Intraoperative Neurophysiological Monitoring during Spine Surgery: A Review

Andres A. Gonzalez, MD; Dhiraj Jeyanandarajan, MD; Chris Hansen, BA, CNIM; Gabriel Zada, MD; Patrick C. Hsieh, MD

Neurosurg Focus. 2009;27(4):E6

Abstract and Introduction

Abstract

Spinal surgery involves a wide spectrum of procedures during which the spinal cord, nerve roots, and key blood vessels are frequently placed at risk for injury. Neuromonitoring provides an opportunity to assess the functional integrity of susceptible neural elements during surgery.

The methodology of obtaining and interpreting data from various neuromonitoring modalities—such as somatosensory evoked potentials, motor evoked potentials, spontaneous electromyography, and triggered electromyography—is reviewed in this report. Also discussed are the major benefits and limitations of each modality, as well as the strength of each alone and in combination with other modalities, with regard to its sensitivity, specificity, and overall value as a diagnostic tool. Finally, key clinical recommendations for the interpretation and step-wise decision-making process for intervention are discussed.

Multimodality neuromonitoring relies on the strengths of different types of neurophysiological modalities to maximize the diagnostic efficacy in regard to sensitivity and specificity in the detection of impending neural injury. Thorough knowledge of the benefits and limitations of each modality helps in optimizing the diagnostic value of intraoperative monitoring during spinal procedures. As many spinal surgeries continue to evolve along a pathway of minimal invasiveness, it is quite likely that the value of neuromonitoring will only continue to become more prominent.

Introduction

Intraoperative neurophysiological monitoring is a continually evolving field that aims to localize and monitor neural structures according to their functional basis and ultimately preserve their structural integrity. During spinal surgery, several structures are placed at risk for potential injury, including the spinal cord, nerve roots, lumbar plexus, and all relevant vascular supply to these elements. Several electrophysiological modalities are currently available for monitoring various aspects of the central and peripheral nervous system, each offering a unique set of benefits, limitations, and sensitivity/specificity as diagnostic techniques. The most frequently used modalities for spinal procedures are SSEPs, MEPs, freerun or spontaneous EMG (sEMG), and triggered EMG (tEMG). To optimally preserve the neural structures during spinal surgery, an interdisciplinary effort among the surgical, neuromonitoring, and neuroanesthesia teams is imperative.[37] Beyond the acquisition and communication required for intraoperative monitoring lies the art and science of interpreting the numerous permutations of results offered by multimodality intraoperative neuromonitoring, during a wide variety of spine surgeries. This article serves as a review of the most commonly used techniques available for the stimulation and recording of neural function in the current era of spinal surgery, the warning criteria used in each modality, and some of the intrinsic technical limitations relevant to each. This is followed by suggested recommendations for monitoring appropriate structures at risk through the application of specific electrophysiological tests, either alone or in combination.

Monitoring Modalities

Somatosensory Evoked Potentials

Spinal cord electrophysiological monitoring techniques arose in the 1970s, when SSEPs were described for monitoring the spinal cord during surgical deformity correction for scoliosis.[34] Since that time, the ability to monitor SSEPs has evolved tremendously, and SSEP monitoring currently remains the mainstay of spinal cord monitoring.[23,25,35] The monitoring of SSEPs is widely used to assess intraoperative neural function during a wide variety of spinal procedures.

Somatosensory evoked potentials provide monitoring of the dorsal column-medial lemniscus pathway, which mediates tactile discrimination, vibration sensation, form recognition, and joint/muscle sensation (conscious proprioception).[10] Receptors in the skin, tendons, and muscles generate information that corresponds to these primary sensory modalities and relay these signals to neurons whose soma are located in dorsal root ganglia at all spinal levels. It should be noted that SSEPs do not involve the spinothalamic (pain and temperature) pathway. Axons from these first-order neurons project to the spinal cord via the medial root entry zone, giving rise to the fasciculi gracilis and cuneatus, which subsequently carry sensory information from the lower and upper extremities, respectively. The first synapse in this pathway occurs in the lower medulla after these tracts ascend via the dorsal columns in the spinal cord. Following a decussation that occurs at the medullary level, the medial lemniscus is formed; it ascends to the thalamus and ultimately relays sensory information to the primary somatosensory cortex (Brodmann areas 3, 1, and 2). Since SSEPs monitor the dorsal column-medial lemniscus pathway, standard patient sensory examination for tactile discrimination, vibration sensation, and joint/muscle sensation (conscious proprioception) is recommended prior to surgery, to document any deficits that may limit intraoperative monitoring.

In the upper extremities, the median nerve (C-6, C-7, C-8, and T-1 roots) and ulnar nerve (C-8 and T-1) are frequently selected for monitoring, whereas the posterior tibial nerve (L-4, L-5, S-1, and S-2) and peroneal nerve (L-4, L-5, and S-1) are typically used in the lower extremities. Somatosensory evoked potentials involve electrical stimulation of mixed sensory and motor fibers caudal to the region of the spinal cord at risk, paired with recording of these signals rostral to the region at risk (typically at the dorsal neck and scalp). Electrical stimulation in the extremities produces major positive and negative deflections as signals ascend via the somatosensory pathway. Most often, a negative potential is measured at the scalp corresponding to the upper extremities at 20 milliseconds (N20), and a positive potential is measured at the scalp corresponding to the lower extremities at 37 milliseconds (P37). Additional subcortical waveforms can be obtained intraoperatively as the electrical volley propagates through the somatosensory pathway (Fig. 1). A peripheral response recorded at the level of the brachial plexus (for the upper extremities) or the popliteal fossa (for the lower extremities) can be performed to ascertain adequacy of stimulation.[19] These peripheral responses can also help to detect peripheral limb ischemia or nerve compression. It is important to note that in the case of SSEPs, these earlier peaks tend to be less sensitive to anesthesia, and can therefore frequently be used to differentiate SSEP monitoring changes resulting from anesthetic effects from those relating to surgical manipulation.

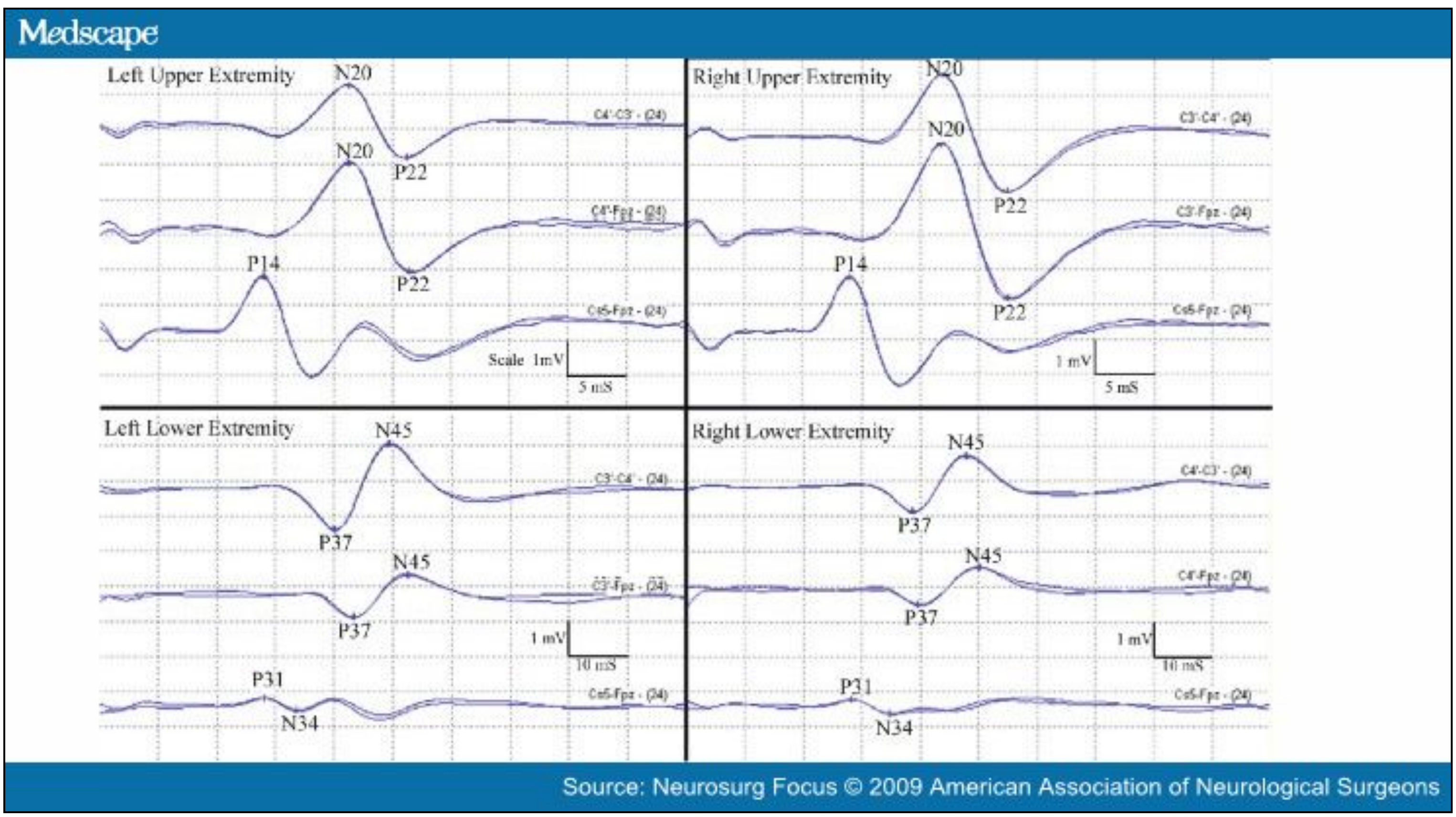

Figure 1.

Normal representations of SSEPs from median nerves and posterior tibial nerves, including cortical and subcortical waveforms.

Alarm criteria of a 50% reduction in amplitude and/or a 10% increase in latency are generally used as guidelines for notifying the surgeon of a potential deficit, and corrective intervention should be considered if these changes correspond to a particular surgical manipulation. The neuromonitoring team must be well versed in the potential causes of changes not directly related to surgery in order to minimize false-positive interpretations. Factors that potentially affect the SSEP amplitude include halogenated agents, nitrous oxide, hypothermia, hypotension, and electrical interference. A common factor affecting SSEP latency readings is temperature. Any SSEP changes with amplitude reduction of more than 50% should also be considered relevant if they are temporally associated with a specific surgical intervention, such as during placement of spinal instrumentation or during correction of a spinal deformity. In a landmark paper published in 1995, Nuwer et al.[35] evaluated the clinical efficacy of intraoperative SSEP monitoring performed during scoliosis surgery in a large multicenter survey of 51,263 spinal surgeries. They reported an overall sensitivity of 92% and specificity of 98.9% in the ability of SSEPs to detect new postoperative neurological deficits.

Although SSEP signals are good basic indicators of spinal cord function, less information is provided regarding nerve root function. Somatosensory evoked potentials are a composite of summated neural signals that enter the spinal cord through multiple segments. In addition, due to central amplification, it is possible for SSEPs to remain completely normal in the face of a nerve root injury. To study sensory nerve root function, various techniques have been developed to specifically stimulate segmental dermatomes with subsequent recording in the cortex, which are collectively known as dermatomal SSEPs. Although dermatomal SSEPs may offer the theoretical advantage of being more useful for monitoring spinal levels than are standard SSEPs, they are typically small, technically demanding, and do not correlate well with clinical outcome.[36,46,47]

Motor Evoked Potentials

Over the past 3 decades, MEPs have emerged as an extremely valuable and efficacious tool in the specialty of intraoperative neurophysiological monitoring. In 1980, work by Merton and Morton demonstrated that a high voltage pulse applied transcranially could elicit contralateral motor activity.[31] The single-pulse stimulation technique was found to be highly sensitive to anesthetic effects, and the technique has since been revised to using multi-pulse stimulation along with various modifications in anesthetic regimens to maximize monitoring ability. By the early 1990s, transcranial electrical stimulation was popularized as a method to monitor the corticospinal tracts[6] (Fig. 2). Additional refinements in methodology over the past 15 years have allowed for further quantification of motor responses related to corticospinal tract function.

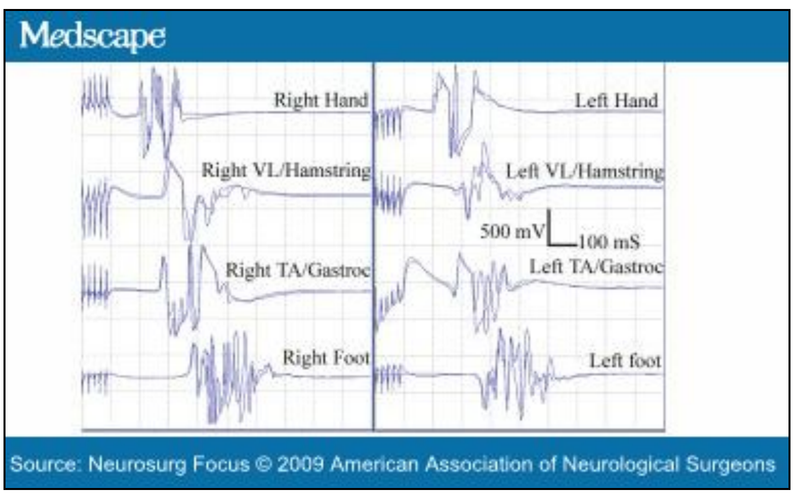

Figure 2.

Normal representations of MEPs from intrinsic hand muscles, vastus lateralis (VL), hamstrings, tibialis anterior (TA), gastrocnemius (Gastroc), and plantar foot muscles.

Prior to the widespread use of MEP monitoring, the only way to assess corticospinal tract integrity and resulting motor function during surgery was the Stagnara wake-up test, which involved waking patients during surgery and asking them to move their feet.[3,49] Although the patient does not feel any pain during this test and is amnestic to it afterward, this technique introduces significant delay times in surgery. Furthermore, this test lacks the obvious benefit of continuous assessment of neural function, and its use is limited in certain patients, such as those with cognitive or hearing deficits. Finally, if the test is positive and the patient has sustained a deficit in extremity function, it is possible that a substantial period of time has elapsed between the injury, its detection, and the ultimate intervention.

Because MEPs effectively monitor function of the corticospinal tract (a pathway that is not covered by SSEP monitoring), changes in MEPs are more sensitive in the detection of postoperative motor deficits.[5,14,16] There are several reported cases of patients demonstrating motor deficits following surgery in which SSEPs alone were monitored but failed to demonstrate any alarm criteria.[2,20] The deficits in these cases were thought to have been caused either through direct mechanical trauma or vascular compromise of the corticospinal tracts. The corticospinal tract and dorsal columns lie in different vascular and anatomical territories, with the dorsal columns receiving the majority of perfusion via the posterior spinal arteries, whereas the lateral corticospinal tracts, the anterior corticospinal tracts, and the anterior horn cells receive the majority of their blood supply via the anterior spinal artery. During scoliosis surgery, for example, small radiculomedullary arteries passing between the osseous rings of adjacent vertebrae may be stretched or compressed during correctional maneuvers, resulting in subsequent ischemia or infarction. If such an injury affects only the anterolateral funiculus, then postoperative motor deficits may occur without changes in SSEPs—with changes detected by MEP monitoring alone.

Monitoring of MEPs is currently used in a variety of spinal surgeries, including correction of spinal deformity, cervical and thoracolumbar degenerative cases, spinal trauma, and neoplasm resection. In addition, MEP monitoring is useful in thoracoabdominal aortic aneurysm repair, where the spinal cord is at significant risk for ischemic injury. Motor evoked potentials can be stimulated either transcranially or via direct cortical stimulation. Transcranial stimulation, in turn, can be performed either electrically or magnetically, with signal recording possible at the level of the muscle (compound muscle action potential), nerve (neurogenic MEP) or spinal cord (direct corticospinal wave [D-wave] recording).[1] Stimulation can also be performed in the spinal cord directly, with recording electrodes either in the nerve or the muscles. Although this technique offers the advantage of being less sensitive to anesthetic agents, responses obtained via direct spinal cord stimulation are less likely to represent motor function, but rather antidromic sensory responses.[32]

For standard transcranial MEP recording (TcMEP), stimulation electrodes are placed at C3 and C4 (10-10 International system) for activation of both upper and lower extremity muscle groups, with alternative sites at C1 and C2 if more focal activation of the lower extremity muscle groups is desired. Establishing a patient setup with multiple sites available for stimulation is recommended, especially in patients with myelopathy, given the greater difficulty in obtaining MEP recordings. The stimulation intensity alters the current field size and distribution to the cortex and subcortical fibers. Increasing stimulation intensity correlates with greater axonal recruitment and spatial summation along with bilateral stimulation. Subcortical white matter motor tracts are activated at the bend of the axon exiting the gray matter, or entering the internal capsule or even brainstem, which is not an issue when the structures at risk are located below the foramen magnum, as is the case in spine surgery. Stimulation trains increase temporal summation at the α-motoneurons, leading to a higher likelihood of achieving a stimulus threshold. Stimulation rates > 200 Hz are typically required for temporal summation at motoneurons. Latencies of 20 msec in the hand and 45 msec in the foot are typically observed, depending on various factors such as the underlying pathological condition, the patient's height, and body temperature. Certain groups have used alternate acquisition parameters for MEP monitoring, with varied success rates. One study determined the efficacy of posttetanic stimulation, in which the target muscle group was stimulated at 50 Hz at 25-50 mA for 2-5 sec, with a 1-5 sec interval before TcMEP. This technique potentiated the response under partial neuromuscular blockade, with a reported improved success rate of obtaining MEPs.[22]

Interpretation of MEP Recording. Currently, 4 methods are routinely used for interpretation for TcMEP responses: 1) the all-or-nothing criterion, 2) the amplitude criterion, 3) the threshold criterion, and 4) the morphology criterion. The all-or-nothing criterion is the most widely cited and used method, given the inherent variability of signals in MEP monitoring.[27] Based on this approach, a complete loss of the MEP signal from a preliminary baseline recording is indicative of a clinically significant event. Because of the all-or-nothing nature of this interpretation, it has been proposed that this method is not sensitive enough in detecting subtle deficits involving the corticospinal tract that may still result in postoperative motor deficits and are potentially correctable if detected.[8]

A modification of the all-or-nothing approach involves measuring the CMAP amplitude at baseline, then measuring relative changes in amplitude to determine if a clinically significant change has occurred. The amplitude criterion, as described by Langeloo et al.,[28] uses an 80% amplitude decrement in at least 1 out of 6 recording sites as a criterion for a clinically significant change. When this criterion were used in a study of 142 patients, a sensitivity of 100% was achieved with a specificity of 91%.

A similar form of reasoning can be applied to the threshold criterion, which analyzes the increases in stimulation threshold required to maintain CMAP responses. Calancie and Molano[8] described their experience using the MEP threshold criteria in a study of 903 subjects undergoing surgery at either cervical, thoracic, or lumbar levels. They reported that increases in the threshold of 100 V or more required for eliciting CMAP responses that are persistent for 1 or more hours and not due to systemic factors were highly correlated with postoperative motor deficits.

Lastly, the morphology criterion looks at impaired motor conduction of the corticospinal tracts by tracking changes in the pattern and duration of MEP waveform morphology. Specifically, Quinones-Hinojosa et al.[40] observed changes in the CMAP waveform elicited during motor stimulation, from a polyphasic to biphasic waveform or from polyphasic to biphasic and ultimately to loss of signals, in a subset of patients undergoing intramedullary spinal cord tumor resection. These changes persisted even after raising the threshold voltage by an average of 175 V, and they correlated significantly with postoperative motor deficits. In the event of observing the morphological changes described above, the neuromonitoring, anesthesia, and surgical team should perform a thorough analysis of factors that may be causing the waveform alteration. Common factors that may alter MEP waveform morphological characteristics include anesthetic fade, body temperature, blood pressure, surgical positioning, and technical pitfalls, among others.

Although MEPs have become the gold standard for neuromonitoring of the motor tracts, there are some disadvantages to MEP monitoring. Perhaps the major drawback of MEP monitoring is the inability to perform continuous monitoring (which can be accomplished with SSEPs), requiring that MEPs be obtained intermittently at given intervals during the surgery. Another inherent limitation of monitoring MEP signals is that they may be more technically challenging to obtain. Current success rates for obtaining MEPs are approximately 94.8% in the upper extremities and 66.6% in lower extremities (compared with 98 and 93%, respectively, for SSEPs).[9] If preoperative motor deficits exist at the time of surgery, the ability to obtain MEPs plummets to approximately 39% in the lower extremities. For optimal acquisition of signals, total IV anesthesia is used, in which compounds such as nitrous oxide, volatile agents, and muscle relaxants are excluded, and short-acting agents such as fentanyl and propofol are relied upon to achieve anesthetic control. Although this may pose more of a challenge to the anesthesia team and possibly the surgeon, given potential movement of the patient, total IV anesthesia offers clear benefits in obtaining MEPs over inhaled anesthetics.[39] Anesthetic inhalants decrease the possible pool of motoneurons available for recruiting. Since the propagation of a peripheral motor response is dependent on indirect wave (I-wave) generation, inhaled agents may interfere with MEP acquisition as they inhibit the interneuron generators of I-waves at the level of the cerebral cortex and the anterior horn cells. Even in cases in which total IV anesthesia is used, higher levels of propofol may cause suppression of α-motoneurons, a factor that should always be considered when interpreting MEP loss or amplitude reduction in this setting.[21] Another limitation of TcMEP monitoring is that it is currently contraindicated in patients with deep brain stimulators or cochlear implants. These, and several other contraindications to MEP monitoring, must always be weighed against the benefits provided by the technique. Although the technique is generally safe, tongue laceration (the most common complication) can occur due to forced contraction of facial muscles.[29] To avoid this complication, a bite block is customarily placed.

Another method of recording MEPs relies on obtaining signals directly from the spinal cord (D-waves and I-waves). This recording technique requires the placement of a direct epidural recording electrode and is thus typically limited to recording above the level of T-11. The major benefits of this modality have been reported during intramedullary spinal cord tumor resection.[11,43] Direct corticospinal waves have been shown to be closely correlated with the postoperative clinical status, in which a complete loss of MEPs with at least 50% preservation of the D-wave amplitude generally results in a transient paraplegia. On the other hand, patients with complete loss of the D-wave amplitude during surgery are likely to have permanent motor deficits.[33]

Spontaneous EMG

Spontaneous EMG activity can be used to intraoperatively monitor the corresponding nerve roots responsible for muscle innervation. This spontaneous motor activity can be measured with recording electrodes placed in the muscles of interest and based on the structures at risk. Although no stimulation is performed for this technique, surgical manipulation such as pulling, stretching, or compression of nerves produces neurotonic discharges resulting in activity in the corresponding innervated muscle(s). Specific muscles are normally paired with single nerve roots, yet in reality some redundancy in innervation occurs, and muscle selection should be made to maximize coverage based on the spinal level the surgeon will be working on (). During cervical spine procedures, the C-5 nerve root is at particular risk of injury and requires particular attention in monitoring.[12,18] For this reason, concurrent monitoring of 2 muscles is recommended to minimize the risk of C-5 nerve root injury. The deltoid (predominantly C-5, also C-6) and biceps brachii (predominantly C-6, also C-5) muscles are typically used to monitor the C-5 level. Spontaneous EMG tends to be quite sensitive to irritation of the nerve root due to retraction, irrigation, and manipulation during surgery.

Table 1. Patterns of nerve root myotomal distribution in muscles frequently used in neuromonitoring*

Root	Muscle	Nerve
C-3, C-4	trapezius	CN XI
C-5, (C-6)	deltoid	axillary
C-5, C-6	biceps brachii	musculocutaneous
C-6, C-7	triceps	radial
(C-8), T-1	abductor pollicis brevis	median
C-8, (T-1)	abductor digiti minimi	ulnar
C-8, (T-1)	adductor pollicis	ulnar
C-8, (T-1)	first dorsal interosseus	ulnar
T-7-12	external oblique	
T-7-12	rectus abdominis	
L-2, L-3, (L-4)	iliacus	lumbar plexus
(L-2), L-3, L-4	vastus lateralis/medialis	femoral
(L-2), L-3, L-4	rectus femoris	femoral
(L-4), L-5, (S-1)	semitendinosus/membranosus	sciatic
L-4, L-5	tibialis anterior	peroneal
L-5, (S-1)	extensor hallucis	peroneal
L-5, (S-1)	extensor digitorum brevis	peroneal
(L-5), S-1	gastrocnemius lateral	tibial
S-1, (S-2)	gastrocnemius medial	tibial
S-1, S-2	abductor hallucis	tibial
S-3, S-4, S-5	external anal sphincter	pudendal
S-3, S-4, S-5	external urethral sphincter	pudendal

* Parentheses indicate nondominant contribution. Abbreviation: CN = cranial nerve.

Relevant sEMG activity that is noted by neurophysiologists includes spikes, bursts, or trains. During surgery, sEMG trains are of clinical significance, and the surgeon is typically notified if these occur (Fig. 3). Trains are continuous, repetitive EMG firing caused by continuous force applied to the nerve root. Trains of higher frequency and/or amplitude tend to represent significant nerve fiber recruitment caused by excessive force on the nerve and are likely to indicate a high probability of nerve injury if a relevant manipulation is sustained. Spontaneous EMG spikes and bursts, on the other hand, often can inform the surgeon of proximity to the nerve root. Not uncommonly, the electrodes will pick up interference from various sources that may be mistaken for spiking or training EMG activity. Potential sources of artifact responses picked up in the EMG window are cautery devices, electrocardiography leads, and high-speed drills. Anesthetic requirements for sEMG mandate that no paralytic agents are used, and that train-of-4 testing should indicate that at least 3 out of 4, if not 4 out of 4 twitches, be present for sEMG to be of value. Alternatively, at least 2 responses in the abductor pollicis brevis exceeding 600 µV in amplitude can be used as a threshold (Minahan, personal communication). It is also important to note that the underlying clinical condition of patients with various neurological disorders may interfere with the ability to acquire EMG signals. Myasthenia gravis, botulinum toxin treatments for dystonia, and muscular dystrophy are classic examples of neurological conditions that interfere with the acquisition of EMG signals.

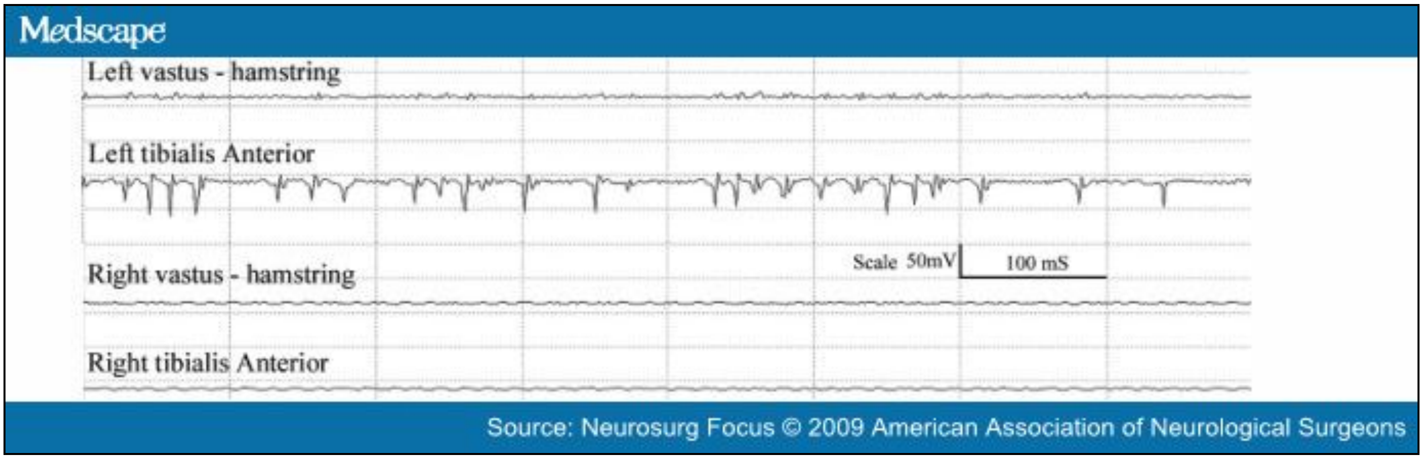

Figure 3.

Spontaneous EMG recording demonstrating a train of activity in the tibialis anterior muscle during nerve root retraction.

Triggered EMG (Pedicle Screw Stimulation)

Over the past 20 years, segmental instrumentation and fusion using pedicle screw constructs have become the standard for spinal stabilization. A potentially preventable risk of pedicle screw placement is a medial screw breach of the pedicle wall into the spinal canal. Triggered EMG is a method that can be used to determine whether screws have breached the medial or inferior pedicle wall and thus pose a risk to the exiting nerve root at that level. When a pedicle screw is accurately placed, the surrounding bone acts as an insulator to electrical conduction, and a higher amount of electrical current is thus required to stimulate the surrounding nerve root. Typically, a monopolar electrode is used to directly stimulate the top of the pedicle screw at increasing current intensities. Needle electrodes in the appropriate muscle groups will measure CMAP time locked to the stimulation. To ensure that the stimulus current is delivered correctly, direct nerve root stimulation using < 2 mA can be attempted to ensure a CMAP response in the appropriate distal muscle group.

When a medial pedicle wall breach occurs, the stimulation threshold is significantly reduced. Due to the variation in thickness and shape between thoracic and lumbar pedicles, different stimulation thresholds exist for these regions. Earlier studies have demonstrated that a threshold < 10 mA for screw stimulation, or 7 mA for probe stimulation, suggest a medial wall breach in the lumbar pedicles.[7] A threshold response between 10 and 20 mA gives a reasonable probability that no of breach of the medial wall has occurred, whereas thresholds > 15 mA indicate a 98% likelihood of accurate screw positioning on postoperative CT scan.[44] Thresholds above 20 mA assure a strong probability that there is no breach of the medial pedicle wall. For thoracic pedicle screw placement, stimulation thresholds < 6 mA suggest a medial pedicle breach.[42]

During pedicle screw stimulation, false-negative responses can occur as a result of various factors, including the use of muscles relaxants, current spread, or preexisting nerve damage. These factors need to be taken into consideration to ensure the accuracy of testing. The degree of muscle relaxation can be measured using a train-of-4 test. Just as in the case of sEMG monitoring, tEMG monitoring requires that no paralytics be used and that 4 of 4 twitches are optimal for reliable recording. Special attention should to be paid to fluid, blood, or soft tissue around the head of the screw at the time of stimulation that could potentially shunt current away from the screw. Furthermore, it is important that the stimulation probe be placed directly on the top of the screw and not the tulip, as these 2 structures are not structurally fused and therefore do not conduct current as a single unit. Once the probe is placed on the screw, current will ideally flow from the screw to an appropriately placed reference electrode in the paraspinal muscles on the contralateral side. A third possible reason for false-negative thresholds is the presence of preexisting nerve root injury. Injured nerve roots will have higher triggering thresholds, with literature reports ranging from 6 to > 10 mA for a chronically compressed root, as compared with 2 mA for a normal nerve root.[15] In nerve roots where there is known or suspected damage, direct nerve root threshold testing is valuable to establish a baseline value. Lastly, advances in materials used in instrumentation may or may not be compatible with current monitoring techniques. For example, hydroxyapatite coating on pedicle screws reduces the conductive capacity of the screws and thereby reduces the capability of electrical stimulation to detect a breach.

Multimodality Monitoring

In an ideal sense, intraoperative monitoring should be designed to serve as a surrogate marker for the intended functional outcome of a given surgical procedure (for example, relief of pain or claudication), as well as to preserve neural function. Current methodology in intraoperative monitoring primarily serves the latter goal. In general, monitoring is tailored based on the structures at risk. In cervical and thoracic procedures, the spinal cord (and to a lesser degree, the nerve roots) are of greater importance when deciding which modalities to use (Fig. 4). Conversely, in lumbar or sacral procedures the nerve roots are at greater risk of injury, and thus modalities that specifically assess these structures are selected for monitoring.

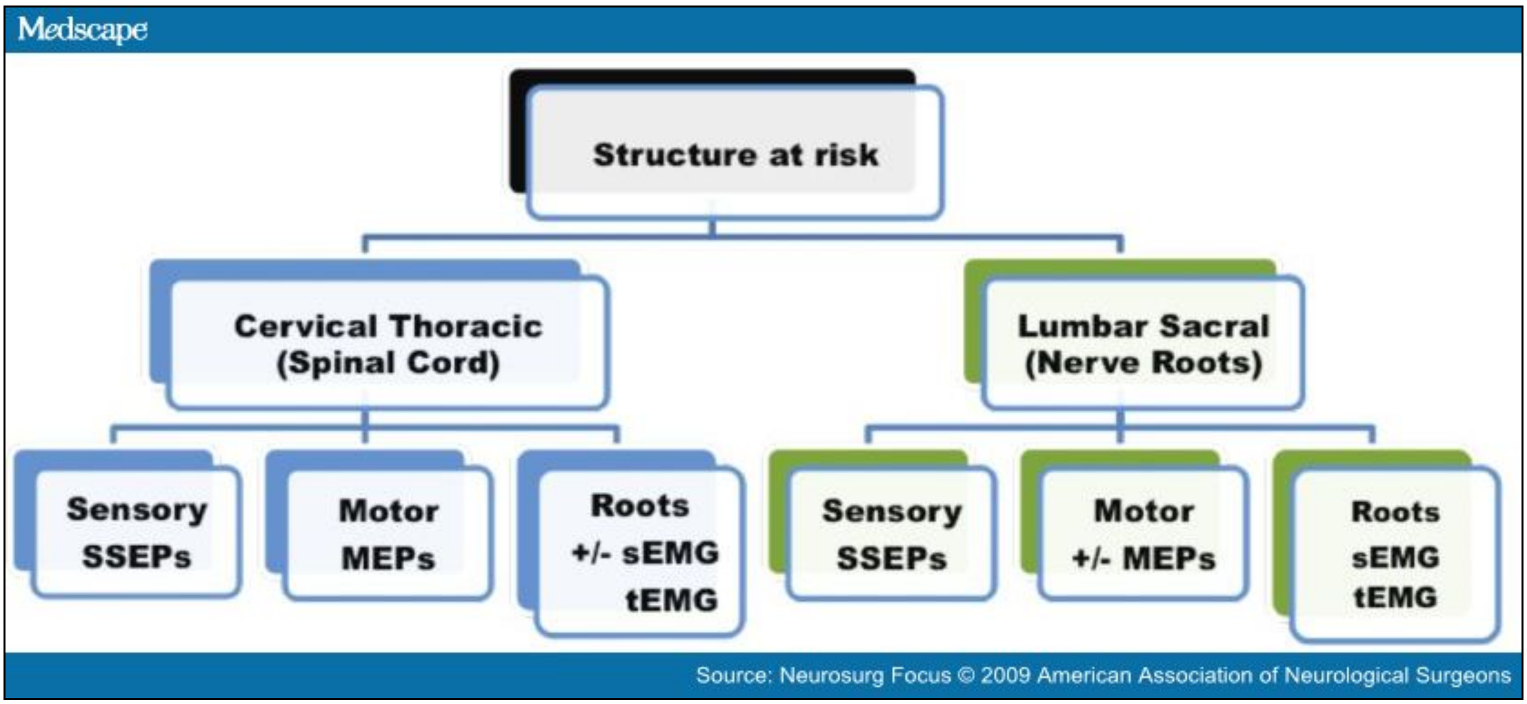

Figure 4.

Overview of frequently used neuromonitoring modalities classified by spinal region.

The concept of multimodality monitoring relies on taking advantage of the individual strengths of its various submodalities, and is thus able to provide a more global and accurate assessment of the dorsal and ventral function of the spinal cord. When EMG is added, the overall function of the nervous system can be monitored, from the level of cortex to the spinal cord, nerve roots, and finally peripheral nerves and muscle. The combined use of SSEPs, MEPs, D-wave monitoring, and both spontaneous and triggered EMG provide the necessary tools required to optimally monitor the functional integrity of the spinal cord during a broad spectrum of routine and complex spinal surgeries, while maximizing the diagnostic efficacy of monitoring in detecting neurological injury.[24,30,41,45] The near real-time information relayed on the integrity of these systems provided by IOM provides an added layer of security for the surgical team during procedures in which neurological injury is a looming possibility.

Monitoring Spinal Procedures

Cervical and Thoracic Spine Surgery

During procedures in the cervical and thoracic spine, preservation of spinal cord integrity is clearly of paramount importance. As mentioned in the modalities section, the use of SSEPs and MEPs in combination is of great value in providing a global assessment of spinal cord function. In a recent study looking at the value of multimodality monitoring in cervical spine surgery,[24] SSEPs were reported to have a sensitivity of 52% and a specificity of 100% in detecting postoperative neurological deficits, whereas MEPs were reported to offer a sensitivity of 100% and a specificity of 96%. Taken together, these results imply that combined SSEP/MEP monitoring offers the most comprehensive way to selectively screen for and identify impending spinal cord injury while minimizing false-positive interpretations. It should be noted, however, that the sensitivity of 52% for SSEPs identified in the study by Kelleher et al.[24] was in large part due to the inclusion of nerve root injuries, for which EMG is a more sensitive modality. Furthermore, the same study determined that recovery of SSEPs following their initial loss reliably predicts the absence of new deficits.

In addition to spinal cord monitoring, nerve root monitoring has retained importance during selected cervical spinal procedures. As an example, during posterior cervical laminoplasty procedures, the risk of nerve root injury ranges between 5.5 and 14.9% in the literature.[48] If isolated nerve root injuries are removed from the analysis of anterior cervical discectomy and fusion surgeries, then both the specificity and negative predictive value for SSEPs alone are reported to be 100%.[25] Currently, freerun EMG (sEMG) has become the modality of choice used to detect potential injuries to spinal nerve roots, as it provides continuous real-time information of nerve root function by monitoring electrical muscle activity in the corresponding myotome. Studies using sEMG monitoring of the deltoid muscle reported a reduction in the incidence of C-5 nerve root palsy from 7.3 to 0.9%.[18] In this same study, no postoperative root deficits occurred if intraoperative evidence of root irritation was absent.

Lumbosacral Spine Surgery

In lumbosacral spinal procedures, the focus on preservation of neurological function shifts to the nerve root level, as only the thecal sac and nerve roots are encountered below the level of the conus medullaris. In this situation, SSEPs in combination with sEMG are the modalities of choice for optimal neurophysiological monitoring. In a 2004 study, Gunnarsson et al.[13] analyzed the sensitivity and specificity of detecting new postoperative motor deficits using multimodality monitoring during thoracolumbar procedures. They reported that sEMG has a sensitivity of 100% with a specificity of 23.7%. On the other hand, SSEPs provided a sensitivity of 28.6% with a specificity of 94.7%. Used concurrently, sEMG and SSEP monitoring are complimentary in preventing nerve root injury during lumbar spine surgery.

During surgery for release of a tethered spinal cord, careful dissection and identification of the lumbosacral nerve roots should be performed prior to relieving the tethering structure. An emphasis is placed on preserving all lumbosacral nerve roots, including nerves that innervate the anal sphincter. Intraoperative monitoring of additional structures, such as the urethral sphincter and the detrusor muscle, has been performed, yet these techniques remain infrequently used mainly because the required setup is cumbersome.[26] However, multimodality monitoring—including SSEPs, sEMG, and tEMG—is routinely used to preserve functional neural structures. The prognostic value of these modalities for tethered cord surgery is similar to the prognostic value for other lumbosacral procedures with regard to the high specificity (nearing 100%) and relatively low sensitivity associated with SSEPs, complemented by a sensitivity of 100% offered by sEMG/tEMG.[38] The selection of lower extremity muscles to be monitored by sEMG and tEMG typically includes those innervated by the nerve roots at or directly above the S-1 level, in addition to monitoring of the anal sphincter (innervated by S-2, S-3, and S-4), with the intention of covering all relevant root-related myotomes () for a particular surgery. As mentioned in the modalities section, sEMG will help warn the surgeon of inadvertent manipulation of the nerve roots, whereas tEMG will aid the surgeon in localizing relevant neural structures. A key maneuver during tethered cord surgery is stimulation of various structures in the surgical field performed in conjunction with tEMG monitoring to determine if they contain any functional neural elements. Bipolar stimulation is preferable, given that it provides a more focal stimulus delivery, yet monopolar stimulation can be used as well. Stimulation intensities of up to 20 mA may be used to elicit neural activity, which can be particularly important for differentiating the filum terminale from a relevant neural structure. A novel technique recently described by Husain and Shah[17] involved comparing the motor threshold obtained with spinal cord stimulation before and after cord untethering. The expected response after untethering is a lower motor threshold, which can be explained in part by improved local cellular metabolism. However, if a higher threshold is observed following untethering, there is a significant likelihood of worsened postoperative motor function.

Table 1. Patterns of nerve root myotomal distribution in muscles frequently used in neuromonitoring*

Root	Muscle	Nerve

C-3, C-4	trapezius	CN XI
C-5, (C-6)	deltoid	axillary
C-5, C-6	biceps brachii	musculocutaneous
C-6, C-7	triceps	radial
(C-8), T-1	abductor pollicis brevis	median
C-8, (T-1)	abductor digiti minimi	ulnar
C-8, (T-1)	adductor pollicis	ulnar
C-8, (T-1)	first dorsal interosseus	ulnar
T-7-12	external oblique	
T-7-12	rectus abdominis	
L-2, L-3, (L-4)	iliacus	lumbar plexus
(L-2), L-3, L-4	vastus lateralis/medialis	femoral
(L-2), L-3, L-4	rectus femoris	femoral
(L-4), L-5, (S-1)	semitendinosus/membranosus	sciatic
L-4, L-5	tibialis anterior	peroneal
L-5, (S-1)	extensor hallucis	peroneal
L-5, (S-1)	extensor digitorum brevis	peroneal
(L-5), S-1	gastrocnemius lateral	tibial
S-1, (S-2)	gastrocnemius medial	tibial
S-1, S-2	abductor hallucis	tibial
S-3, S-4, S-5	external anal sphincter	pudendal
S-3, S-4, S-5	external urethral sphincter	pudendal

* Parentheses indicate nondominant contribution. Abbreviation: CN = cranial nerve.

All Spine Surgeries

The sensitivity and specificity of several modalities of neurophysiological monitoring for a variety of spinal surgeries are summarized in . A large prospective study conducted by Sutter et al.[45] evaluated the diagnostic value of multimodality monitoring in patients undergoing surgery for spinal stenosis, deformities, and spinal tumors. The authors of this study reported a sensitivity of 89% and a specificity of 99% in the detection of postoperative neurological deficits. In a recent study, Quraishi et al.[41] prospectively evaluated 102 patients undergoing correction for adult spinal deformities with the use of multimodality monitoring including SSEP, MEP, and EMG, and demonstrated an overall sensitivity of 100% and specificity of 84.3%. Although Class I evidence supporting the use of monitoring in cervical, thoracic, and lumbar spinal surgeries is lacking, IOM during spine surgery is currently accepted as standard practice for many procedures and is used at the discretion of the surgeon to improve outcomes of spinal surgery.

Table 2. Summary of major studies reporting the sensitivity and specificity of various individual and multimodality monitoring techniques

Authors & Year	Spinal Area or Condition	No. of Procedures Monitored	SSEPs		MEPs		EMG	
			Sensitivity	Specificity	Sensitivity	Specificity	Sensitivity	Specificity

Nuwer et al., 1995	scoliosis	51,263	92%	98.9%				
Kelleher et al., 2008	cervical-thoracic spine	1055	52%	100%	100%	96%	46%	73%
Gunnarson et al., 2004	lumbar spine	213	28.6%	98.7%			100%	23.7%
Paradiso et al., 2006	tethered cord	44	50%	100%			100%	19%
Multimodality Monitoring: Combined SSEPs, MEPs, EMG								
			Overall Sensitivity	**Overall Specificity**				
Sutter et al., 2007	all spine	1017	89%	99%				
Quraishi et al., 2009	all spine	102	100%	84.3%				

Minimally Invasive Spine Surgery

Spinal surgery, like many other surgical disciplines, is evolving according to a paradigm of minimal invasiveness that holds the potential for reduced morbidity and pain in many instances. Several minimal invasive spine surgical techniques are currently used with the aim of improving surgical outcomes and postoperative recovery times. Minimally invasive techniques are gaining favor, largely because of the potential for decreased blood loss, decreased postoperative pain, shorter hospital stays, and quicker recovery times that they offer to patients. However, the obvious drawback of these procedures is minimizing exposure of the relevant anatomy and work space, potentially placing the normal or affected neural elements at increased risk of injury. Indeed, the role of neuromonitoring will likely become more prominent as various types of spinal surgery continue to become less invasive, and surgeons rely less on direct observation of anatomical structures and more on real-time functional assessment of key structures.

Minimally invasive spinal techniques are currently used to perform a variety of surgical procedures, including microdiscectomy, laminectomy, spinal fusion, and spinal deformity correction surgeries. From a monitoring perspective, as in open cases, the focus depends on the type of procedure performed. In cases in which pedicle screw placement is monitored with triggered EMG, a longer probe can be used for stimulation, often through an expandable retractor.[4] Additionally, a variety of customized instruments have been developed specifically for monitoring during minimally invasive procedures. Synthes' Oracle system contains several components that can be used to create a surgical corridor through the psoas muscle to gain access to the anterior lumbar spine. The dilators provided in this system have an attached monopolar stimulator for monitoring tEMG responses during this approach. Other tools have been designed to monitor nerve root function during interbody fusion. NuVasive's XLIF procedures are performed with the assistance of a monitoring system designed to alert the surgeon to nerve proximity by automated interpretation of EMG signals, recorded by surface electrodes after stimulation by electrodes attached to the tissue dilators and retractor assemblies.

Spontaneous EMG is frequently used to detect injury to the nerve, plexus, and roots during minimally invasive spine surgery. Depending on the approach and phase of the surgery, different structures may be at risk during different stages of the procedure. During anterior or lateral approaches for lumbar interbody fusion, the ilioinguinal nerve, iliohypogastric nerve, L-1 and L-2 nerve roots, lumbar plexus, and genitofemoral nerve may be at risk at various time points during the case. Spontaneous EMG monitoring provides useful feedback to the surgeon to avoid direct contact with various nerves as the spine is approached. Spike or burst sEMG activity indicates brief direct or indirect contact to a given nerve and can assist the surgeon in navigating away from a particular trajectory. Train activity or neurotonic discharges on sEMG indicate excessive direct or indirect nerve contact, and correction should be taken to avoid nerve injury. If concurrent sEMG activity is present with both SSEPs and TcMEP monitoring, it is desirable to determine the extent and level of involvement of the nerve root(s) that may be at risk.

Conclusions

Multimodality neurophysiological monitoring is extremely valuable in the prevention of neurological injury during spine procedures. A thorough familiarity with the spectrum of modalities available for neuromonitoring—including SSEPs, MEPs, sEMG, and tEMG—provides a highly sensitive and specific diagnostic array for preventing neurological deficits tailored to a particular spinal level. Knowledge of the benefits and limitations of each modality helps maximize the diagnostic value of IOM during spinal procedures. An interdisciplinary approach to intraoperative monitoring facilitates the optimization of this technique in preventing neurological injury.

References

1. Aglio LS, Romero R, Desai S, Ramirez M, Gonzalez AA, Gugino LD: The use of transcranial magnetic stimulation for monitoring descending spinal cord motor function. Clin Electroencephalogr 33:30-41, 2002

2. Ben-David B, Haller G, Taylor P: Anterior spinal fusion complicated by paraplegia. A case report of a false-negative somatosensory-evoked potential. Spine 12:536-539, 1987

3. Ben-David B, Taylor PD, Haller GS: Posterior spinal fusion complicated by posterior column injury. A case report of a false-negative wake-up test. Spine 12:540-543, 1987

4. Bindal RK, Ghosh S: Intraoperative electromyography monitoring in minimally invasive transforaminal lumbar interbody fusion. J Neurosurg Spine 6:126-132, 2007

5. Bose B, Sestokas AK, Schwartz DM: Neurophysiological monitoring of spinal cord function during instrumented anterior cervical fusion. Spine J 4:202-207,2004

6. Burke D, Hicks R, Stephen J, Woodforth I, Crawford M: Assessment of corticospinal and somatosensory conduction simultaneously during scoliosis surgery. Electroencephalogr Clin Neurophysiol 85:388-396, 1992

7. Calancie B, Madsen P, Lebwohl N: Stimulus-evoked EMG monitoring during transpedicular lumbosacral spine instrumentation. Initial clinical results. Spine 19:2780-2786, 1994

8. Calancie B, Molano MR: Alarm criteria for motor-evoked potentials: what's wrong with the "presence-or-absence" approach?. Spine 33:406-414, 2008

9. Chen X, Sterio D, Ming X, Para DD, Butusova M, Tong T, et al.: Success rate of motor evoked potentials for intraoperative neurophysiologic monitoring: effects of age, lesion location, and preoperative neurologic deficits. J Clin Neurophysiol 24:281-285, 2007

10. Chiappa K, Hill R, Short Latency Somatosensory Evoked Potentials: methodology. Chiappa K: Evoked Potentials in Clinical Medicine Philadelphia,Lippincott-Raven, 1997

11. Deletis V, Sala F: Intraoperative neurophysiological monitoring of the spinal cord during spinal cord and spine surgery: a review focus on the corticospinal tracts. Clin Neurophysiol 119:248-264, 2008

12. Fan D, Schwartz DM, Vaccaro AR, Hilibrand AS, Albert TJ: Intraoperative neurophysiologic detection of iatrogenic C5 nerve root injury during laminectomy for cervical compression myelopathy. Spine 27:2499-2502, 2002

13. Gunnarsson T, Krassioukov AV, Sarjeant R, Fehlings MG: Real-time continuous intraoperative electromyographic and somatosensory evoked potential recordings in spinal surgery: correlation of clinical and electrophysiologic findings in a prospective, consecutive series of 213 cases. Spine 29:677-684, 2004

14. Hilibrand AS, Schwartz DM, Sethuraman V, Vaccaro AR, Albert TJ: Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. J Bone Joint Surg Am 86-A:1248-1253, 2004

15. Holland NR: Intraoperative electromyography during thoracolumbar spinal surgery. Spine 23:1915-1922, 1998

16. Hsu B, Cree AK, Lagopoulos J, Cummine JL: Transcranial motor-evoked potentials combined with response recording through compound muscle action potential as the sole modality of spinal cord monitoring in spinal deformity surgery. Spine 33:1100-1106, 2008

17. Husain AM, Shah D: Prognostic value of neurophysiologic intraoperative monitoring in tethered cord syndrome surgery. J Clin Neurophysiol 26:244-247,2009

18. Jimenez JC, Sani S, Braverman B, Deutsch H, Ratliff JK: Palsies of the fifth cervical nerve root after cervical decompression: prevention using continuous intraoperative electromyography monitoring. J Neurosurg Spine 3:92-97, 2005

19. Jones SC, Fernau R, Woeltjen BL: Use of somatosensory evoked potentials to detect peripheral ischemia and potential injury resulting from positioning of the surgical patient: case reports and discussion. Spine J 4:360-362, 2004

20. Jones SJ, Buonamassa S, Crockard HA: Two cases of quadriparesis following anterior cervical discectomy, with normal perioperative somatosensory evoked potentials. J Neurol Neurosurg Psychiatry 74:273-276, 2003

21. Kalkman CJ, Drummond JC, Kennelly NA, Patel PM, Partridge BL: Intraoperative monitoring of tibialis anterior muscle motor evoked responses to transcranial electrical stimulation during partial neuromuscular blockade. Anesth Analg 75:584-589, 1992

22. Kawaguchi M, Hayashi H, Yamamoto Y, Furuya H: Recent advances in the monitoring of myogenic motor-evoked potentials: development of post-tetanic motor-evoked potentials. J Anesth 22:489-492, 2008

23. Keith RW, Stambough JL, Awender SH: Somatosensory cortical evoked potentials: a review of 100 cases of intraoperative spinal surgery monitoring. J Spinal Disord 3:220-226, 1990

24. Kelleher MO, Tan G, Sarjeant R, Fehlings MG: Predictive value of intraoperative neurophysiological monitoring during cervical spine surgery: a prospective analysis of 1055 consecutive patients. J Neurosurg Spine 8:215-221, 2008

25. Khan MH, Smith PN, Balzer JR, Crammond D, Welch WC, Gerszten P, et al.: Intraoperative somatosensory evoked potential monitoring during cervical spine corpectomy surgery: experience with 508 cases. Spine 31:E105-E113, 2006

26. Khealani B, Husain AM: Neurophysiologic intraoperative monitoring during surgery for tethered cord syndrome. J Clin Neurophysiol 26:76-81, 2009

27. Kothbauer KF, Deletis V, Epstein FJ: Motor-evoked potential monitoring for intramedullary spinal cord tumor surgery: correlation of clinical and neurophysiological data in a series of 100 consecutive procedures. Neurosurg Focus 4:5e1, 1998

28. Langeloo DD, Lelivelt A, Louis Journee H, Slappendel R, de Kleuver M: Transcranial electrical motor-evoked potential monitoring during surgery for spinal deformity: a study of 145 patients. Spine 28:1043-1050, 2003

29. Macdonald DB: Intraoperative motor evoked potential monitoring: overview and update. J Clin Monit Comput 20:347-377, 2006

30. MacDonald DB, Al Zayed Z, Khoudeir I, Stigsby B: Monitoring scoliosis surgery with combined multiple pulse transcranial electric motor and cortical somatosensory-evoked potentials from the lower and upper extremities. Spine 28:194-203, 2003

31. Merton PA, Morton HB: Stimulation of the cerebral cortex in the intact human subject. Nature 285:227, 1980

32. Minahan RE, Sepkuty JP, Lesser RP, Sponseller PD, Kostuik JP: Anterior spinal cord injury with preserved neurogenic

'motor' evoked potentials. Clin Neurophysiol 112:1442-1450, 2001

33. Morota N, Deletis V, Constantini S, Kofler M, Cohen H, Epstein FJ: The role of motor evoked potentials during surgery for intramedullary spinal cord tumors. Neurosurgery 41:1327-1336, 1997

34. Nash CL Jr, Lorig RA, Schatzinger LA, Brown RH: Spinal cord monitoring during operative treatment of the spine. Clin Orthop Relat Res 100-105, 1977

35. Nuwer MR, Dawson EG, Carlson LG, Kanim LE, Sherman JE: Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. Electroencephalogr Clin Neurophysiol 96:6-11, 1995

36. Owen JH, Padberg AM, Spahr-Holland L, Bridwell KH, Keppler L, Steffee AD: Clinical correlation between degenerative spine disease and dermatomal somatosensory-evoked potentials in humans. Spine 16:6 SupplS201-S205, 1991

37. Pajewski TN, Arlet V, Phillips LH: Current approach on spinal cord monitoring: the point of view of the neurologist, the anesthesiologist and the spine surgeon. Eur Spine J 16:2 SupplS115-S129, 2007

38. Paradiso G, Lee GY, Sarjeant R, Hoang L, Massicotte EM, Fehlings MG: Multimodality intraoperative neurophysiologic monitoring findings during surgery for adult tethered cord syndrome: analysis of a series of 44 patients with long-term follow-up. Spine (Phila Pa 1976) 31:2095-2102, 2006

39. Pechstein U, Nadstawek J, Zentner J, Schramm J: Isoflurane plus nitrous oxide versus propofol for recording of motor evoked potentials after high frequency repetitive electrical stimulation. Electroencephalogr Clin Neurophysiol 108:175-181, 1998

40. Quinones-Hinojosa A, Lyon R, Zada G, Lamborn KR, Gupta N, Parsa AT, et al.: Changes in transcranial motor evoked potentials during intramedullary spinal cord tumor resection correlate with postoperative motor function. Neurosurgery 56:982-993, 2005

41. Quraishi NA, Lewis SJ, Kelleher MO, Sarjeant R, Rampersaud YR, Fehlings MG: Intraoperative multimodality monitoring in adult spinal deformity: analysis of a prospective series of one hundred two cases with independent evaluation. Spine (Phila Pa 1976) 34:1504-1512, 2009

42. Raynor BL, Lenke LG, Kim Y, Hanson DS, Wilson-Holden TJ, Bridwell KH, et al.: Can triggered electromyograph thresholds predict safe thoracic pedicle screw placement?. Spine 27:2030-2035, 2002

43. Sala F: Improving spinal cord monitoring: a neurosurgeon's view. Clin Neurophysiol 120:649-650, 2009

44. Shi YB, Binette M, Martin WH, Pearson JM, Hart RA: Electrical stimulation for intraoperative evaluation of thoracic pedicle screw placement. Spine 28:595-601, 2003

45. Sutter M, Eggspuehler A, Muller A, Dvorak J: Multimodal intraoperative monitoring: an overview and proposal of methodology based on 1,017 cases. Eur Spine J 16:Suppl 2S153-S161, 2007

46. Tsai RY, Yang RS, Nuwer MR, Kanim LE, Delamarter RB, Dawson EG: Intraoperative dermatomal evoked potential monitoring fails to predict outcome from lumbar decompression surgery. Spine 22:1970-1975, 1997

47. Tsai TM, Tsai CL, Lin TS, Lin CC, Jou IM: Value of dermatomal somatosensory evoked potentials in detecting acute nerve root injury: an experimental study with special emphasis on stimulus intensity. Spine 30:E540-E546, 2005

48. Uematsu Y, Tokuhashi Y, Matsuzaki H: Radiculopathy after laminoplasty of the cervical spine. Spine 23:2057-2062, 1998

49. Vauzelle C, Stagnara P, Jouvinroux P: Functional monitoring of spinal cord activity during spinal surgery. Clin Orthop Relat Res 173-178, 1973

Abbreviations used in this paper
CMAP = compound muscle action potential; EMG = electromyography; IOM = intraoperative monitoring; IV = intravenous; MEP = motor evoked potential; sEMG = spontaneous EMG; SSEP = somatosensory evoked potential; TcMEP = transcranial MEP; tEMG = triggered EMG.