Intraoperative Neurophysiologic Monitoring During Spinal Surgery

Abstract
Intraoperative neurophysiologic monitoring (IONM) is a battery of neurophysiologic tests used to assess the functional integrity of the spinal cord, nerve roots, and other peripheral nervous system structures (eg, brachial plexus) during spinal surgery. The underlying principle of IONM is to identify emerging insult to nervous system structures, pathways, and/or related vascular supply and to provide feedback regarding correlative changes in neural function before development of irreversible neural injury. IONM data provide an opportunity for intervention to prevent or minimize postoperative neurologic deficit. Current multimodality monitoring techniques permit intraoperative assessment of the functional integrity of afferent dorsal sensory spinal cord tracts, efferent ventral spinal cord motor tracts, and nerve roots. Combined use of these techniques is useful during complex spinal surgery because these monitoring modalities provide important complementary information to the surgery team.

Intraoperative neurophysiologic monitoring (IONM) refers to the various neurophysiologic tests used to assess functional integrity of the central and peripheral nervous systems during surgical procedures that place these structures at risk for iatrogenic injury. IONM is currently used during a wide variety of surgical procedures, including spinal surgery, intracranial neurosurgery, interventional neuroradiology, otolaryngology, internal fixation of pelvic fractures, carotid endarterectomies, and thoracic aortic aneurysm repair. The purpose of IONM is to provide feedback regarding changes in neural function before the development of irreversible neural injury, thereby permitting intervention to prevent or minimize postoperative neurologic deficit.

Limitations of clinically based monitoring tests stimulated the development of contemporary IONM techniques. Somatosensory-evoked potentials (SSEPs) were the first to be developed; they provide direct information regarding dorsally located ascending spinal cord sensory tracts and indirect information regarding integrity of ventrally located spinal cord motor tracts. SSEPs offer no information regarding individual nerve root function. The introduction of transcranial electric motor-evoked potentials (tceMEPs) during the last decade addressed the limitations of SSEPs by permitting direct evaluation of the functional properties of...
the corticospinal motor tracts, spinal nerve roots, peripheral nerves, and nerve plexuses. The combination of SSEPs and tceMEPs provides global monitoring coverage of spinal cord function. The application of electromyographic monitoring techniques permits real-time display of nerve root irritation during surgical manipulation and can be used to test nerve root integrity via application of electrical stimulation. Contemporary IONM uses a combination of neurophysiologic monitoring modalities to provide continuous assessment of neural structures at risk during a specific surgical procedure.

**Mechanisms and Pathophysiology of Spinal Monitoring Changes**

The neural structures at risk during spinal surgery include the spinal cord and/or nerve roots at the surgical site as well as neural structures remote from the surgical site that are at risk for intraoperative injury because of positioning of the extremities, head, and neck. Neurologic complications may arise as the result of mechanical and/or vascular etiologies. Mechanical causes include direct injury (eg, contusion), distortion of neural elements following application of corrective forces to the spinal column, and injuries secondary to patient positioning. Complications related to surgical positioning range from isolated nerve injuries (eg, peroneal nerve, lateral femoral cutaneous nerve) to brachial plexopathy or even quadriplegia resulting from hyperextension positioning of the stenotic cervical spine.1 Spinal cord ischemia may result from the following: stretching of critical spinal cord vascular supply (eg, following correction of spinal deformity or placement of an anterior strut graft or cage); prolonged hypotension; or ligation of anterior segmental arteries in the critical vascular zone of the spinal cord (T4-T9).

By convention, all evoked potentials are evaluated in terms of measured amplitude (voltage), latency (time), and morphology (shape). When injury occurs from any cause, a cascade of changes involving sodium, potassium, and calcium channels occurs. This cascade causes blockage of axonal transmission, which leads ultimately to an uncoupling of oxidative phosphorylation. The net result is loss of cellular function and structural integrity that manifests as a voltage drop in evoked-potential amplitude, not a prolongation of latency. Evoked-potential latency rarely changes in the absence of an amplitude loss except for latency shifts associated with increased concentration of inhalational or intravenous agents, lowering of core body or limb temperature, or perhaps hypercarbia.

Spinal cord contusion causes a transient spinal cord conduction block, resulting in marked amplitude suppression (50% to 75%) of SSEPs and/or tceMEPs that typically resolves within 15 to 20 minutes. Reversal of these changes may be aided by increasing mean arterial blood pressure to improve spinal cord perfusion and by temporarily stopping further surgical maneuvers. More serious concussive injury will obliterate both somatosensory- and motor-evoked potentials entirely.

Spinal cord ischemia can have a varied presentation. Spinal cord sensory and motor pathways are physically separate from each other and have separate vascular supplies (ie, anterior and posterior spinal arteries). It is entirely possible to have selective loss of SSEPs with complete sparing of motor function. Conversely, selective ischemia of the anterior spinal cord region may manifest as a loss of motor-evoked potential amplitude in the absence of concurrent change in somatosensory-evoked potentials. Prolonged hypotension, whether deliberate or systemic, can result in spinal cord vascular injury. tceMEPs are particularly sensitive to blood pressure changes and can be used quite effectively to titrate the degree of hypotensive state the spinal cord will withstand.

Spinal nerve roots are susceptible to injury resulting from mechanical or ischemic insult. The division site at which the dorsal and ventral roots split into rootlets and mini rootlets is the location where the nerve root is susceptible to mechanical injury. Here, the axons—enclosed by a thin root sheath, cerebrospinal fluid, and meninges—lack the protective covering of epineurium and perineurium present in peripheral nerves. An area of hypovascularity exists between the proximal and middle third of the dorsal and ventral roots where the nerve is susceptible to both mechanical and ischemic insult. If microtrauma leads to mechanical or metabolic nerve root irritation, the nerve root will depolarize. An action potential results that can be identified both visually and acoustically using electromyographic monitoring techniques.

**Overview of Spinal Monitoring Techniques**

**Clinically Based Tests**

The Stagnara wake-up test was the first widely used method for intraoperative spinal monitoring.2 It requires reversal of general anesthesia to permit an intraoperative neurologic examination. Applied initially to patients undergoing scoliosis correction, the technique permits assessment of the gross integrity of spinal cord motor tract function. It cannot provide information about spinal cord sensory tract function, individual nerve root function, or peripheral nerves, and it cannot be administered in a continuous fashion during surgery. The wake-up test does not permit identification of the specific factors responsible for neurologic injury nor does it permit timely intervention to prevent or minimize neurologic deficit. Potential complications associated with
The wake-up test include accidental extubation, patient recall of intraoperative events, and difficulty performing the test in young children or in the presence of language barriers.

The ankle clonus test assesses whether the components of the lower extremity stretch reflex remain intact. Sudden passive dorsiflexion of the foot is performed to stimulate the stretch reflex and produce rhythmic contraction of the calf muscles (clonus). In the normal awake person, clonus cannot be elicited because of central reflex inhibition. In neurologically intact patients emerging from general anesthesia, however, clonus may be elicited as lower motor neuron function returns before the return of inhibitory upper motor neuron impulses. Detection of clonus indicates that central and peripheral neuroanatomic structures remain functionally intact. Absence of transient ankle clonus may indicate spinal cord injury. However, this finding may also indicate that the level of anesthesia is too light to produce cortical inhibition and elicitation of clonus. As a result, the clonus test is not sufficiently reliable for use as a primary test to monitor spinal cord function.

**Neurophysiologic Methods**

**Monitoring of Spinal Cord Function**

**Somatosensory-Evoked Potentials**

SSEPs are cortical or subcortical responses to repetitive electrical stimulation of a mixed peripheral nerve. SSEPs represent signal-averaged data in which multiple small-amplitude responses are recorded over repeated trials via instrumentation that amplifies and filters the signal to provide a measurable response (Figure 1). Strictly speaking, SSEP data are not a real-time measurement because there is a slight delay (typically <1 minute) while the SSEP response is averaged for extraction from background physiologic and ambient noise. Typical stimulation sites include the posterior tibial nerve (ankle), the peroneal nerve (fibular head), and the ulnar or median nerves (wrist). The ulnar nerve is the preferred stimulation site for upper extremity SSEPs because the lower spinal nerve entry between C7 and T1 permits assessment of the entire cervical neural axis. Electrical stimulation applied to a peripheral nerve creates an afferent volley that enters the spinal cord through dorsal nerve roots over several segmental levels. The general consensus is that the posterior column spinal pathways are the site of primary mediation for SSEPs. After synapsing in the medullary nuclei, the neural signal crosses the brainstem and ascends in the medial lemniscal pathways. It synapses once again in the thalamic nuclei and projects to the sensorimotor cortex.

Data, including signal amplitude (power) and latency (velocity), are recorded continuously during surgery and compared with baseline and recently acquired data. Of these two parameters, amplitude is more relevant; sustaining a spinal cord injury without amplitude changes is unlikely. However, changes in latency are quite common although less significant. Criteria for surgeon notification vary from center to center but generally include an intraoperative unilateral or bilateral amplitude loss of at least 50% to 60%. Factors other than neurologic injury that may compromise SSEP recordings include halogenated anesthetic agents,

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**Figure 1**

nitrous oxide, hypothermia, and hypotension. In addition, electrical interference from a variety of sources (eg, electric tables, fluid and body warmers, microscopes) may contaminate the SSEP by affecting amplitude and can lead to interpretative ambiguity.

SSEPs directly assess spinal cord sensory tracts but provide only indirect information about motor tracts. Damage to the spinal cord motor tracts can occur without a concomitant change in SSEPs. In addition, SSEPs may be poorly defined or unrecordable in patients with severe myelopathy, spinal cord tumor, obesity, or peripheral neuropathy. Despite the high negative predictive value of SSEPs for ruling out motor deficit during surgical correction for adolescent scoliosis, SSEPs used as a single monitoring modality have been less helpful in monitoring other spinal pathologies.

**Transcranial Electric Motor-Evoked Potentials**

Motor-evoked potentials (MEPs) are neuroelectric impulses elicited from descending motor pathways, including the corticospinal tract, spinal cord interneurons, anterior horn cells, peripheral nerves, and skeletal muscles innervated by excited α-motor neurons, following the transcranial application of a high-voltage electrical stimulus. Although MEPs also can be elicited by transcranial magnetic stimulation, the technical challenges for intraoperative recording are too great to warrant its use, particularly given the simplicity of electric stimulation. A low-output impedance electrical stimulator is used to generate a high-volume, short-duration stimulus (pulse train) via a series of electrodes that are placed over various scalp regions and that excite a selected area of the motor cortex (Figure 2). This stimulates corticospinal tract axons, which course from the cortex through the internal capsule to the caudal medulla. Here, the fibers cross over in the lower lateral brainstem and descend into the lateral and anterior funiculi of the spinal cord. In contrast with white matter-mediated SSEPs, corticospinal tract axons that originate in the premotor and motor cortex enter the spinal cord gray matter, where they interact with spinal interneurons. The axons go on to synapse with α-motor neurons, which innervate peripheral muscle.

MEPs can be recorded either directly from the spinal cord (D- and I-waves) or from muscle (ie, compound muscle action potential [CMAP]). The requirement of electrode placement either percutaneously or through a laminotomy to record D-waves from the epidural space precludes routine use. (One exception is excision of intramedullary spinal cord tumors.) It is both easier and preferable to record myogenic motor responses (ie, CMAPs) from upper (control) and lower extremity peripheral muscles. CMAPs may be recorded either from surface electrodes or subdermal needle electrodes placed over key peripheral muscles. A warning criterion is typically a decrease in CMAP amplitude.
≥75%, but this must be individualized based on a variety of patient-specific factors. tceMEPs are exquisitely sensitive and specific for the diagnosis of impending intraoperative spinal cord injury as well as neural injury due to insufficient spinal cord perfusion pressure.1

Monitoring of Nerve Root Function

Electromyography

SSEPs are neither sensitive nor specific for identification of injury to a specific spinal nerve root because of their multiple nerve root mediation. Electromyographic techniques overcome this limitation and can be classified into two categories based on method of elicitation—mechanical and electrical. Mechanically elicited electromyography (EMG), also called spontaneous or free-running EMG, may be useful during the dynamic phases of surgery (eg, implant placement, nerve root manipulation) or can help identify and map a nerve root. Electrically elicited EMG, also called stimulus-evoked EMG or triggered EMG, may be useful during static phases of surgery (eg, testing pedicle screws after placement). Together, these electromyographic techniques encourage early detection of excessive nerve root traction, mechanical injury, or cortical breach.

Microtrauma to a spinal nerve root provokes ion depolarization, and the resultant muscle or motor unit potential can be recorded from a muscle innervated by that specific nerve root. Abrupt traction of a spinal nerve root or mechanical contact by a surgical instrument elicits intermittent electromyographic “burst” or sustained “train” activity. Gradual traction may elicit a smaller response or even no response. Simple burst activity reflects mechanical contact with a nerve root and has no diagnostic significance. Sustained train activity reflects a state of traction, mechanical irritation, or thermal change (eg, secondary to cool irrigation). Although the occurrence of long-term unresolved trains suggests that the root is highly irritated, it should not be interpreted as correlating with an injury or predicting neurologic deficit.

The stimulus-evoked EMG principle for identifying cortical breach resulting from placement of pedicle screws is based on the fact that cortical bone has high resistivity [low conductivity] to electrical current flow, whereas soft tissue has low electrical resistivity. The tip of a monopolar probe is touched to the screw, and the electrical current output is increased via an electrical triggering device. When there is a cortical perforation, the normally high resistance of the intact bony wall is reduced, and the flow of electrical current takes the path of least resistance, namely through the breach to the root (Figure 3). As a result, the nerve root depolarizes at a much lower current (<7.0 mA) compared with an intact pedicle (10 to 12 mA). Subsequently, the root fires, and the peripherally innervated muscle contracts. This is recorded as a CMAP. This screw stimulation technique has been most widely used in the lumbar region and has subsequently been adapted to the thoracic and cervical regions.

Chronically compressed motor nerve roots have an elevated threshold and may not fire spontaneously or with stimulus-evoked EMG, resulting in a false-negative test result. A quiet, spontaneous electromyogram of a chronically compressed nerve root does not necessarily mean that the root is not undergoing injury by traction or mechanical contact. Thresholds for stimulation of normal nerve roots do not apply to chronically compressed nerve roots. Chronically compressed roots must serve as their own control to establish a safe, stimulus-evoked EMG threshold.9

Brachial Plexus and Lumbosacral Plexus Monitoring

A tangential benefit of IONM is the ability of SSEPs and/or tceMEPs to identify impending brachial plexus...
opathy or ulnar nerve neuropathy secondary to malpositioning. Intermittent monitoring of ulnar nerve SSEPs, recorded either directly from the brachial plexus (ie, Erb’s point) or the cervical spine and coupled with tceMEPS recorded over deltoid, extensor carpi radialis, and intrinsic first dorsal interosseous muscles, are highly effective for this purpose.10,11 During anterior procedures, monitoring of peroneal and femoral nerve function may be helpful. Peroneal nerve SSEP monitoring can alert staff to the onset of impending peroneal nerve palsy secondary to pressure of the leg resulting from positioning. During anterior surgery, monitoring femoral nerve SSEPs or recording tceMEPs from the iliopsoas muscle can alert the surgeon to excessive traction on the iliopsoas muscle as well as the adjacent nerve roots and thus prevent femoral nerve injury.

Effects of Anesthetics on Neurophysiologic Signals

The success of intraoperative monitoring is dependent on appropriate anesthetic management. Essentially all anesthetic agents depress synaptic function, both in the brain and spinal cord gray matter. In spinal cord monitoring, the margin for interpretation error is narrow because the signal amplitudes are inherently quite small. When signal amplitude is artificially depressed and fluctuant because of anesthesia, it creates a situation in which signal change must be interpreted in the presence of extreme clinical uncertainty.

In general, all inhalational agents produce a dose-related increase in latency and reduction in amplitude of the cortical SSEP. When generation of a cortical signal, either ascending [SSEP] or descending [tceMEP], is necessary, it is best to avoid inhalational agents soon after induction and intubation. On the basis of the unpredictable amplitude variability and depression associated both with volatile agents and nitrous oxide, it has become routine in many high-volume spinal surgery centers to use a total intravenous anesthetic regimen. Although neuromuscular relaxants have no adverse effect on SSEPs, neuromuscular blockade will compromise tceMEP and EMG recordings. All depolarizing and nondepolarizing paralytic agents should be avoided, except as required at the beginning of the operation during spinal exposure, because these agents block the neuromuscular junction and preclude muscle contraction.12

Spinal Monitoring Plan

Just as the surgeon develops a surgical plan before spinal surgery, an appropriate IONM plan is developed to monitor “at risk” neurologic structures specific to a particular spinal procedure.13 The surgical and anesthesia team requires a basic working knowledge of IONM to assess the appropriateness of the monitoring plan. The team should be knowledgeable and prepared to respond to a critical neurophysiologic alert during surgery (Table 1).

Spinal Monitoring Personnel Qualifications

A variety of personnel may provide intraoperative spinal monitoring services (Table 2). The surgeon should be knowledgeable regarding the credentials of the providers of spinal monitoring services at his or her hospital. If the surgeon uses a provider who is not certified to interpret neurophysiologic potentials, the medicolegal burden of interpretation becomes the responsibility of the surgeon. Currently, there are two types of certification for IONM personnel; one is professional board certification (D.ABNM) and the other is technician-based (CNIM) (Table 3).
SSEPs failed to identify any changes in one of these two patients. In patients who had major potential changes detected by both SSEPs and tceMEPs, SSEP changes lagged behind tceMEP changes by an average of 16 minutes. This delay reduces the window of opportunity for intervention and could theoretically prevent or compromise reversal of spinal cord injury if patients were monitored with only SSEPs. In addition, all except 1 of the 12 patients who developed tceMEP changes underwent surgery for cervical spondylotic myelopathy, and 4 patients also presented with ossification of the posterior longitudinal ligament. In general, the authors strongly recommend the use of both tceMEPs and SSEPs when operating on a patient with cervical spondylotic myelopathy, and especially when the patient has ossification of the posterior longitudinal ligament. Lee et al\(^1\) recently reported on the utility of tceMEP monitoring during cervical corpectomy for identifying evolving cervical hematoma and evaluating spinal cord recovery after emergent evacuation.

Postoperative C5 nerve root palsy remains problematic in patients who undergo cervical decompressive procedures. Postoperative C5 nerve root palsy is incompletely understood and is considered to have multiple potential etiologies.\(^{17}\) Nerve root monitoring with EMG and tceMEP has been reported to play a role in recognition of intraoperative C5 root impairment because of direct trauma or positioning,\(^{18,19}\) but it is not currently helpful in predicting delayed-onset root impairment that develops during the postoperative period.

The use of IONM during anterior cervical surgery for radiculopathy continues to be debated. Opponents report that the incidence of spinal cord injury is so low that the cost of IONM is not justified.\(^{20}\) Proponents confirm the benefits of identifying excessive neck extension during positioning, excessive vertebral distraction, graft misplacement, ischemic injury, impending brachial plexopathy, C5 root injury, and recurrent laryngeal nerve palsy.\(^{21,22}\)

### Intraoperative Monitoring During Thoracic Spine Surgery

Use of IONM during thoracic spine surgery is widely accepted for a variety of spinal pathologies. Thoracic spinal deformities, fractures,
mors, and infections may require anterior, posterior, or circumferential surgical approaches that expose the neural elements to various potential injury mechanisms. Ischemic injury may occur as a result of hypotension, blood loss, or stretching of the spinal cord vascular supply following corrective maneuvers or insertion of strut grafts. In patients at increased risk for cord dysfunction following surgical intervention (eg, those with congenital kyphosis, syringomyelia, congenital scoliosis), segmental artery ligation during anterior procedures may lead to neurologic injury because of resultant spinal cord ischemia. Temporary occlusion of segmental vessels under tceMEP monitoring before segmental vessel ligation can identify critical vessels that must be preserved in such high-risk cases to prevent neurologic injury. Mechanical injury may occur through direct mechanisms, such as cord compression by spinal implants (eg, hooks, screws, wires, cages, strut grafts), retropulsed material, hematoma, or infolded ligamentum flavum, as well as during spinal deformity correction. IONM has been used during spinal deformity surgery for more than 25 years. Early results of large, multicenter studies confirmed that spinal cord monitoring using SSEPs was a clinically useful, valid procedure that reduced neurologic deficits related to spinal deformity surgery. However, SSEPs failed to detect 28% of postoperative neurologic deficits. During this era, many spine surgeons used a combination of SSEPs and the wake-up test for intraoperative monitoring. Current technology has been developed to the point that direct monitoring of descending motor tracts during spinal surgery is practical and can be combined with SSEPs to provide surveillance of both sensory and motor pathways. Specific monitoring protocols exist for adolescent idiopathic scoliosis, neuromuscular scoliosis, and scoliosis associated with spinal cord abnormalities.

The increasing popularity of thoracic pedicle fixation has led to interest in monitoring thoracic pedicle screw placement with stimulus-evoked EMG techniques. However, electrical stimulation of thoracic screws provides information about medial pedicle wall breach only; it cannot provide information regarding excessive anterior or lateral vertebral body penetration with its associated potentially adverse clinical consequences.

Table 3
Certification for Intraoperative Neurophysiologic Monitoring Personnel

| Diplomate of the American Board of Neurophysiological Monitoring (D.ABNM) | The American Board of Neurophysiological Monitoring introduced the diplomate certification examination in 1999 for individuals seeking to obtain credentialing that attests to their ability to supervise IONM technical personnel and interpret IONM data. This was the first clinical board certification in IONM and remains the only recognized professional credential today. This examination is open only to individuals with advanced graduate degrees in the basic sciences, neurosciences, or clinical health care specialties. Because professionals from a variety of different backgrounds are involved in IONM, and because the ABNM board of directors does not have the assurance that all candidates will have completed a standard recognizable training program, the following criteria must be met to ensure eligibility for the examination: 1. Minimum of an earned master’s degree or equivalent 2. Primary responsibility for supervising and/or monitoring a minimum of 300 surgical procedures over a period of at least 2 years 3. Two letters from surgeons attesting to the experience and time components 4. Successful completion of a written examination administered and scored by Educational Testing Service (Princeton, NJ) 5. Successful completion of an oral clinical examination administered and scored by members of the American Board of Neurophysiological Monitoring. |
| CNIM personnel are capable of performing intraoperative monitoring but must practice under the indirect supervision of an MD or a D.ABNM. The role of the technologist is defined through two major documents: Guidelines on Intraoperative Electroencephalography for Technologists, published by the American Society of Electroneurodiagnostic Technologists, and Guidelines for Intraoperative Monitoring of Sensory Evoked Potentials, published by the American Clinical Neurophysiology Society. The American Board of Electroencephalographic and Evoked Potential Technologists, Inc, is the certifying body for the CNIM credential. CNIM personnel are required to have a minimum of a bachelor’s degree in health sciences or possess a current health care provider license (eg, registered nurse) or registration as a neurophysiology technologist (ie, registered EEG technologist, EP [evoked potential] technologist). In addition, the applicant must show evidence of having monitored at least 100 spine cases and must pass a written examination. |
Neurophysiologic monitoring during cervical spine surgery. Upper cervical procedures (eg, C1-C2) carry a risk of brainstem infarct secondary to vertebral artery injury in addition to the risk of spinal cord injury. Somatosensory evoked potentials (SSEPs) and transcranial electric motor evoked potentials (tceMEPs) recorded from upper and lower extremities provide excellent coverage of ventral and dorsal spinal cord tracts and can also be used to monitor for positional brachial plexopathy. In procedures below C4, the vertebral artery is not generally at high risk; emphasis shifts to monitoring for potential injury to cervical nerve roots, especially C5, using spontaneous EMG and tceMEPs recorded from the deltoid as well as hand muscles. When pedicle screws or lateral mass screws are used, stimulus-evoked EMG is appropriate. Monitoring of cord function is performed with tceMEPs and SSEPs recorded from both upper and lower extremities. In a subset of patients with cervical myelopathy, SSEPs are poorly defined and not able to be monitored. spEMG = spontaneous electromyography, stEMG = stimulus-evoked electromyography. (Adapted with permission from Schwartz DM, Sestokas AK: A systems-based algorithmic approach to intraoperative neurophysiological monitoring during spine surgery. Semin Spine Surg 2002;14:136-145.)

**Intraoperative Monitoring During Lumbar Spine Surgery**

IONM is used with increasing frequency during lumbar spine surgery, especially when pedicle fixation is used (Figure 6). Failure to detect intraoperative pedicle screw misplacement can occur despite the use of fluoroscopy, radiographs, palpation of the pedicle channel, and direct visualization of the medial pedicle wall. Development of minimally invasive techniques for lumbar pedicle screw placement has stimulated interest in adjunctive methods for confirming appropriate intrasosseous screw placement. The increasing complexity of current lumbar spine procedures, including increased application of spinal osteotomies and posterior approaches for interbody fusion, has enhanced interest in neurologic surveillance to decrease complications related to intraoperative manipulation of neural structures.

Calancie et al were the first to report the use of intraoperative EMG monitoring for evaluation of lumbar pedicle screw placement. Intraoperative EMG monitoring in 18 patients (102 screws) detected 21 perforations of the medial wall, half of which would have been unrecognized without EMG monitoring. Glassman et al correlated EMG monitoring during lumbar screw placement with postoperative CT. Threshold intensities >15 mA were reported to be 98% accurate for determining that a screw was located within the pedicle. Toleikis et al confirmed the efficacy of pedicle screw stimulation in a series of 662 patients (3,409 pedicle screws) in which none of the patients in the study experienced any new postoperative neurologic deficits.

By stimulating polyaxial-type pedicle screws, Anderson et al documented the importance of placing the EMG probe in contact with the...
hexagonal port or directly with the screw shank to avoid false-negative results that could occur when only the mobile crown was stimulated. Bose et al reported continuous EMG and evoked EMG monitoring of lumbar pedicle screws in a series of 61 patients. Significant neurophysiologic events occurred in 13 of 61 patients (21%). Continuous EMG monitoring detected sustained neurotonic electromyographic discharges in 5 of 40 patients during placement of interbody fusion cages, in 2 patients during placement of transpedicular screws, and in 1 patient during rod tightening. Pedicle screw stimulation detected pedicle cortex breach in six patients. Following surgery, no new neurologic deficits were found in 60 of 61 patients. The authors suggested that intraoperative EMG monitoring permitted real-time detection of impending spinal nerve root injury, thereby allowing for timely intervention and minimization of negative postoperative sequelae.

In a series of complex thoracolumbar procedures, Gunnarsson et al reported significant EMG activation in 77.5% of cases, with postoperative neurologic deterioration noted in only 6.6% of cases. The authors suggested that the surgeon was often able to avoid permanent injury by changing surgical strategy based on monitoring. In a subsequent study, Krassioukov et al combined SSEP and EMG monitoring of lower limb muscles with EMG monitoring of the external anal and urethral sphincters; they reported the combined monitoring to be practical and reliable for monitoring S2–4 nerve root integrity during complex intradural lumbar procedures. The use of anal sphincter EMG in combination with other IONM modalities has been popularized by Schwartz and Sestokas to identify impending nerve root injury during placement of lumbar interbody cages.

The routine use of IONM for instrumented lumbar procedures is not universally accepted. Opponents report that the medical literature does not support the hypothesis that intraoperative monitoring improves patient outcomes following instrumented surgery for lumbar degenerative disorders. Conversely, proponents cite data supporting pedicle screw stimulation as highly predictive of acceptable screw placement. Proponents also cite studies that suggest that EMG data can provide the surgeon with a warning before actual neural injury occurs, thus facilitating rapid and appropriate intervention.

In addition, use of IONM permits identification of impending brachial plexus injury from prolonged prone positioning, thereby increasing the overall safety of surgery.

### Evidence-based Medicine

Medical evidence [level I, diagnostic] exists to support the validity of IONM as a diagnostic tool for assessment of spinal cord and nerve root function during spinal surgery in the cervical, thoracic, and lumbar regions. In addition, multiple studies [level I, diagnostic] support EMG monitoring as highly reliable for prediction of intrapedicular screw placement. IONM is based on an injury-detection model, and its use is not intended to improve or predict surgical outcomes.

According to the tenets of evidence-based medicine, in the absence of randomized controlled trials, statements regarding efficacy of IONM toward improving neurologic outcomes following surgery are not conclusive. Thus, recommendations regarding use of IONM represent only options and do not reflect any consensus guidelines or standard of care. Randomized prospective studies comparing clinical and radio-
graphic outcomes in similar groups of patients undergoing surgery, with or without IONM, would provide high-quality evidence supporting or refuting the hypothesis that IONM improves neurologic outcomes; however, completion of a meaningful study is impractical because accepted contemporary surgical practice demands that the surgical procedure, and therefore its outcome, be influenced by monitoring.

Summary
Extensive medical evidence exists to support the validity of neurophysiologic monitoring as a diagnostic tool for identification of emerging neurologic injury during spinal surgery. When information is desired regarding spinal cord function, recording of both SSEPs and tceMEPs should be performed because they provide complementary information and monitor different spinal cord tracts. Use of EMG monitoring is required when data are desired regarding nerve root function during surgery. The Stagnara wake-up test can be used when the intraoperative neurophysiologic data demonstrate significant abnormalities.

References

Evidence-based Medicine: There are four level I/II prospective, randomized studies: references 8, 13, 34, and 38.

Citation numbers printed in bold type indicate references published within the past 5 years.


