Recording only two instead of six muscles also lowers the sensitivity. Although there is a gain in specificity, the importance of preventing the clinical consequences of a false-negative (undetected neurologic event) is so great that the advantage of monitoring two instead of six muscle sites does not outweigh the cost of permanent neurologic damage in the three patients who would not have been detected. Although 16 neurologic events are too few for finding any statistically significant differences between the results of the various criteria, the 95% confidence intervals suggest that the actual sensitivity, when Criteria B and C are applied, may be as low as 0.54 and 0.62, respectively. Because falsenegatives are absent when criterion A is used, the lower limit of the 95% CI indicates that clinicians may confidently conclude the actual sensitivity is at least 0.97.

Furthermore, in clinical practice, the great added advantage of monitoring six instead of two muscles is the greater possibility of interpreting and judging the changes intraoperatively when strict criteria cannot be applied, as in patients with complex neurology or during hypotension or hypothermia. Therefore, in the authors’ opinion, the use of multiple monitoring sites must be encouraged considering the minimal extra effort required.

A known disadvantage of neuromonitoring (SSEP and MEP) is the variability of response amplitudes caused by anesthetic and systemic changes.9,16,20,21

In this study, TCE–MEP monitoring was performed in combination with a strict anesthetic regimen and a three-step protocol to evaluate the clinical conditions such as technical failures or anesthetic or systemic changes. Severe amplitude decreases (80% or more) caused by systemic problems such as hypotension occurred in 10 patients (7%). Transcranial motor-evoked potentials allow reliable neuromonitoring of almost all patients undergoing corrective spinal surgery, including patients with preexisting neurologic deficits. As a result, it seems plausible to assume that neurologic deficits were prevented in 11 of the 145 patients in this study group. A strict anesthetic protocol is essential, and the team approach of surgeon, anesthesiologist, and electrophysiologist is particularly important.

Although the current study population seemed quite large, because the number of positive outcomes was small, it was not possible to show any statistically significant differences in the success of the criteria tested. Therefore, only descriptive results can be provided. Despite this, the authors consider that one of six muscle-site responses showing a amplitude decrease of 80% or more (providing the patient is hemodynamically stable) is a safe criterion that warns of impending neurologic deficits. Six muscle monitoring sites make the interpretation of results easier in difficult cases and may increase sensitivity.

### Key Points

- Intraoperative neuromonitoring; SSEP and TCE–MEP monitoring.
- TCE–MEP in 145 patients undergoing spinal deformity surgery.
- Nonsurgical amplitude changes: the use of the three-step protocol.
- Definitions of neurologic events, clinical outcome and monitoring outcome.
- Criteria of TCE–MEP monitoring.

## References


