Focus on the Spine

**TRANSCRANIAL MAGNETIC MOTOR-EVOKED POTENTIALS IN SCOLIOSIS SURGERY**

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**ABSTRACT**

Spinal cord monitoring using SSEPs is an accepted adjunct in the surgical correction of spinal deformities, but does not directly assess motor function. Motor-evoked potentials have been introduced in an effort to meet this important need. In this series of 18 patients, the feasibility of intraoperative monitoring using transcranial magnetic motor-evoked potentials is documented. The potential value of this neurophysiologic monitoring technique, as well as the pitfalls in interpretation, are reviewed.

Spinal cord monitoring using somatosensory-evoked potentials (SSEP) has become an important adjunct in the surgical correction of spinal deformities. Although SSEP monitoring has been effective in minimizing the incidence of neurologic complications, it does not directly assess function of the susceptible descending motor pathways of the spinal cord. Both false negative and false positive SSEP results follow-

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had Type I, 1 had Type II, and 1 had a left thoracolumbar curve. One patient had a double major scoliosis secondary to Marfan’s syndrome. Two patients had neurofibromatosis, one with an idiopathic-like right thoracic curve and the other with a high thoracic angular kyphoscoliosis. Two patients had congenital scoliosis; a kyphoscoliosis secondary to a dorsolateral hemivertebrae, and a complex lumbar curve.

Preoperative neurologic examination was normal in all cases. Twelve patients underwent preoperative bilateral posterior tibial nerve SSEP recordings. Stimulus intensity was a constant current set at the induction of toe flexion with a 5.64 stimulus per second repetition rate. Cortical and cervical responses were recorded from a CZ-FZ, and CS2-FZ or CS5-FZ montage using a 10-1000 Hz bandpass, and averaged over 500 repetitions. Response was evaluated based on P37 and N45 wave scalp components and C2 or C5 cervical potentials. A band electrode around the calf was utilized as a ground. All preoperative SSEPs were normal.

Preoperative tcMMEPs were also performed in 12 cases. Motor-evoked potentials were elicited by delivering a transcranial magnetically induced electrical stimulation generated by a Cadwell MES-10 stimulator (Cadwell Corp, Kennewick, Wash) (Fig 1). A Cadwell adult cap coil (Cadwell Corp, Kennewick, Wash) was placed on the calvarial vertex. Stimuli were presented at an intensity of 60% to 80% output of the 2 Tesla stimulator, although intensity was increased to 100% (187 volts) if the stimulation was well tolerated. The pulse width of the stimulus was 70 μsec. Evoked activity was recorded using a Cadwell Excel electrophysiologic monitor (Cadwell Corp, Kennewick, Wash) via surface electrodes overlying the left and right tibialis anterior (TA) muscles. Patients received only a single stimulation in most cases. Patients were not considered candidates for MEP monitoring if they had a history of a seizure disorder, had an infected pacemaker, had undergone previous surgery involving metallic implants in or around the brain, or if preoperative tcMMEPs could not be elicited. The study was performed with the approval of the Human Experimentation Committee of the University of Louisville, and informed consent was obtained prior to tcMMEP testing.

Preoperatively, 36° standing anteroposterior, lateral, and supine bending radiographs were performed. The primary curve ranged from 42° to 85° (mean: 57°). The compensatory curve ranged from 29° to 61° (mean: 54°). Curve flexibility on bending films was calculated as percent correction, and ranged from 21% to 71% in the primary curvature, and 30% to 100% in the compensatory curvature.

Anesthesia was induced using sodium thiomephal (125 to 150 mg) in 11 cases. Because of the global suppression of tcMMEPs seen with thiopental induction, etomidate (0.3 mg/kg) was chosen for induction in seven cases during the latter aspect of the series. Although etomidate caused minimal suppression of tcMMEP responses, a brief myoclonic seizure was noted in one patient on induction, but prior to any tcMMEP testing. The seizure was treated by administration of neuromuscular blocking agent, without sequelae.

Anesthesia was maintained using 60% nitrous oxide in combination with fentanyl in 13 patients, and with sufentanil in 5 patients. Neuromuscular blockade was produced using atracurium in 12 patients, and vecuronium in 6 patients. Neuromuscular blockade was administered until the residual neuromuscular activity was approximately 20% of normal, as measured by change in amplitude of the electromyographic responses in the first interosseous muscle following ulnar nerve stimulation. Peak to peak amplitude was quantified using the Relaxograph monitor (Datex Instrument Corp, Helsinki, Finland), with the exception of 3 cases in which Relaxograph malfunction occurred.

Intraoperatively, tcMMEP and SEP responses were recorded in all patients. SEP parameters were similar to the preoperative recordings with the exception that stimulus intensity was standardized at 30-40 mAmps. TcMMEP technique was also similar to the preoperative studies; however, responses were recorded using needle electrodes rather than surface electrodes, and assessment was based
on the average of five stimulations at a rate of 0.3 stimuli per second. Correlations between electrophysiologic potentials and anesthetic regimen were monitored. A wake-up test was performed in 14 cases. Neurophysiologic responses were examined carefully for any inter-test variation between SSEP, tcMMEP, and the wake-up test. Surgical approach, operative time, blood loss, and any change in clinical stability were noted.

Postoperatively, 36° standing anterioposterior and lateral radiographs were repeated. Instrumentation levels and curve correction were recorded. Postoperative neurologic examination was also recorded.

RESULTS

Neurophysiologic Data. Preoperative SSEP data in 12 patients demonstrated bilateral symmetry of the P37 and N45 peaks with mean latencies of 38.2 ms (SD = 2.5 ms) and 45.6 ms (SD = 2.9 ms) versus 37.7 ms (SD = 2.8 ms) and 46.3 ms (SD = 3.0 ms) from the left and right, respectively. In no instance was the variation between the left and right side response greater than 10% in any individual patient. Preoperative tcMMEP data revealed symmetric responses recorded from the legs in 11 of 12 patients. Mean preoperative onset latency was 29.2 ms (SD = 2.2 ms) on the left and 28.8 ms (SD = 1.9 ms) on the right. In one instance of kyphoscoliosis secondary to a dorsolateral thoracolumbar hemivertebra, significant asymmetry of the waveform was noted. In this patient, SSEP and upper extremity tcMMEP latencies were comparable; however, lower extremity tcMMEP onset latency was 26 ms on the left and 33 ms on the right (Fig 2). Neurologic examination was normal.

Intraoperative SSEPs and tcMMEPs were attempted in all patients. SSEPs were successfully recorded in each instance. Fourteen patients underwent a wake-up test, with one patient requiring serial wake-up tests. All wake-up tests revealed normal function. The first two patients in the series had only unilateral tcMMEP responses; however, no attempt was made to reposition the coil location to obtain bilateral responses. Bilateral tcMMEP responses were recorded in the next 16 patients in the prone position, although isolated unilateral responses were frequent while the patient was in the lateral decubitus position for the anterior approach. In one patient, bilateral tcMMEP responses could not be elicited with a single coil location, but either side could be recorded with coil adjustment. Relaxograph malfunction resulted in inability to adequately assess neuromuscular blockade, resulting in intermittent loss of tcMMEPs, without change in SSEPs, in three cases.

Fig 2: Preoperative TcMMEP recordings from the left and right tibialis anterior muscles demonstrate asymmetric onset latencies in this patient with kyphoscoliosis secondary to a dorsolateral hemivertebra body.

Alterations in tcMMEP responses related to operative manipulation were noted in three cases. Case 1 was an 11-year-old girl undergoing an anterior hemivertebra body resection for a 42° kyphosis at T11-12 who had a unilateral tcMMEP latency increase and amplitude depression noted with an apparently atraumatic resection of the posterior cortex of the hemivertebra body (Fig 3). Associated SSEP changes were recorded as well. Both tcMMEPs and SSEPs returned to baseline following completion of the anterior body resection. A wake-up test performed following the posterior instrumentation was normal.

In two patients tcMMEP changes were noted in conjunction with placement and manipulation of spinal instrumentation. Case 2 was a 13-year-old boy with a 42° idiopathic scoliosis (King Type V) who had prolonged latency and decreased amplitude noted bilaterally during placement of the left-sided rod. Following adjustment of the rod, bilateral tcMMEP onset latency and right-sided, peak-to-peak amplitude returned to baseline, although the left-sided amplitude remained depressed. On the wake-up test the patient moved his feet symmetrically to command. Case 3 was a 12-year-old girl with an angular kyphoscoliosis secondary to neurofibromatosis who underwent right thoracotomy for multiple anterior discectomies. The right-sided tcMMEP response and bilateral SEP responses were reproducible. No left-sided tcMMEP response was obtained. Bilateral tcMMEP responses returned when the patient was placed in the prone position for the posterior approach. During placement of the posterior instrumentation, both tcMMEP and SEP responses were lost on the right side only. The wake-up test, performed following adjustment of the instrumentation, revealed normal function. Right-sided responses subsequently returned, although onset latencies remained delayed and peak-to-peak amplitudes were decreased. With further manipulation of the instrumentation, responses were again lost and
Fig 3: Degradation of TcMMEP response on the right during resection of the posterior cortex of a hemivertebra body (A). Associated SSEP changes during hemivertebra body resection (B). Both TcMMEPs and SSEPs recover following completion of the anterior body resection.

Fig 3A.

Fig 3B.

then returned. A second wake-up test prior to closure was again normal (Fig 4).

Surgical Data. Posterior instrumented fusion was performed in eight patients, and combined anterior and posterior procedures were performed in 10 patients. Length of surgery varied from 2 hours, 55 minutes to 7 hours, 55 minutes (mean: 3 hrs, 40 min) in the posterior group vs 5 hours, 10 minutes to 9 hours, 15 minutes (mean: 7 hrs, 30 min) in the combined anterionposterior group. Estimated blood loss ranged from 600 cc to 3500 cc (mean: 1600 cc). Patients received cell saver transfusion of between 100 cc and 625 cc (mean: 409 cc) and transfusion of 0 to 3 units (mean 1.2) of autologous packed red blood cells.

Postoperatively, the corrected primary curve measured between 6° and 48° (mean: 14°). Percent correction of the preoperative deformity ranged from 44% to 89% (mean: 73%), compared to 45% correction seen on preoperative bending films. Correction of the compensatory curve ranged from 28% to 100% (mean: 47%).

No new neurologic deficits were detected postoperatively.

DISCUSSION

Since the introduction of the Harrington rod in 1962, spinal instrumentation has been widely used in the treatment of scoliosis and other spinal deformities. As an integral part of this treatment, considerable attention has been directed toward minimizing the risk of neurologic injury associated with the surgical correction of spine deformity. This effort includes advances in intraoperative neuromonitoring techniques as well as surgical procedures designed to limit mechanical or physiologic stress to the spinal cord.

Intraoperative monitoring of motor function in the extremities was initially performed by the Stagnara wake-up test. Electrophysiologic spinal cord monitoring using somatosensory-evoked potentials (SSEPs) has subsequently become an important clinical tool. SSEPs are advantageous in that they are noninvasive and provide continuous feedback as to sensory neurologic function throughout an entire operative procedure. However, SSEPs are unable to monitor descending motor pathways of the spinal cord. Continuous assessment of motor function remains an important goal for neurophysiologic monitoring during correction of spinal deformities. TcMMEPs provide such a continuous monitoring capability. Further, animal studies suggest that MEPs may be more sensitive than SSEPs in identifying compromise of spinal cord function. The greater sensitivity of MEPs may provide an early warning system for impending spinal cord injury.

TcMMEP technique has been established in animal models and in diagnostic clinical testing, but it has not achieved widespread use as an intraoperative monitoring technique. Limitations to intraoperative utilization of tcmMMEPs include the complexity of the technique as well as the effect of anesthetics and neuromuscular blocking agents in suppressing the responses. Recent advances,
such as the development of a cap coil which generates a more focused magnetic field and the use of a Relaxograph monitor which more accurately detects the level of neuromuscular blockade, have facilitated the clinical application of intraoperative tcMMEPs. Increased awareness and attention to the importance of the anesthetic regimen on the production of tcMMEPs also has dramatically improved reliability and reproducibility of tcMMEPs.

The effect of anesthetic agents including halothane, sodium thiopental, ketamine, etomidate, and fentanyl on tcMMEPs has been studied in a dog model. That study demonstrated that the magnitude and duration of tcMMEP suppression seen under anesthetic is dependent on the specific anesthetic agent used. In the present clinical study, anesthetic was induced using sodium thiopental in the first 10 patients. Because of the transient suppression of tcMMEPs seen with thiopental induction, etomidate was chosen for induction in 7 of the remaining 8 patients. Although use of etomidate facilitated production of tcMMEP responses, an etomidate induced seizure was noted in 1 patient and was readily treated with neuromuscular blockade. This is a recognized risk of etomidate. Several patients experienced postoperative nausea, which was treated with an antiemetic agent.

Anesthesia was maintained using nitrous oxide in combination with fentanyl in 13 patients, and with sufentanil in 3 patients. Neuromuscular blockade was produced using atracurium in 12 patients, and vecuronium in 6 patients. No significant differences in either latencies or amplitudes of the tcMMEPs were noted comparing fentanyl and sufentanil, or atracurium and vecuronium. Neuromuscular blockade was quantified using the Relaxograph monitor, with the exception of 3 cases in which Relaxograph malfunction occurred. In these 3 patients, tcMMEPs were lost bilaterally without change in SSEPs. While blockade of up to 80% of neuromuscular activity is compatible with the production of reliable tcMMEPs, accurate measurement of the degree of neuromuscular blockade with the use of a Relaxograph monitor has greatly facilitated the interaction between anesthetic and neuromonitoring requirements. Reliance on peripheral nerve stimulation to assess the depth of neuromuscular blockade results in less reproducible tcMMEP responses.

There are several distinct advantages of transcranial stimulation to produce tcMMEPs. Initially, motor-evoked potentials were elicited by electrical stimulation induced by passing current between two electrodes. To stimulate deeper regions within the brain, the flow of current between the electrodes must be increased. As the current flow is increased, pain fibers are activated and the test becomes painful in the awake patient. Alternatively, the nervous system can be stimulated via current induced by a time-varying magnetic field. Tissues such as the scalp and skull are transparent to the magnetic field and, therefore, the stimulation intensity required to elicit a response from the deeper motor cortex does not produce pain in the superficial structures. This phenomenon allows for tcMMEPs to be produced painlessly in an awake patient. Awake stimulation permits measurement of a preoperative baseline in each patient, for comparison with intraoperative recordings. Asymmetry seen subsequently in the intraoperative responses would therefore not be misinterpreted as a clinically relevant change secondary to induction of anesthesia or positioning of the patient.

Second, induction of tcMMEPs from a site outside of the surgical field allows ongoing monitoring concurrent to surgical manipulation. This
external technique also excludes any added source of infection associated with stimulating equipment within the surgical field. Thirdly, stimulation at a site distant from the lower motor neurons avoids inadvertent direct stimulation of peripheral nerve fibers. A study of direct magnetic stimulation of the spinal cord, evaluated before and after root lesioning, indicated that the nerve roots were actually being stimulated distal to their point of exit from the spinal cord. Transcranial stimulation minimizes the likelihood of peripheral nerve stimulation which might compromise the clinical reliability of the recorded responses.

The occurrence of transient tcMMEP changes in three patients provides a preliminary demonstration of the benefits as well as the pitfalls associated with clinical application of motor evoked potentials. Preoperative asymmetry was noted in only one patient, with kyphoscoliosis secondary to a dorsolateral hemivertebraal body. This raises the question of subclinical anterior or anterolateral cord compression, which is consistent with the known risk of neurologic compromise associated with congenital kyphosis. TcMMEP responses were significantly altered during an apparently atraumatic resection of the posterior cortex of the hemivertebraal body, but returned promptly after the dissection was completed. Concurrently, SSEP responses were lost; however, their rapid return with a waveform unaltered from baseline might have obscured the validity of these transient SSEP changes. The fact that tcMMEP and SSEP changes occurred simultaneously and in conjunction with spinal canal manipulation strongly suggests that the monitored changes reflect a true pathologic event. Although the resection of the posterior wall of the vertebral body seemed atraumatic, the dissection technique may have caused sufficient compression to produce the tcMMEP findings. The clinical impact was apparently inconsequential, as a subsequent wake-up test was normal and the patient had no neurologic deficit postoperatively.

One case of instrumentation-related tcMMEP changes occurred early in the series, and concurrent SSEP data were not recorded at the time that tcMMEP changes were observed. The temporal association of the tcMMEP alterations with distraction, as well as the recovery of tcMMEP responses with adjustment of the rods, suggests an accurate neurophysiologic assessment. Further interpretation is, however, difficult in the absence of comparative SSEP responses.

In the second instance of instrumentation-related tcMMEP changes, corroborative SSEP data are available, and are consistent with the tcMMEP findings. Despite this correlation, interpretation of the neuromonitoring results remains complicated. Two subsequent wake-up tests were normal. This may have been the result of instrumentation adjustments made in response to the neuromonitoring, or an indication that tcMMEP changes are so sensitive that they identify subclinical events. Further, as the patient had neurofibromatosis and a dystrophic deformity, the neurophysiologic responses to either operative stimuli or magnetic stimulation may be different than would be seen in idiopathic scoliosis.

Despite significant advances, these three cases demonstrate that difficulties remain in the clinical application of tcMMEPs. More accurate interpretation of awake baseline tcMMEPs will require collection of further normative data. Although development of the cap coil has markedly improved tcMMEP reproducibility, further standardization of coil and recording site placement would be beneficial. At this point, interpretation of tcMMEP response is based largely on measurement of onset latency. While onset latency is a reproducible parameter, quantification of the measured changes for correlation to clinical neurologic deficit will require further experience. The significance of changes in tcMMEP peak-to-peak amplitude, if any, remains to be evaluated. The relationship between tcMMEPs and SSEPs must be studied with respect to type of deformity, curve severity, curve flexibility, and associated diagnostic entities. Investigation as to the role of patient positioning may clarify whether variation in potentials with the patient in the lateral decubitus versus prone position represents recording artifact or an actual physiologic alteration.

While it is important to recognize deficiencies of the technique so that improvement will continue, the tcMMEP has progressed from the theoretical stage to a clinically applicable tool. TcMMEPs are now used as an adjunct in anterior cervical disectomy in addition to the correction of spinal deformities (Shields CB, personal communication, 1993). Intraoperative tcMMEPs have proven sufficiently reproducible to provide clinically useful information as to the function of the motor pathways in some cases. The frequency of motor deficits following deformity surgery is small, so that a large volume of cases will be required to demonstrate significant differences in the predictive capability of the tcMMEP as compared to the SSEP. However, as seen in previous animal studies, the MEP appears extremely sensitive in detecting subtle changes in neurologic function. Finally, concurrent measurement of SSEPs and tcMMEPs has enhanced the interpretation of marginal SSEP changes that might otherwise be overlooked.

The correlation between electrophysiologic and clinical assessments of lower limb motor function during surgery is presented. The importance of an anesthetic approach encompassing
precise, monitored infusion of both narcotic and short-acting, nondepolarizing, neuromuscular blocking agents is emphasized. While the tcMMEP provides an important addition to neuromonitoring capabilities, the wake-up test remains the standard against which other modalities must be measured. Further, it should be noted that while transcranial magnetic stimulation produced no adverse effects in this series, the technique has not been approved by the FDA for use outside of an investigational setting. It seems prudent to gain additional experience before this new technique and concurrent SSEP monitoring might replace the wake-up test.

REFERENCES