REVIEW

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Intraoperative Neurophysiological Monitoring in Spine Surgery: Modalities, Interpretation, and Clinical Applications

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Abstract

Neurological injury remains one of the most serious complications of spine surgery. Intraoperative neurophysiological monitoring (IONM) provides continuous, real-time functional assessment of the spinal cord and nerve roots, and is increasingly integrated into spinal procedures to mitigate the risk of perioperative neurological deficits. The principal IONM modalities used in spine surgery include motor evoked potentials (MEPs), somatosensory evoked potentials (SSEPs), electromyography (EMG), and spinal cord and nerve root mapping. MEPs are highly sensitive to dysfunction of the corticospinal tracts; SSEPs evaluate the integrity of the dorsal column-medial lemniscal pathway; EMG detects nerve root irritation or injury; and mapping techniques facilitate safe surgical navigation, particularly when anatomical landmarks are distorted or obscured. Each modality interrogates distinct neural pathways and is characterized by specific strengths and inherent limitations. When appropriately selected, systematically applied, and accurately interpreted, multimodal IONM enhances intraoperative decision-making, improves surgical safety, and supports maximal safe resection-particularly during high-risk procedures such as spinal deformity correction, intramedullary spinal cord tumor resection, and operations involving the conus medullaris or cauda equina. This review delineates the underlying neurophysiological principles and alarm criteria of these modalities, examines anesthetic considerations that influence signal reliability, and synthesizes current evidence regarding their clinical applications across diverse spinal procedures.

Keywords: Intraoperative neurophysiological monitoring, spinal cord mapping, spine surgery, motor evoked potential, somatosensory evoked potential

INTRODUCTION

Neurological injury remains one of the most devastating complications associated with spinal surgery, often resulting in permanent functional deficits and substantial impairment of quality of life. In this context, intraoperative neurophysiological monitoring (IONM) has become an integral component of contemporary spinal surgical practice. IONM provides continuous, real-time assessment of the functional integrity of the spinal cord, nerve roots, and peripheral neural pathways, thereby furnishing the surgeon with immediate feedback during critical phases of the procedure.[1] Through the integrated use of advanced electrophysiological modalities, IONM facilitates precise neural mapping, early detection of impending neural damage, and timely intervention to mitigate the risk of irreversible neurological injury.[1]

Spinal surgeries most commonly rely on neurophysiological monitoring modalities such as motor evoked potentials (MEPs), somatosensory evoked potentials (SSEPs), and both free-running and triggered electromyography (EMG). Additional techniques-including D-wave recording, bulbocavernosus reflex (BCR) monitoring, and spinal cord and nerve root mapping-are used in spinal procedures to provide further information on neural structures and their functional status.

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Although each modality possesses distinct strengths and inherent limitations, these approaches are complementary and together enable comprehensive multimodal monitoring of spinal cord and nerve root function.

This review discusses the fundamental IONM modalities and their applications in commonly performed spinal surgeries.

Intraoperative Neurophysiological Monitoring Techniques In Spine Surgeries

Neurophysiological Monitoring Modalities:

Transcranial Motor evoked potentials and D-wave recording

Avoiding postoperative paralysis remains a primary objective of spine surgery, and intraoperative monitoring of motor pathways enables early detection of impending motor compromise. MEPs provide real-time assessment of the functional integrity of descending motor pathways and are widely applied across a broad spectrum of spinal procedures.[2,3]

MEPs primarily assess fast-conducting corticospinal tract (CST) fibers that project monosynaptically to anterior horn cells, with subsequent transmission through peripheral nerves to target muscles.[4] MEPs are most commonly elicited via transcranial electrical stimulation using scalp electrodes positioned over the motor cortex (Figure 1).

In awake individuals, single-pulse stimulation of the motor cortex produces a series of descending volleys that can be recorded from the spinal cord (Figure 2). The initial response, termed the D-wave, represents direct activation of corticospinal axons, whereas subsequent I-waves are generated through indirect transsynaptic activation mediated by intracortical interneuronal circuits.[5] In conscious subjects, temporal summation of excitatory postsynaptic potentials generated by D- and I-waves leads to the activation of lower motor neurons (LMNs).

General anesthesia profoundly alters this physiology by suppressing intracortical synaptic transmission, thereby attenuating or abolishing I-waves and reducing LMN excitability.[3,6] As a result, single-pulse stimulation is typically insufficient to elicit reliable muscle MEPs under general anesthesia. To overcome this limitation during IONM, short trains of electrical stimuli are delivered, generating multiple descending volleys whose temporal summation facilitates LMN depolarization and produces reliable myogenic MEP responses.[3]

Myogenic MEPs are recorded from multiple limb muscle groups using surface electrodes, subdermal electrodes, or intramuscular needle electrodes. Because of their high signal-to-noise ratios, signal averaging is not required. In the upper extremities, recordings are commonly obtained from intrinsic hand muscles such as the abductor pollicis brevis, abductor digiti minimi, or first dorsal interosseous. In the lower extremities, commonly monitored muscles include the tibialis anterior and abductor hallucis. The selection of additional muscles spanning different spinal segments is tailored to the surgical level.[3]

In contrast to myogenic MEPs, D-waves provide a direct electrophysiological measure of CST integrity. D-waves are recorded from the spinal cord using epidural or subdural electrodes placed caudal to the surgical field and are elicited by single-pulse transcranial electrical stimulation. Placement of an additional rostral control electrode enables differentiation between global physiological changes and focal spinal cord injury.[7] However, D-wave recording is not feasible below the T10-T11 spinal level because insufficient CST fibers are present to generate a recordable signal.[7]

Somatosensory evoked potentials

SSEPs are among the most commonly used IONM modalities in spine surgery. SSEPs assess the functional integrity of ascending sensory pathways by recording cortical and subcortical responses following electrical stimulation of peripheral nerves.

Peripheral nerve stimulation is delivered through surface or needle electrodes placed distally on the limbs, generating afferent action potentials that ascend via the dorsal column-medial lemniscal pathway to the somatosensory cortex.[8,9] In routine clinical practice, SSEPs are elicited by stimulation of the median or ulnar nerves for the upper extremities and the posterior tibial or common peroneal nerves for the lower extremities (Figure 3). Responses are recorded from multiple sites, including the scalp, cervical spine, and peripheral locations, allowing assessment of neural conduction across different anatomical levels.[8,9]

Because SSEPs are low-amplitude signals embedded within background electroencephalographic activity, signal averaging is required to achieve an adequate signal-to-noise ratio.[10,11] Consequently, acquisition of

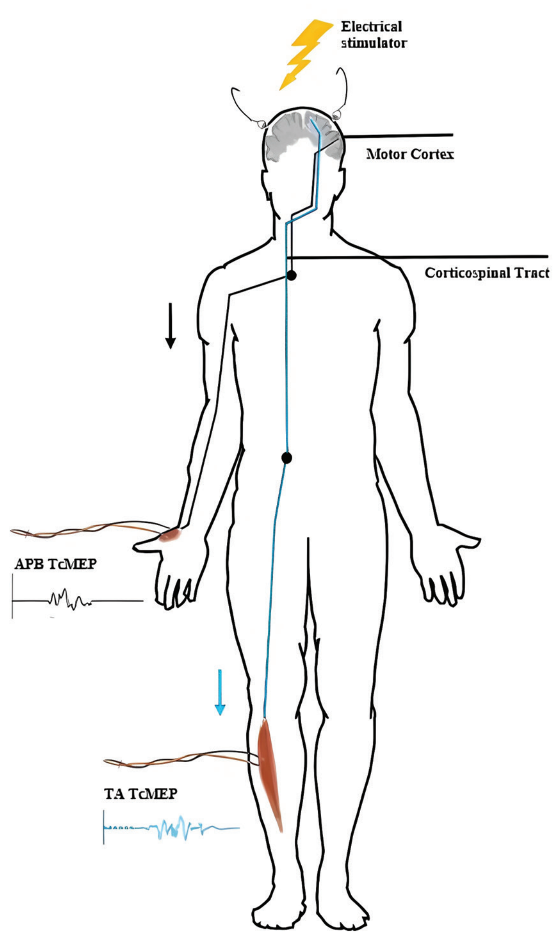

Figure 1. Schematic representation of TcMEP recordings from the upper (black) and lower (blue) extremities.

APB: Abductor pollicis brevis, TA: Tibialis anterior, TcMEP: Transcranial motor evoked potential.

stable SSEP waveforms typically requires repeated stimulation over time, which may delay the detection of acute neurological compromise compared with myogenic MEPs.[11]

Free-running and triggered electromyography

EMG is a fundamental IONM modality for assessing the functional integrity of individual nerve roots during spine surgery. EMG is particularly valuable for detecting neurotonic discharges and reducing the risk of postoperative radiculopathy, particularly during procedures involving pedicle screw placement.[9]

Free-running electromyography: Free-running, or spontaneous, EMG involves recording muscle electrical activity from selected muscle groups innervated by nerve roots at risk during surgery. Appropriate muscle selection should sample the relevant spinal nerve roots, with one representative muscle per nerve root generally being sufficient for effective monitoring.

Common EMG recording sites for cervical nerve roots include the trapezius (C3-4), deltoid (C5-6), biceps brachii (C5-6), brachioradialis (C6), triceps brachii (C6-7), extensor digitorum communis (C7), abductor pollicis brevis (C8-T1), first dorsal interosseous (C8-T1), and abductor digiti minimi (C8-T1). Upper thoracic roots can be monitored by recording from intercostal or paraspinal muscles. For lower thoracic and lumbosacral roots, commonly monitored muscles include the intercostal muscles, paraspinal muscles, rectus abdominis (T7-12), internal oblique (L1-2), adductor longus (L2-3), vastus lateralis (L2-4), tibialis anterior (L4-5), gastrocnemius (S1-S2), abductor hallucis (S1-2), and external anal sphincter (EAS) (S2-4).

Needle electrodes placed in selected muscle groups continuously record muscle fiber activity, thereby enabling real-time monitoring throughout the surgical procedure. EMG monitoring is performed in the absence of neuromuscular blockade. Under adequate general anesthesia and in the absence of nerve irritation, intact nerve roots typically exhibit no spontaneous EMG activity. However, nerve dissection, mechanical or thermal irritation, prolonged traction, or compression of a nerve root during surgery may elicit distinct EMG patterns, some of which are suggestive of axonal injury.[12]

Triggered electromyography: Triggered EMG is a technique that uses electrical stimulation delivered via a handheld probe to evoke and record compound muscle action potentials (CMAPs) from targeted muscles. Intraoperative triggered EMG during spinal surgery is used to identify and map functional motor nerve roots and to differentiate viable neural tissue from non-neural structures during tumor resection or tethered cord release procedures.[13,14]

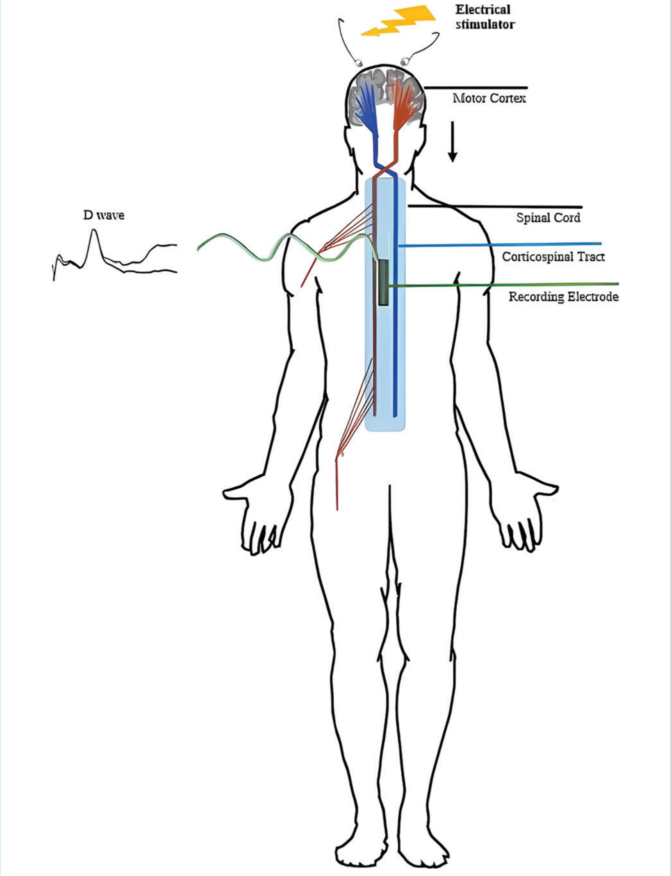

Figure 2. Schematic representation of D-wave recording.

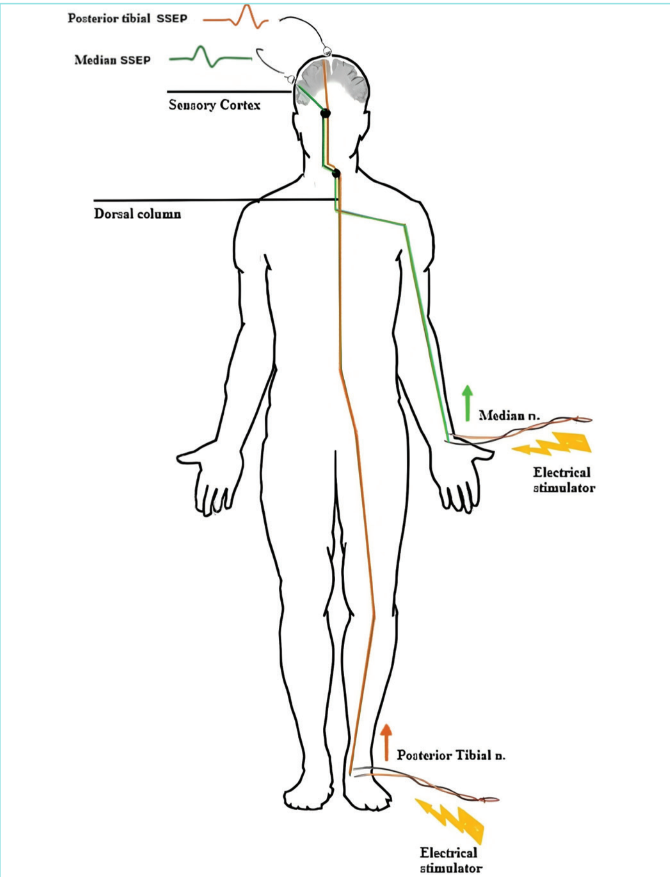

Figure 3. Schematic representation of SSEP recordings from the upper (green) and lower (orange) extremities.

SSEP: Somatosensory evoked potentials.

Triggered EMG is most commonly applied during spinal instrumentation procedures, particularly for assessing pedicle screw placement. In this technique, a handheld monopolar stimulating probe is applied directly to the pedicle holes or implanted screws to evaluate a potential breach of the pedicle wall and the proximity to adjacent nerve roots. When a pedicle screw is correctly positioned, the surrounding cortical bone acts as an electrical insulator, requiring relatively higher stimulation currents to evoke a CMAP response.[15] If the screw breaches the medial pedicle wall, the reduced impedance permits electrical current to reach the adjacent nerve root, thereby eliciting an EMG response at lower stimulation thresholds.[15]

The bulbocavernosus reflex

Intraoperative BCR monitoring is a specialized neurophysiological technique used during spinal surgery involving the conus medullaris and cauda equina to preserve bowel, bladder, and sexual function.[16] BCR monitoring provides real-time assessment of the functional integrity of the sacral sensory and motor nerve roots and the S2-S4 spinal cord segments.

The reflex is elicited by electrical stimulation of the dorsal penile nerve in males or of the dorsal clitoral nerve in females, with recordings obtained from the EAS muscle (Figure 4). Activation of this reflex arc reflects intact afferent sensory input, sacral spinal cord interneuronal processing, and efferent motor output to the EAS.[16]

In males, surface electrodes are placed on the dorsum of the penis for stimulation. In females, the cathode is positioned over the clitoris and the anode is positioned on the adjacent labium. Electromyographic responses are recorded from the EAS using wire or needle electrodes. To improve reliability under general anesthesia, stimulation is typically delivered as short trains of 2-5 pulses or using a double-train paradigm, which enhances temporal summation and increases the likelihood of eliciting a reproducible reflex response.[17]

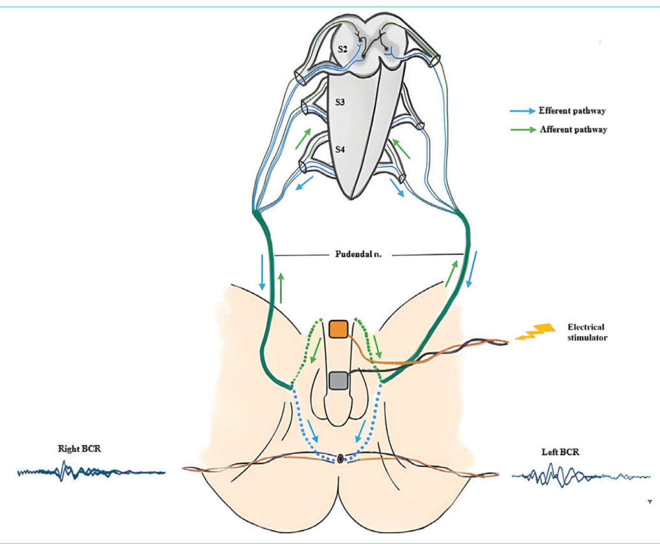

Figure 4. Schematic representation of BCR recording during dorsal penile nerve stimulation in males.

BCR: Bulbocavernous reflex.

Spinal Cord and Nerve Root Mapping Modalities:

Neurophysiological spinal cord and nerve root mapping techniques enable accurate intraoperative identification of critical neuroanatomical structures within the surgical field, thereby reducing the risk of iatrogenic neural injury.

The principal mapping modalities used in spine surgery include dorsal column mapping, CST mapping, motor root mapping, and sensory root mapping. Among these, dorsal column and CST mapping are most commonly applied during intramedullary spinal cord tumor (IMSCT) resection.[13] In contrast, nerve root mapping techniques are primarily used during procedures involving the cauda equina to differentiate functional neural tissue and during instrumented spinal surgeries to assess the osseous integrity of instrumented pedicles.[14]

Dorsal column mapping

Surgical treatment of IMSCTs often involves a posterior midline myelotomy performed through the posterior median sulcus between the right and left dorsal columns.[18] The dorsal columns consist of large-diameter, heavily myelinated sensory fibers responsible for proprioception, vibration sense, and fine touch. Injury to these pathways during myelotomy may result in postoperative numbness, dysesthesias, impaired proprioception, and sensory ataxia.

Because pathological processes may obscure or displace normal surface landmarks, dorsal column mapping has become an essential adjunct for identifying the physiological midline of the spinal cord and delineating the boundaries between the left and right dorsal columns. Accurate localization of the midline enables the surgeon to perform a safer myelotomy while minimizing the risk of posterior column dysfunction.

Several neurophysiological techniques have been described for dorsal column mapping. One approach involves direct electrical stimulation of the exposed dorsal columns with recording of antidromic sensory nerve action potentials from a peripheral nerve.[19] A second technique relies on recording scalp SSEPs and identifying a phase reversal following dorsal column stimulation, which corresponds to the functional midline.[20] A third method employs peripheral nerve stimulation with recording of SSEPs directly from the exposed spinal cord using a multielectrode grid placed perpendicular to the longitudinal axis of the cord.[21] In this configuration, an amplitude gradient across the grid reflects the somatotopic organization of the dorsal columns and allows precise identification of the physiological midline.

Corticospinal tract mapping

Another critical structure at risk during intramedullary tumor resection is the CST. CST mapping is performed using direct electrical stimulation within the resection cavity, typically with a handheld bipolar probe, to assess proximity to descending motor pathways and to guide safe tumor removal.

Stimulation of the CST produces myogenic responses in limb muscles; however, similar muscle responses may also arise from stimulation of the dorsal columns through activation of spinal interneurons, resulting in a centrally mediated reflex resembling the H-reflex.[22] To distinguish CST activation from dorsal column-mediated responses, a double-train stimulation paradigm can be applied.[23]

This technique exploits differences in the recovery times of interneuronal circuits within the spinal gray matter.[23] Interneurons activated by CST fibers exhibit a shorter refractory period than those activated by dorsal column fibers. When two stimulus trains are delivered with an intertrain interval of approximately 60 ms, stimulation near the CST is expected to evoke muscle responses following both the first and second trains. In contrast, stimulation near the dorsal columns typically produces a response only to the first train because dorsal column-related interneurons remain in their refractory period during the second train.

Accordingly, persistence of a muscle response after both stimulus trains indicates close proximity to the CST, whereas absence of a response to the second train suggests stimulation of dorsal column pathways.[23] This differentiation provides valuable real-time information regarding the spatial relationship between the surgical field and critical motor tracts, thereby facilitating maximal tumor resection while preserving neurological function.

Motor and sensory root mapping

Intraoperative motor and sensory root mapping employs direct electrical stimulation to precisely identify individual nerve roots within the surgical field. This technique is particularly valuable in procedures involving the cauda equina, resection of intradural extramedullary tumors (IDEMTs), and revision surgeries, in which normal anatomy may be distorted by tumor infiltration, inflammation, or scar tissue. Accurate root identification facilitates safe dissection, prevents iatrogenic neural injury, and optimizes surgical outcomes.

Motor root mapping is performed by directly stimulating a nerve root with a handheld monopolar or bipolar probe while recording CMAPs from muscles innervated by the corresponding myotome. This technique allows the surgeon to distinguish functional motor roots from non-neural tissue and non-functional roots, thereby preserving motor function during lesion resection.

Electrical stimulation of a sensory nerve root may also evoke a muscle response, which can complicate interpretation. This response does not result from direct motor fiber activation but instead represents a posterior root-muscle reflex (PRMR), analogous to the H-reflex mediated by proximally excited sensory axons near the spinal cord.[24] PRMRs arise from monosynaptic activation of alpha motor neurons in the anterior horn following afferent stimulation of the dorsal root.[24] Compared with CMAPs generated by motor root stimulation, PRMRs are characterized by longer latency, lower amplitude, and a higher stimulation threshold.[25] Despite these distinguishing features, overlap in response characteristics may occur, necessitating additional strategies to reliably differentiate sensory from motor roots.

Reliable differentiation between motor root-evoked CMAPs and sensory root-mediated PRMRs can be achieved using a double-train stimulation paradigm.[25] When two stimulus trains are delivered with an interstimulus interval of 60 ms, stimulation of either motor or sensory roots produces a muscle response following the first stimulus.[25] However, after stimulation of a sensory root, the reflex arc remains within its refractory period, thereby preventing the generation of a second response. In contrast, motor axons recover more rapidly, allowing stimulation of a motor root to elicit a second CMAP in response to the second stimulus.

Warning Criteria for Intraoperative Neurophysiological Monitoring Modalities

Practice guidelines and technical standards have been issued by professional societies such as the American Clinical Neurophysiology Society; however, no universally accepted, procedure-independent alarm criteria exist across all IONM modalities.[2] Interpretation of intraoperative changes therefore requires integration of neurophysiological findings with clinical judgment and the specific surgical context.

Motor evoked potentials and D-waves

Commonly used alarm criteria for MEPs are based on amplitude reduction or complete signal loss, with thresholds ranging from 50% to 80% reported in the literature.[26]

Alternative criteria-such as increased stimulation threshold, waveform simplification, or morphological changes-have also been described;[2] however, these approaches are technically demanding, time-consuming, and less frequently used in routine clinical practice.

As an indicator of irreversible CST injury, D-wave monitoring provides complementary prognostic information to MEPs in spinal cord neuromonitoring, particularly during intramedullary tumor resection.[3,27] Whereas MEPs primarily reflect immediate postoperative motor function, D-wave recordings are more predictive of long-term motor outcomes and functional recovery.

A reduction in D-wave amplitude of more than 50% or its complete disappearance, indicates significant CST injury and is associated with a high-risk of permanent motor deficit during intramedullary tumor surgery. In contrast, depending on surgical risk and tumor characteristics, resection may be continued despite loss of MEPs if the D-wave amplitude remains within 50% of baseline. Such preservation is strongly associated with favorable long-term motor outcomes, even in the presence of significant transient postoperative weakness.[27]

In addition to intramedullary tumor surgery, D-wave recording can be applied in selected cases involving IDEMTs and syringomyelia.[28,29] However, its utility in scoliosis correction and other orthopedic procedures remains uncertain.

Somatosensory evoked potentials

SSEPs are typically monitored continuously throughout surgery to detect changes suggestive of evolving spinal cord or nerve injury. Commonly accepted alarm criteria include a reduction in amplitude greater than 50% and/or a latency prolongation exceeding 10% relative to baseline recordings.[9,10]

Bulbocavernosus reflex

The presence of a stable BCR waveform with preserved amplitude and morphology throughout the procedure indicates intact sacral reflex arc function and sphincter control.[17,30] Conversely, intraoperative attenuation or loss of the BCR may reflect transient or permanent compromise of sacral sensory or motor pathways and has been associated with postoperative bowel, bladder, or sexual dysfunction, particularly when the loss is sustained and not attributable to anesthetic or technical factors.[30]

Free-running and triggered electromyography

Continuous free-running EMG is recorded from multiple muscle groups to detect electromyographic discharges indicative of motor nerve root irritation or mechanical compromise. Normal EMG recordings are electrically silent; however, intraoperative injury to motor roots may evoke high-frequency burst or train activity.

During surgery, mechanical or thermal irritation of a nerve root-such as traction, compression, stretching, cold irrigation, or electrocautery-may elicit spikes, burst discharges, or short-lasting, low-frequency train activity.[9,12,31] Short-lasting, intermittent burst activity is often associated with transient nerve root contact or decompression and generally reflects proximity rather than structural injury, being associated with a low risk of permanent nerve damage.[9,32]

Another form of EMG activity observed during IONM is long-lasting, high-frequency train activity (A-trains), also referred to as neurotonic discharges. This pattern is more commonly associated with prolonged traction or compression and is considered a warning sign of potential nerve injury if not promptly addressed. Accordingly, sustained or repetitive neurotonic discharges suggestive of possible axonal injury should be distinguished from transient irritation-related activity.[31]

In addition, preexisting chronic radiculopathy may produce baseline low-amplitude, low-frequency EMG activity that can confound interpretation; however, this activity is typically present from the onset of monitoring and lacks temporal correlation with surgical manipulation.[32] In some situations, such as sharp dissection of a motor nerve root, no EMG activity may be observed despite nerve injury, thereby creating a false-negative interpretation regarding nerve integrity.[12]

In addition to continuous EMG monitoring to detect spike, burst, or train-type discharges, triggered EMG is useful for evaluating the presence of functional neural tissue, differentiating neural tissue from scar tissue, and mapping motor roots entrapped within a tumor. When electrical stimulation of a suspected motor nerve root with a handheld probe within the surgical field evokes CMAPs in innervated muscles, the location of motor fibers can be inferred based on the stimulation threshold, latency, and amplitude of the CMAPs. Generally, obtaining a CMAP response with a stimulation threshold of 1 mA or less indicates close proximity to functional motor roots that should be preserved.[33]

Triggered EMG is also used to detect pedicle screw breach based on stimulation thresholds. The stimulation threshold reflects the proximity of the screw to adjacent neural structures. Reported warning thresholds indicating a low likelihood of medial pedicle wall breach typically range from 6 to 11 mA.[34] An EMG response elicited at currents below these thresholds raises concern for screw malposition and warrants further evaluation.[35]

However, the spinal level should be taken into account when determining appropriate warning thresholds. Threshold values vary by region and are generally higher in the cervical spine. Moreover, in the presence of osteoporosis, the stimulation threshold required to elicit an EMG response may be reduced because of decreased bone mineral density.

Several additional factors may limit the reliability of triggered EMG. Chronically compressed or injured nerve roots may exhibit elevated stimulation thresholds, potentially resulting in false-negative findings.[14] In addition, current shunting may occur when stimulation is delivered in the presence of conductive fluids, such as saline irrigation, within the surgical field, thereby further increasing the risk of false-negative results.[14]

Anesthetic Consideration During Intraoperative Neurophysiological Monitoring

Any pharmacological agent or physiological parameter that influences axonal conduction, synaptic transmission, or motor neuron excitability may alter evoked potential waveforms during IONM. In general, neural pathways with longer conduction distances and a greater number of synapses are more sensitive to anesthetic effects.[36] Accordingly, SSEPs, MEPs, EMG activity, and reflex-based responses such as the BCR are all affected-albeit to differing degrees-by anesthetic agents in a dose- and mechanism-dependent manner.

Appropriate selection of anesthetic agents and close coordination between them are therefore essential to obtain stable and interpretable IONM recordings. Most anesthetic agents depress synaptic transmission, resulting in reduced waveform amplitudes and prolonged latencies.[37] Although both inhalational and intravenous anesthetics exert these effects, inhalational agents have a more pronounced suppressive impact and are more likely to degrade or abolish IONM signals, particularly at higher concentrations.[38]

Among the various modalities, MEPs are generally more sensitive to anesthetic suppression than SSEPs, reflecting their dependence on intact corticospinal excitability and spinal motor neuron recruitment.[36] In addition, both MEPs and EMG responses are markedly attenuated by neuromuscular blocking agents.[14,36] For this reason, neuromuscular blockade is typically limited to facilitating tracheal intubation and is avoided thereafter in procedures requiring motor pathway or EMG monitoring.

Special anesthetic considerations are required for BCR monitoring. Because the BCR is an oligosynaptic reflex, it is particularly sensitive to anesthetic agents. Neuromuscular blocking agents and inhalational anesthetics can significantly suppress or abolish the reflex and should therefore be avoided.[16]

Consequently, total intravenous anesthesia-most commonly using propofol in combination with a short-acting opioid such as remifentanil-without maintenance neuromuscular blockade is widely regarded as the anesthetic technique of choice for IONM.[36,39] Avoiding large bolus doses and maintaining stable drug infusion rates further enhance signal reliability and reduce abrupt changes in evoked potential recordings.

Interpretation of Intraoperative Neurophysiological Monitoring Signal Changes

IONM is typically performed by an IONM technologist under the supervision of an IONM professional, such as a qualified physician, a neurologist, or a clinical neurophysiologist. The IONM technologist carries out electrode placement, signal acquisition, and artifact management. The technologist plays a critical role in maintaining signal integrity, ensuring accurate documentation of baseline recordings and intraoperative events, and adhering to established monitoring protocols. Professional guidelines emphasize that high-quality data acquisition and timely reporting are essential components of safe IONM practice.

However, interpretation of neurophysiological data, assessment of alarm significance, diagnostic decision-making, and intraoperative clinical judgment remain the responsibility of the supervising physician or clinical neurophysiologist.[2,31]

When a significant change in waveforms is detected by the IONM technologist, non-surgical causes should be excluded before issuing a warning. Technical factors should be verified, including correct placement of stimulating and recording electrodes and proper functioning of the monitoring equipment. Interpretation of intraoperative changes also requires careful consideration of confounding systemic factors, including hypotension, hypothermia, anemia, depth of anesthesia, and bolus administration of anesthetic agents.[38,39] Monitoring SSEPs and MEPs from rostral control recording electrodes is useful for distinguishing global physiological effects from focal spinal cord compromise. Additionally, focal MEP and SSEP changes resulting from surgical manipulation must be differentiated from peripheral nerve dysfunction caused by limb malpositioning, compression, or ischemia. If no correctable cause is identified, attention should be directed toward recent surgical maneuvers-particularly those temporally associated with an intraoperative potential change-with consideration given to reversing or modifying these actions and assessing signal recovery.

Intraoperative Neurophysiological Monitoring Practice in Spinal Surgeries

In current practice, IONM is employed during a wide range of spinal operations, including surgery for degenerative disease, spinal deformity, intramedullary tumors and IDEMTs, and tethered cord syndrome.

The selection of monitoring modalities is influenced by several factors, including the surgical approach, anatomical level, underlying pathology, and surgeon preference. During procedures involving the cervical and thoracic spine, preservation of the integrity of motor and sensory pathways within the spinal cord is critical. In addition to long-tract monitoring, nerve root monitoring remains important in selected cervical and lumbosacral surgeries, particularly those performed below the conus medullaris, where the thecal sac and cauda equina nerve roots are encountered. The most commonly used monitoring modalities in spine surgery include MEPs, SSEPs, and EMG; their techniques, advantages, disadvantages, and typical clinical applications are summarized in Table 1.

Although the clinical value of IONM is increasingly recognized, no universal consensus exists regarding its routine use across all spinal procedures.[1] Numerous studies have demonstrated that multimodal monitoring provides superior sensitivity and predictive value compared with single-modality techniques, particularly in high-risk procedures.[1]

IONM is generally accepted as an effective adjunct for predicting and reducing neurological injury in complex, high-risk spine and spinal cord surgeries, whereas its role in routine, low-risk cervical and lumbar procedures remains controversial because of limited and inconsistent supporting evidence.[40]

Degenerative spine disease

Degenerative disease of the cervical and lumbar spine encompasses a spectrum of conditions, including intervertebral disc degeneration, spondylolisthesis, and spinal canal or foraminal stenosis. Surgical management is primarily directed toward neural decompression and/or stabilization with instrumentation and fusion.

For routine, low-risk degenerative cervical and lumbar procedures-particularly single-level lumbar decompressions or fusions in patients without preoperative neurological deficits-the benefit of routine IONM remains controversial.[41] Current evidence does not consistently support the routine use of IONM in low-risk degenerative spine surgery.

In contrast, in patients with degenerative cervical myelopathy (DCM), in whom chronic compression of the cervical spinal cord is present, IONM may play an important role in reducing the risk of perioperative neurological injury.[42] Surgical treatment of DCM, using anterior, posterior, or combined approaches, aims to decompress the spinal cord, restore cervical alignment, and achieve spinal stability. However, these procedures carry an inherent risk of perioperative spinal cord injury. Neurological compromise during DCM surgery may occur at multiple stages, including induction of anesthesia, patient positioning (particularly prone positioning or excessive cervical extension), decompression maneuvers, instrumentation, deformity correction, or intraoperative hypotension with impaired spinal cord perfusion. Multimodal IONM has therefore emerged as a valuable adjunct in DCM surgery, providing real-time functional assessment of the spinal cord and nerve roots. The combined use of SSEPs, MEPs, and EMG improves diagnostic sensitivity and specificity compared with single-modality monitoring, allowing earlier detection of evolving spinal cord dysfunction and enabling timely corrective interventions, such as adjustment of surgical maneuvers, optimization of blood pressure, revision of instrumentation, or modification of patient positioning.[42]

Spinal deformity surgery

The utility of IONM in spinal deformity surgery is well established and widely accepted.[43] Surgical correction of spinal deformities-particularly in cases involving scoliosis, kyphosis, or complex multiplanar deformities-carries a substantial risk of neurological injury. Such injury may result from direct mechanical trauma to the spinal cord, ischemia secondary to compromised spinal cord perfusion, excessive distraction, compression during corrective maneuvers, or malpositioned instrumentation.[43]

Accordingly, continuous intraoperative assessment of both motor and sensory pathway integrity is critical throughout all phases of deformity correction, including positioning, exposure, deformity manipulation, osteotomy, and instrumentation.

The combined multimodal application of SSEPs and MEPs is now considered the standard of care in most centers performing complex spinal deformity surgery, particularly in pediatric and adult patients undergoing high-risk corrective procedures.[44,45]

Spinal tumor surgery

Although spinal cord tumors are relatively uncommon, their close proximity to critical neural structures-including long ascending and descending tracts, nerve roots, and segmental vascular supply-places patients at substantial risk for perioperative neurological morbidity.

Depending on their anatomical location, spinal tumors are broadly classified into two groups: extradural and intradural. Extradural spinal tumors, which are most commonly of metastatic origin,

Table 1. MEP, SSEP, and EMG in spine surgery: a comparative summary

	SSEP	MEP	EMG (free-running)	EMG (triggered)
Stimulation	Electrical stimulation of peripheral nerves (e.g., median, ulnar, posterior tibial)	Transcranial electrical stimulation over the motor cortex	None	Direct electrical stimulation with a handheld probe
Recording	Scalp (cortical responses) ± subcortical/spinal recordings	Extremity muscles	Myotome-specific muscles	Myotome-specific muscles
Modality type	Sensory (dorsal column pathways)	Motor (corticospinal tract)	Motor (nerve root irritation)	Motor (nerve root integrity testing)
Pathway monitored	Dorsal column-medial lemniscus pathways	Corticospinal tracts	Motor nerve roots	Motor nerve roots
Monitoring style	Near-continuous (requires signal averaging → delayed detection)	Intermittent (stimulus-evoked)	Continuous (real-time activity)	Intermittent (stimulus-dependent)
Advantages	Continuous monitoring; relatively resistant to anesthetic effects	Direct motor pathway assessment; large signal amplitude (no averaging required)	Real-time detection of nerve root irritation	Localizes and tests specific neural structures (e.g., pedicle screws)
Disadvantages	Small amplitude → requires averaging, delayed detection; does not assess motor pathways	Highly sensitive to anesthesia (especially inhalational agents); not continuous	Monitors only motor nerve roots; limited anatomical localization; may miss silent injury	Not continuous; operator-dependent; threshold variability (false-positive or false-negative results)
Typical clinical use	Monitor functional integrity of dorsal column sensory pathways	Monitor functional integrity of motor tracts (e.g., deformity surgery)	Detect nerve root irritation during instrumentation	Confirm safe pedicle screw placement or root proximity; map neural elements at risk

EMG: Electromyography, MEP: Motor evoked potential, SSEP: Somatosensory evoked potential.

produce neurological deficits secondary to spinal cord or nerve root compression. Intradural tumors arise within the dura and are further subdivided, based on their relationship to the spinal cord parenchyma, into intramedullary and extramedullary categories.

Approximately two-thirds of intradural spinal cord tumors are IDEMTs, which typically include meningiomas and nerve sheath tumors. IDEMTs are usually benign and well circumscribed, allowing total resection in most cases.[46] However, IDEMT surgery can be technically demanding because of limited operative corridors, spinal cord displacement, and close adherence to nerve roots or the pial surface. IONM assists in preserving neurological function while enabling complete tumor removal.[47] SSEPs, MEPs, and D-wave recordings are the IONM modalities most commonly used during IDEMT surgery to reduce the risk of spinal cord injury and improve surgical outcomes.[48]

IMSCTs are rare, accounting for approximately 20-35% of all intradural spinal cord tumors, and most commonly include ependymomas, astrocytomas, and hemangioblastomas.[49] Surgical resection is the standard of care for these lesions, although the extent of resection is strongly influenced by tumor histology, growth pattern, and the presence or absence of a well-defined tumor-cord interface.[49] Because IMSCTs arise within the spinal cord parenchyma, surgical manipulation inherently places the CST, dorsal columns, and segmental gray matter at high-risk of injury from traction, compression, or vascular compromise. In this setting, IONM is of particular importance and has become an integral component of modern IMSCT surgery. Clinical studies have demonstrated that IONM provides critical real-time functional feedback that can guide the extent of resection and facilitate maximal safe tumor removal.[50] Commonly employed modalities include SSEPs, MEPs, D-wave recordings, and free-running and triggered EMG.[27,48] In addition, functional mapping techniques-such as dorsal column mapping and CST mapping-can assist in identifying safe entry zones and minimizing injury to eloquent spinal cord regions.[51]

Conus medullaris and cauda equina surgeries

Surgical procedures involving the conus medullaris and cauda equina-including decompressive surgery, intradural and extradural tumor resection, and tethered cord release-are associated with a substantial risk of neurological injury. Owing to the dense concentration of motor, sensory, and autonomic pathways within this region, even limited intraoperative insult may result in significant postoperative deficits affecting lower extremity motor function, sensation, and bladder, bowel, or sexual function.

During these procedures, the conus medullaris or the individual lumbosacral nerve roots may be compromised by traction, compression, thermal injury (from coagulation), ischemia, or inadvertent transection. The risk is further heightened by distorted anatomy caused by tumors, adhesions, lipomas, prior surgery, or congenital malformations, which may obscure visual identification of neural structures. Consequently, reliance on anatomical landmarks alone may be insufficient to ensure neurological preservation.

Accordingly, a multimodal IONM strategy integrating monitoring and mapping techniques is typically employed in conus medullaris and cauda equina surgery. Commonly used modalities include MEPs, SSEPs, and free-running and triggered EMG.[52] In addition, BCR monitoring provides real-time assessment of sacral reflex arcs and autonomic pathways, particularly those arising from sacral segments S2-S4, which are critical for sphincter function.[52]

Root mapping plays a particularly important role in these surgeries, especially when normal anatomy is obscured. By applying focal electrical stimulation to suspected neural tissue and observing corresponding EMG responses, root mapping enables differentiation between functional nerve roots and non-neural structures such as fibrous tissue, tumor capsule, or lipomatous elements.[52] This technique is especially valuable in tethered cord release and intradural tumor surgery, where preservation of functional nerve roots is essential to prevent irreversible motor or sphincter deficits.[52,53]

CONCLUSION

IONM has become an integral component of modern spine and spinal cord surgery, providing real-time functional assessment of neural structures at risk during operative intervention. By enabling early detection of evolving neurological compromise, IONM facilitates timely corrective measures that may prevent or mitigate permanent postoperative deficits. The effectiveness of neuromonitoring is closely linked to the appropriate selection, interpretation, and integration of multiple complementary modalities rather than to reliance on a single technique.

MEPs, SSEPs, EMG, reflex monitoring, and mapping techniques each interrogate distinct aspects of neural function and exhibit differing sensitivities to mechanical, ischemic, anesthetic, and physiological perturbations. Multimodal IONM therefore offers a more comprehensive evaluation of spinal cord and nerve root integrity, particularly in high-risk procedures such as deformity correction, IMSCT resection, and surgery involving the conus medullaris and cauda equina.

Despite its widespread adoption, the routine use of IONM in low-risk degenerative spinal procedures remains controversial, reflecting variability in the evidence base, cost considerations, and practice patterns. Importantly, IONM should be regarded as an adjunct to-not a substitute for-meticulous surgical technique, sound anatomical knowledge, and close interdisciplinary communication among the surgical, anesthesia, and neurophysiology teams.

Future advances in quantitative signal analysis, standardized alarm criteria, and integration of emerging technologies may further refine the clinical utility of IONM. Continued prospective studies are needed to better define procedure-specific indications and associated outcome benefits. When appropriately applied and interpreted, IONM remains a powerful tool for enhancing surgical safety and optimizing neurological outcomes in spine surgery.

MAIN POINTS

- Intraoperative neurophysiological monitoring (IONM) has become a cornerstone of contemporary spine surgery by enabling real-time functional assessment of neural structures and facilitating early identification of impending neurological injury.
- Multimodal IONM, rather than reliance on a single modality, provides the most comprehensive assessment and confers the greatest benefit in high-risk procedures.
- The routine application of IONM in low-risk degenerative spine surgery remains a subject of ongoing debate.

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