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Operative Techniques in
Orthopaedics

Evolving Indications for Neuromonitoring in Spinal Surgery: What and When to Monitor

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Intraoperative neuromonitoring (IONM) is utilized during spine surgery to help prevent intraoperative neurologic injury. The first reported use of IONM in humans occurred more than four decades ago. Since its initial inception, technological advances such as the ability to monitor afferent sensory pathways and efferent motor pathways has greatly improved the efficiency and accuracy of IONM.

Clinical research has established the superiority of multimodal IONM over unimodal techniques. However, controversy still exists regarding the most appropriate use of IONM. Currently, the surgeon is responsible for the interpretation of neuromonitoring alerts with the assistance of technicians and neurologists. Furthermore, the surgeon must determine the interventions necessary to mitigate neurologic risk according to such alerts. To that end, this chapter provides a historical context for IONM, reviews the physiologic mechanisms of common IONM modalities and examines the clinical evidence for IONM use.

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Introduction

The goal of intraoperative neurophysiologic neuromonitoring (IONM) in spine surgery is to alert the surgical staff to ongoing or impending neurologic injury. With this knowledge and appropriate recourse, permanent injury can be avoided. The past four decades have seen major advancements in the feasibility and reliability of IONM during surgical procedures. In part, this is due to the development of different measurement modalities. Multimodal IONM has become the standard of care during high-risk spine surgery. Nevertheless, there is a continuing debate about the definition of "high-risk." Additionally, medicolegal considerations play an outsized role in the IONM debate relative to other topics in spine surgery.

Despite the varied opinions regarding utilization of IONM, its use is prevalent in spine surgery. As such, spine surgeons should be familiar with the current evidence on IONM efficacy and have a basic understanding of the underlying physiology. This knowledge helps guide preoperative decisions for incorporating IONM and allows the surgeon to make informed decisions intraoperatively in the face of signal changes. The purpose of this article is to concisely review the history of IONM development, discuss the basic science and physiology of IONM, and examine the existing evidence for its use.

History of IONM Development

Prior to the 1970s, intraoperative determination of neurologic integrity was made via the Stagnara wake-up test.[1] This test involves careful down-titration of the anesthetic to the point where the patient is able to fire muscle groups on command. Although crude, many still consider this the gold standard as it provides direct observation of intact neural pathways. While the development of short acting injectable anesthetic regimens such as propofol and remifentanil have made this test easier to perform, there remain a number of potential downsides to this method of IONM. For the patient, there is the possibility of accidental awareness during emergence. For the anesthesiologist, it requires careful modifications that risk hemodynamic instability. For the surgeon, this test lacks reproducibility and perhaps most importantly, it fails to identify the moment of neurologic injury that may occur during surgery. Additionally, this test relies upon preoperative education of the patient of the possibility of performing this test, which may be variable in practice.

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The advent of Harrington instrumentation in the 1960s allowed spine surgeons to perform more dramatic corrections of spinal deformities.[2] As such, the number of deformity corrections increased in the following decade. Unfortunately, the rate of neurologic injury increased along with the amount of achievable correction. Spinal cord traction and ischemia were the most common culprits and by 1981, the Scoliosis Research Society published a report documenting a 0.5% incidence of spinal cord injury during deformity correction surgery.[3] These observations spurred the spine community to develop reliable methods of monitoring spinal cord integrity.

In Japan, Tamaki et al developed a method of measuring potentials evoked from an electrode placed on the spinal cord in the epidural space.[4] Spinal cord evoked potentials (SCEP) are measured within the subarachnoid space at the level of the conus medullaris under the control the surgeon. SCEP signals do not need to be repeatedly performed or averaged due to the relatively large signal amplitude produced. Potential disadvantages include violating the epidural space, lack of distal inquiry and inability to monitor efferent motor tracts due to masking from sensory potentials.

The use of cortical somatosensory evoked potentials (SSEP) in the clinical setting was pioneered by McCallum et al and Nash et al[5,6] in the mid-1970s. This modality of IONM gained widespread acceptance and is the most prevalent modality used today. The major drawback to SSEP monitoring is that evaluation is limited to the dorsal column-medial lemniscus pathways. If a detrimental process is affecting the entire spinal cord, the SSEP signals will reflect that alteration from baseline. However, isolated injury to the motor pathways (as in the case with anterior vasculature disruption) can occur undetected. This phenomenon is borne out in the literature through multiple reports of a relatively high false negative rate. Furthermore, the low amplitude of SSEP signals requires signal averaging over a period of minutes and can result in delayed alerts in the setting of active injury. Therefore, unimodal SSEP is not recommended if multimodal IONM is available.

The 1980 publication by Merton and Morton describes the first measurement of transcranial motor-evoked potentials (tcMEP) in an awake subject.[7] It was later discovered that the predominance of volatile gases used for anesthetic presented a challenge when trying to adopt this technology intraoperatively. The anesthetic gases produce a depressant effect on alpha-motor neurons making it difficult to accurately record MEP.[8] Additionally, there were technological limitations to adopting tcMEP due to the high voltages required. The development of equipment that provided a stimulus through an electrode placed in the cancellous portion of the skull along with the anesthetic protocols excluding inhalational gases allowed for the increased utilization of this IONM modality. In contrast to SSEP monitoring, tcMEP has a high sensitivity to injury but this lends to a high false positive rate. The false positive rate is often preferred to the alternative given the catastrophic outcome of permanent neurologic injury. In addition, the amplitude variability between tcMEP measurements can be large, which makes it difficult to ascertain subtle injury. As such, some advocate that tcMEP reports be considered in binary fashion.

Physiology of IONM

SSEP

An electrical stimulus supplied to a peripheral nerve can be recorded transcranially. These signals can be obtained from cutaneous stimulation, but this generally results in lower amplitude signals. Therefore, transdermal needle electrodes are most commonly used. The signal travels along large diameter nerve fibers in the extremities and then rostral within the dorsal column-medial lemniscus pathway of the spinal cord. The signals decussate in the midbrain before entering the ventral posterolateral and posteromedial nuclei of the thalamus. Finally, the signals are projected to the somatosensory cortex, which resides in the postcentral gyrus of the parietal lobe (Brodmann Areas 3, 1, and 2). Understanding this neuroanatomy helps explain signal changes intraoperatively as well as difficulty obtaining preoperative baseline signals due to prior injury (such as cerebrovascular accident) (Fig. 1).

The two important components of SSEP signals are amplitude and latency. The stimulus intensity can affect the amplitude whereas the patient's age, height, limb length, and body temperature can affect the latency. Therefore, postanesthesia baseline values are patient-specific and population norms are not applicable for intraoperative SSEP. Generally, the median or ulnar nerve is measured in the upper extremities and tibial nerve in the lower extremities as these are mixed nerves

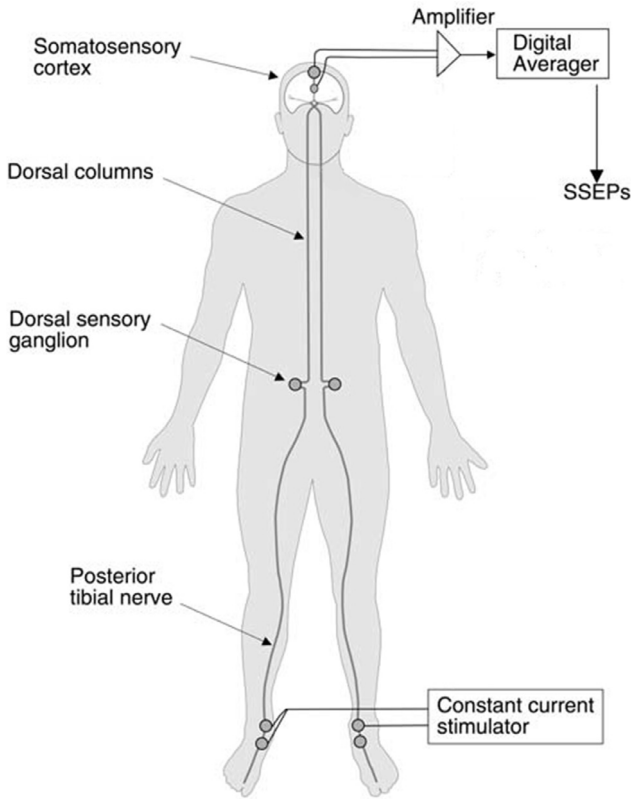

Figure 1 Cortical somatosensory-evoked potential (SSEP) recording, constant-current stimulation of the posterior tibial nerve at the ankle with recording of responses from the somatosensory cortex.[20] (Adapted with permission.)

containing both sensory and motor fibers. potentials from each nerve give a characteristic signal and are named with an N or P (to describe polarity) and a number (to describe latency in milliseconds). For example, stimulus at the median nerve evokes the N20 potential whereas the tibial nerve evokes the P37 potential (Fig. 2).

Relative to motor activity, the amplitudes of SSEP are relatively low. As such, substantial artifact can be obtained when reading SSEP's even in an anesthetized patient due to ongoing biologic (EEG) and electrical (eg, 60-Hz) background disturbance. Pulsing the stimulus and averaging the potentials allows the noise to be filtered. Accurate filtration relies on the assumption that the noise and signal are not synchronous. The practical implication of averaging, however, is a delay in feedback and may cause the surgeon to inaccurately attribute the alert.[9]

The thresholds for an alert set by the American Society of Neurophysiological Monitoring include a 10% increase in latency or a 50% decrease in amplitude when compared to baseline. After repeating the signals and confirming an alert,

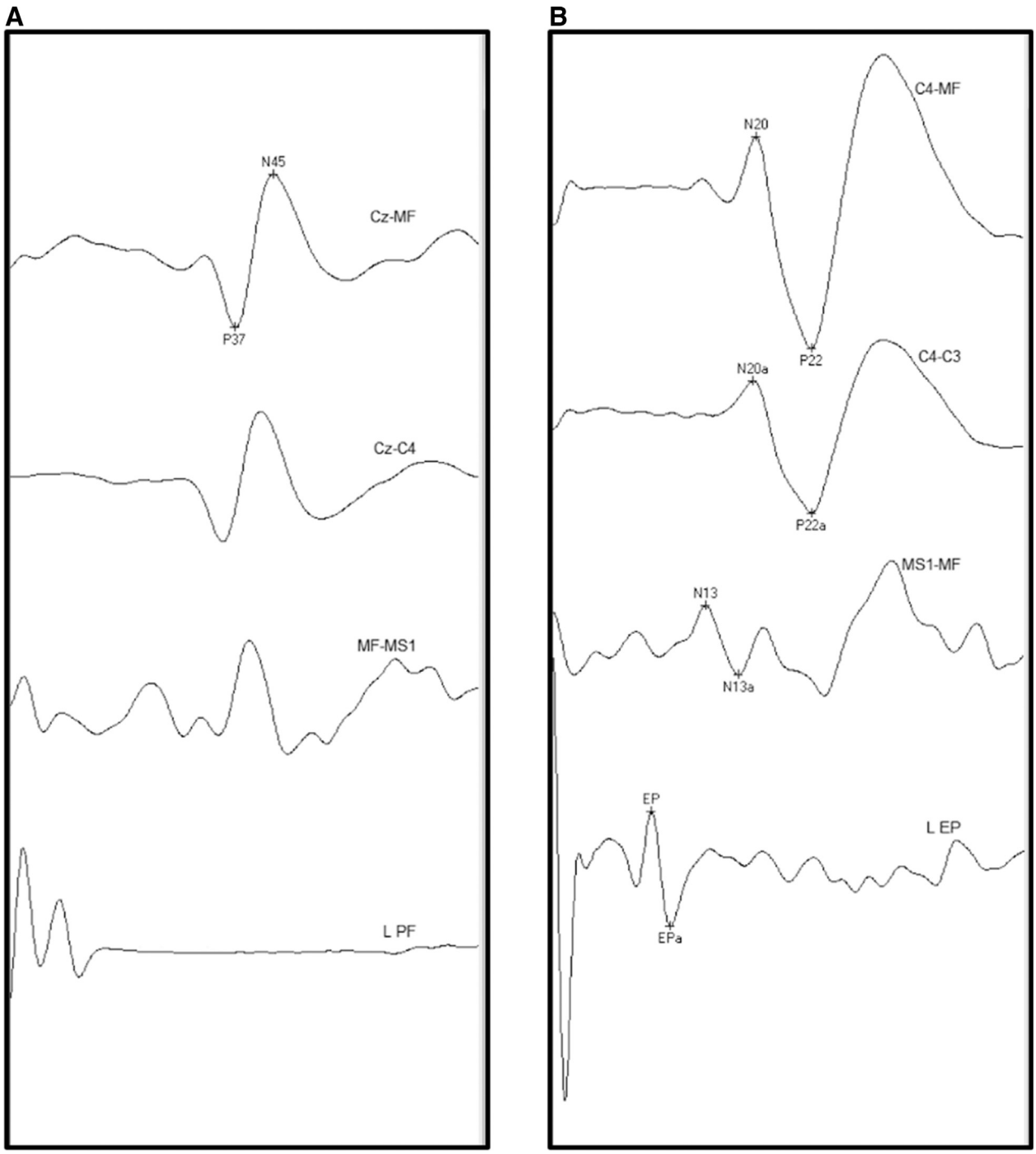

Figure 2 Baseline somatosensory evoked potential from both upper and lower extremities. **(A)** Upper extremity SSEP. **(B)** Lower extremity SSEP. SSEP, somatosensory-evoked potential.

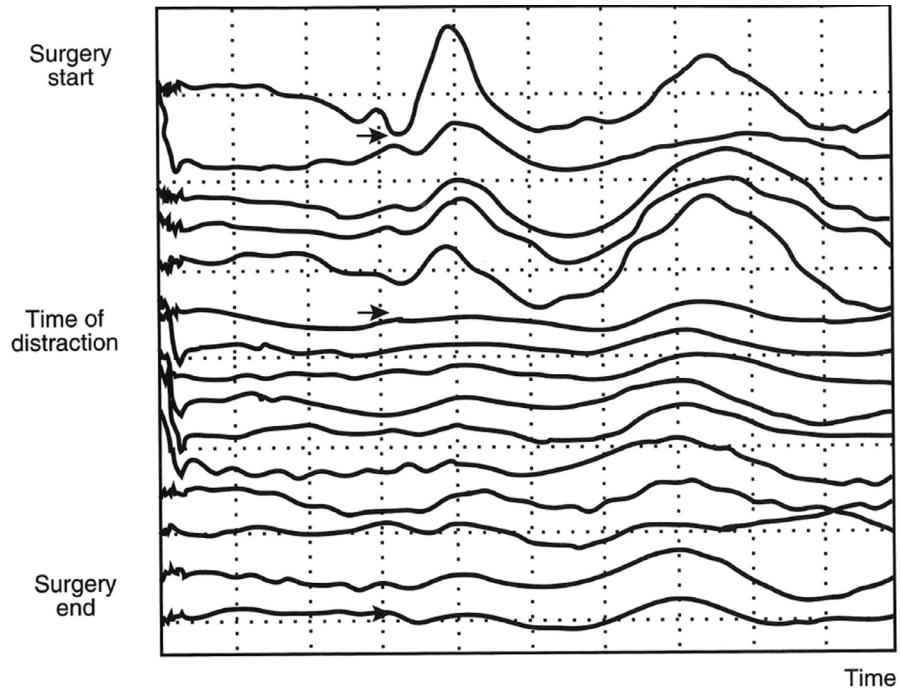

Figure 3 Example of intraoperative SSEP recording (tibial nerve stimuli) from a deformity correction procedure. During the first stage of surgery, the P32 potential is evidenced (top arrow), but soon after surgical distraction, the potential almost disappears (middle arrow). The surgeon was informed, and the distraction was reversed. The potential returned at the end of the procedure, but with smaller amplitude (bottom arrow).[21] (Reproduced with permission Benzel, Edward, Spine Surgery, Techniques, Complication Avoidance, and Management. 2nd edition. 2005.)

the surgeon should take action in context with the preceding surgical steps (Fig. 3). If it is determined that instrumentation or a distraction maneuver is not responsible for the signal changes, electrode placement, patient positioning, mean arterial pressure and use of volatile anesthetic should be questioned. Measurement of signals is often made concurrently at the popliteal fossa. This provides the ability to quickly ascertain stimulus electrode dislodgment.

tcMEP

An electrical stimulus applied transcranially can be recorded in the periphery.[7] The electrode is usually affixed to the cancellous portion of the cranium. A signal is transmitted from the primary motor cortex, which resides in the posterior aspect of the frontal lobe (Brodmann area 4). The signal then travels along axons coalescing to form the posterior limb of the internal capsule. From there, the signal travels through the brainstem where a portion decussates in the medulla oblongata and runs caudally along the lateral corticospinal tract of the spinal cord. A signal that does not decussate in the brain stem travels down the ventral corticospinal tract before reaching lower motor neurons and traveling into the periphery (Fig. 4).

The motor evoked potential can be measured on the surface of the skin, subdermally or intramuscularly. The latter provides the highest amplitude reading with a relatively high signal-to-noise ratio. As previously mentioned, the potentials do not have to be averaged, a distinguishing feature between tcMEP and SSEP IONM. Stimulation of the pyramidal cell

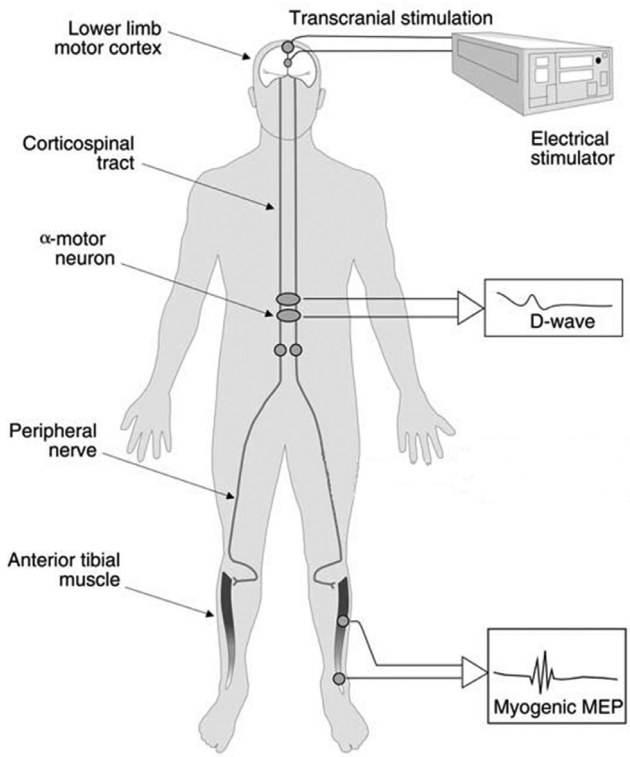

Figure 4 Transcranial electric motor-evoked potential (tcMEP) recording, after transcranial electrical stimulation, the motor cortex is activated. The signal travels along the corticospinal tract and activates the anterior horn motor neuron. Myogenic MEP are most commonly recorded.[20] (Adapted with permission.)

axons that comprise the corticospinal tract can result in direct waves (D-waves) or indirect waves (I-waves).[10] When a D-wave creates a muscle contraction, that myogenic potential can be measured and is known as a M-wave. Anesthetic protocols make I-waves unmeasurable and D-waves are typically measured directly from a caudal location directly the spinal cord. Therefore, M-waves are most commonly utilized since they can be reproducibly and reliably measured from a location outside of the surgical field (Fig. 5). In general, neuromuscular blockade should be avoided if accurate measurements are desired during the procedure. If initial neuromuscular blockade is utilized during intubation, reliable use of tcMEP will be available only after complete reversal has been accomplished.

Two important variables when interpreting tcMEP signals are amplitude and threshold voltage. In contrast to SSEP, the amplitude of tcMEP can vary significantly between measurements. This variance has prevented neurophysiologists from uniformly agreeing on an amplitude reduction that would trigger an alert for the surgeon. Some have argued for a reduction of greater than 50% while others argue that even reductions greater than 80% are false positive findings. Conversely, a threshold voltage increase of more than 100 volts from the baseline is established as an alert. A reduction in signal is considered a moderate alert whereas a complete disappearance of tcMEP signals should be treated as a major alert.[11]

Interpreting an tcMEP alert can be challenging for the surgeon and requires a systematic review of physiologic

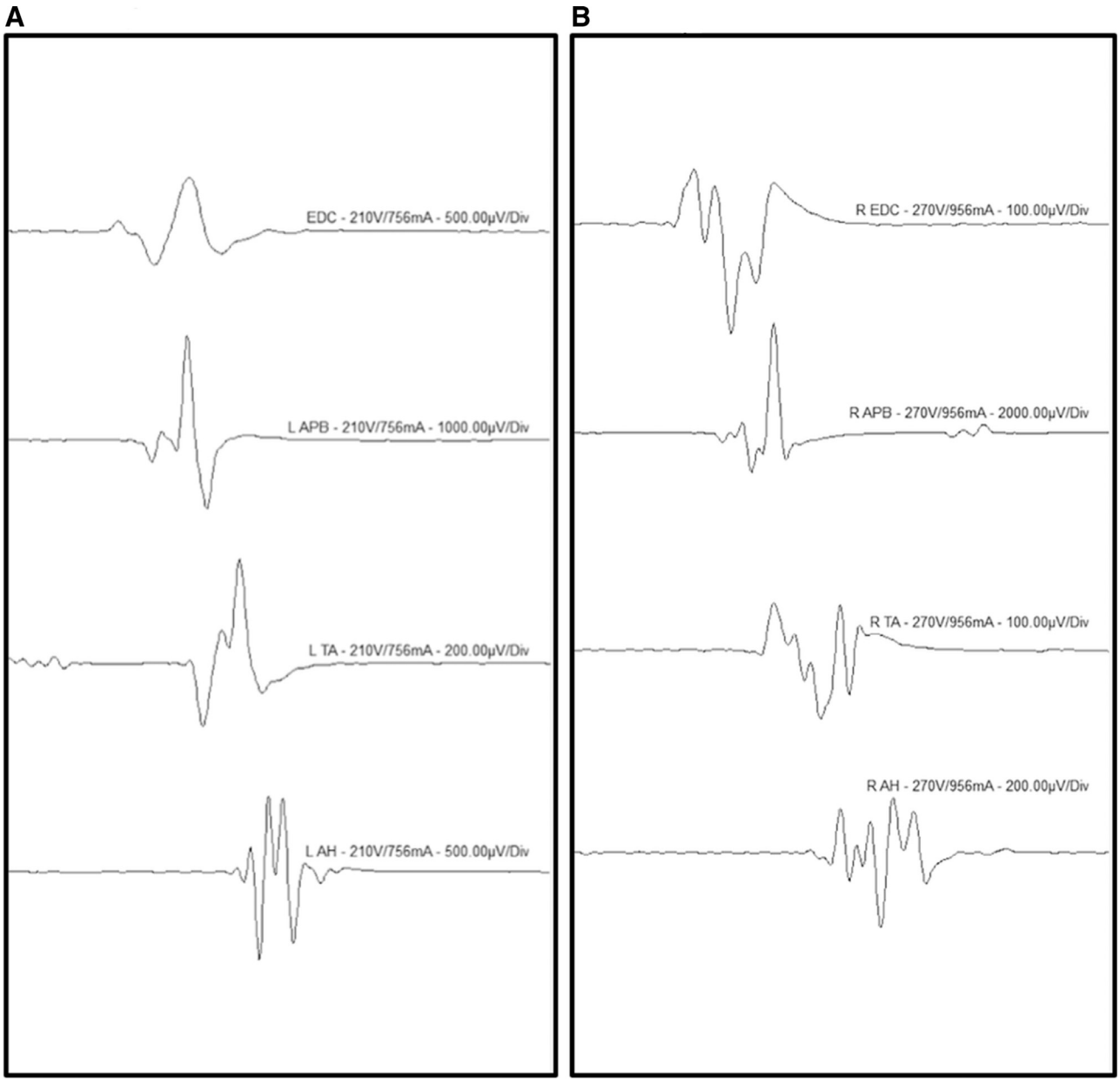

Figure 5 Baseline tcMEP. (A) Left extremity. (B) Right extremity. AH, anterior hallucis; APB, abductor pollicis brevis; EDC, extensor digitorum comminus; TA, tibialis anterior.

parameters within the context of previous surgical maneuvers. An alert can be classified as generalized or focal depending on the muscle groups affected. In the absence of recent instrumentation or deformity correction, further investigation is warranted to determine if a false positive alert has occurred. Patient positioning should be considered as cause of generalized signal decrease. This is especially important in the setting of tandem stenosis where inadvertent neck extension can cause spinal cord injury. Common causes of false positive generalized alerts include introduction or increase of volatile anesthetic gas, hypoperfusion, hypothermia and neuromuscular blockade. Discussion with anesthesia staff can quickly ascertain recent volatile anesthetic or neuromuscular blockade use. Additionally, mean arterial pressure and internal body temperature can be determined through discussion with anesthesia. Focal deteriorations often occur secondary to positioning. Global upper extremity alerts suggest stress on the brachial plexus whereas isolated muscle group alerts suggest padding or single joint malposition. Finally, correlation with concurrent SSEP and EMG signals is important for determining if an alert is a false positive. Each alert should be quickly and efficiently evaluated. Following a stepwise algorithm such as the one proposed by Ziewacz et al can improve the surgical teams response to IONM alerts (Fig. 6).

EMG

Electromyography recording can be performed with or without stimulation. Unstimulated EMG, or free-running EMG, is the most commonly utilized form of EMG in North America. Free-running EMG records electrical depolarization of a peripheral nerve via intramuscular electrodes. Suppositions for the accuracy of this modality include an intact motor end plate without substantial pre-existing peripheral neuropathy. Free-running EMG signals are observed as tonic or phasic.

Tonic signals are defined as sustained electrical activity that can last for several minutes. Often, tonic signals occur in the setting of neural ischemia secondary to traction or thermal injury. In contrast, phasic signals occur in short bursts and most often are in response to compression of a nerve (eg, bordering anatomic structures, surgical instrumentation, positioning). Intraoperative uses of free-running EMG include prevention of excessive radicular manipulation during nerve root decompression and interrogation of pedicle

IONM Alert Checklist

Surgeon

- Cease surgical manipulation
- Access surgical field for structural cord and/or nerve root compression
- Consider reversing surgical correction of deformity

Neurophysiologist

- Repeat trials of SSEPs and tcMEP to rule out potential false positive
- Ensure all leads are secure, add leads to proximal muscle groups if needed
- Assess the pattern of changes
  - Asymmetric – associated with cord or nerve root injury
  - Symmetric – associated with anesthetic or hypotension issues
- Quantify improvement and discuss with surgical team

Anesthesiologist

- Determine is neuromuscular blockade is present
- Verify no change in anesthetic administration occurred prior to alert
- Access anesthetic depth
  - Blood pressure
  - Heart rate
  - Respiratory rate
- Restore blood pressure (mean arterial pressure goal 80-100)
- Check hemoglobin/hematocrit (goal hemoglobin >9-10)
- Check temperature and input/output to ensure adequate resuscitation
- Check extremity position (plexus tension)
- Lighten depth of anesthesia

Figure 6 IONM alert checklist. SSEP, somatosensory evoked potential; tcMEP, transcutaneous motor-evoked potential.

screw placement through direct stimulation of a screw. In general, if more than 8 milliamperes (mA) of current is needed to produce an EMG recording, the position of the screw is likely within the pedicle borders.[12] However, some authors argue that a concrete threshold cannot be established that ensures accurate screw placement and advise direct assessment rather than reliance on EMG.[13]

Clinical Evidence for IONM

The available clinical research for IONM use in spine surgery varies substantially. This has made it difficult for the spine surgery community to develop a consensus-based clinical practice guideline for absolute and relative indications. In general, the available studies are retrospective, involve single or multimodal IONM, and report on the ability of IONM to identify neurologic injury (sensitivity, specificity, positive/negative predictive values).

In 2010, Fehlings et al performed a systematic review of IONM in spine surgery and made several important conclusions.[14] First, the existing evidence suggests tcMEP is more sensitive than SSEP or EMG, with similar specificity amongst the 3 modalities. Secondly, at the time of that systematic review and since then there have been no studies that directly compare tcMEP to SSEP techniques. Nonetheless, the established sensitivities and specificities for the individual modalities supply a large body of evidence that multimodal IONM is capable of detecting neurologic injury with a high sensitivity and specificity.

Currently, there are no studies to suggest IONM prevents new neurologic deficits. The ideal study would compare groups undergoing similar types of surgery with and without IONM utilization. Sala et al performed a retrospective study using a historical control group and concluded that postoperative neurologic status was better in the group that underwent IONM.[15] However, this study involved patients undergoing intramedullary tumor resection and one could argue this data is not generalizable to patients who are undergoing decompression and fusion for cervical spondylotic myelopathy or degenerative scoliosis with neurogenic claudication.

Cohort heterogeneity is a pervasive concern in the existing literature on IONM. For example, Yoshida et al published a multicenter study on IONM and reported a 9.5% IONM alert rate with over half of those resolving with intraoperative interventions.[16] However, there was a significant increase in the incidence of IONM alerts for high-risk pathology such as thoracic ossification of the posterior longitudinal ligament or intramedullary spinal cord tumor resections. This supports the notion that a critical review of IONM literature necessitates more specific inclusion criteria than "spine surgery."

Badhiwala et al used data from the Nationwide Inpatient Sample to compare patients undergoing anterior cervical discectomy and fusion with or without IONM.[17] Propensity matching techniques were used to control certain selection biases. The authors concluded there was no difference in the neurologic complication rate with or without IONM but patients who had IONM had an additional hospital charge of $6843. The financial implications of IONM are likely most relevant in the United States where a fragmented payer system exists. For example, a 2018 clinical policy bulletin for a large insurance company considers the use of EMG monitoring during spinal surgery "experimental and investigational".[18] The complex and varying coverage schemes can result in tremendous financial burdens shifted onto the patient.[19]

Authors' Preferred Use

The authors recognize the current prevalence of IONM in spine surgery and the substantial technological advances in the past decades that allow IONM to be readily available. Additionally, the authors recognize regional variance in medicolegal norms, which can be a substantial driver for utilization. Furthermore, surgeon discretion for IONM use can be influenced by utilization habits where training occurred along with any previous positive or negative experiences with IONM. However, the available evidence suggests nondiscriminatory use is not warranted.

A judicious approach to IONM involves considering the patient's baseline neurologic status, pathology, and surgical approach. In general, the authors recommend IONM for traumatic cases involving unstable injuries at the spinal cord level. Additionally, surgical procedures addressing acute or degenerative (ie, spondylotic myelopathy) spinal cord injuries as well as deformity cases involving vertebral segments at or cephalad to the conus medullaris should utilize IONM. An argument can be made to support the use of neuromonitoring for any instrumentation at the level of the spinal cord. However, the authors contend there is low evidence to support IONM during procedures that address radiculopathy or are caudal to the spinal cord, regardless of the use of instrumentation.

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