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Intraoperative Electrophysiological Monitoring in Spine Surgery

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Study Design. Review of the literature with analysis of pooled data.

Objective. To assess common intraoperative neuromonitoring (IOM) changes that occur during the course of spinal surgery, potential causes of change, and determine appropriate responses. Further, there will be discussion of appropriate application of IOM, and medical legal aspects. The structured literature review will answer the following questions: What are the various IOM methods currently available for spinal surgery? What are the sensitivities and specificities of each modality for neural element injury? How are the changes in each modality best interpreted? What is the appropriate response to indicated changes? Recommendations will be made as to the interpretation and appropriate response to IOM changes.

Summary of Background Data. Total number of abstracts identified and reviewed was 187. Full review was performed on 18 articles.

Methods. The MEDLINE database was queried using the search terms IOM, spinal surgery, SSEP, wake-up test, MEP, spontaneous and triggered electromyography alone and in various combinations. Abstracts were identified and reviewed. Individual case reports were excluded. Detailed information and data from appropriate articles were assessed and compiled.

Results. Ability to achieve IOM baseline data varied from 70% to 98% for somatosensory-evoked potentials (SSEP) and 66% to 100% for motor-evoked potentials (MEP) in absence of neural axis abnormality. Multimodality intraoperative neuromonitoring (MIOM) provided false negatives in 0% to 0.79% of cases, whereas isolated SSEP monitoring alone provided false negative in 0.063% to 2.7% of cases. MIOM provided false positive warning in 0.6% to 1.38% of cases.

Conclusion. As spine surgery, and patient comorbidity, becomes increasingly complex, IOM permits more aggressive deformity correction and tumor resection. Combination of SSEP and MEP monitoring provides assessment of entire spinal cord functionality in real time. Spontaneous and triggered electromyography add assessment of nerve roots. The wake-up test can continue to serve as a supplement when needed. MIOM may prove useful in preservation of neurologic function where an alteration of approach is possible. IOM is a valuable tool for optimization of outcome in complex spinal surgery.

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Spinal surgery entails known risks to the neural elements. In order to avert complications and optimize outcome, intraoperative neuromonitoring (IOM) has been developed to provide real-time assessment of neurologic condition. Interpretation of neuromonitoring output, as well as determination of appropriate response, can present a significant challenge to even the most accomplished spine surgeon.

For IOM to be beneficial, it must provide warning early enough to permit injury to be reversed or minimized. Furthermore, false positives should be rare, and false negatives that lead to false confidence should be virtually nonexistent. Finally, monitoring must only minimally alter the surgical approach, be easily interpreted, readily available, and be cost effective.

IOM approaches include wake-up test, somatosensory-evoked potentials (SSEP), transcranial motor-evoked potentials (tcMEP), spinal cord MEPs (neurogenic MEP [nMEP]), spontaneous electromyography (sEMG), and triggered electromyography (tEMG). Primary attention has been directed at preventing motor deficit because of its importance in lifestyle, employment, and its medicolegal ramifications. This article will review prominent IOM methods, discuss interpretation, and offer possible responses.

Spinal Surgery Risk Assessment

Neurologic complications of spinal surgery are most strongly associated with prolonged complex surgery, large blood loss, combined anterior/posterior procedures, multistage surgery, congenital kyphosis or scoliosis, large or rigid spinal curves, and intramedullary spinal cord tumors (IMSCT). Further risk factors include tethered cord, Chiari malformation, syringomyelia, and split cord malformations.

Vascular injury or insufficiency during the course of surgery may present in a delayed manner. Hypotension (*i.e.*, mean arterial pressure [MAP] below 60 mm Hg) and mechanical damage can result in loss of autoregulation, thus making spinal cord perfusion dependent on blood pressure and increasing the risk of focal ischemia.

The incidence of neurologic injury has been reported for various procedures. Using scoliosis as an example, MacEwen *et al* noted a 0.72% incidence of spinal motor deficit in 86 patients subsequent to placement of Harrington rods.[1] The British scoliosis society reported a

1.3% risk of neurologic injury in 1116 patients in 1985. While voluntary, and thus subject to underreporting, the scoliosis research society surveyed 9426 procedures on 10,203 patients in 1987 and noted a 0.48% incidence of spinal cord injury and 0.49% incidence of *cauda equina* or nerve root injury.

Materials and Methods

The MEDLINE database was queried using the search terms IOM, spinal surgery, somatosensory-evoked potentials (SSEP), wake-up test, MEPs, sEMG and tEMG. Abstracts were identified and reviewed. Individual case reports were excluded. Detailed information and data from appropriate articles were assessed and compiled.

Results

Total number of abstracts identified and reviewed was 187. Full review was performed on 18 articles. Ability to achieve IOM baseline data varied from 70% to 98% for SSEPs and 66% to 100% for MEPs in absence of neural axis abnormality. Multimodality intraoperative neuromonitoring (MIOM) provided false negatives in 0% to 0.79% of cases, whereas isolated SSEP monitoring alone provided false negative in 0.063% to 2.7% of cases. MIOM provided false positive warning in 0.6% to 1.38% of cases.

Discussion

Common IOM Methods

Stagnera Wake-Up Test. Among the first tests to provide intraoperative neural element monitoring data were the Stagnara wake-up, so named for one of the original implementers.[2,3] The intraoperative wake-up test involves the gradual lightening of anesthesia until the patient can voluntarily move the lower extremities.[4] An alternative test developed at the same time as wake-up is the clonus test. This test has not proven reliable[5] and will not be discussed.

Applicable Anatomy and Methodology. The wake-up test assesses primary motor cortex, anterior motor pathways of the spinal cord, nerve roots, and peripheral nerves, however, gives only a gross approximation of the function of all these elements. Patient participation can dramatically impact this assessment. The wake-up test does not directly measure any components of the sensory system.[5]

Planned wake-up requires preoperative discussion and preparation for optimal results. The anesthesiologist must be prepared and the patient willing, and cognitively able, to participate. Some advocate practice runs with the patient before surgery.[5] Intraoperatively, the anesthesia team should be forewarned to permit anesthetic dose planning. Degree of wakefulness is assessed, and then symmetry of movement is gauged for both upper and lower extremities by an unscrubbed examiner.

Avoiding Performance Obstacles. Short acting anesthetic agents and reasonably reversible ones permit wakeful state. Warning the anesthetist 15 to 30 minutes before planned wake-up is commonly adequate and assessment will consume 15 to 20 minutes, permitting easy application once per case.[5]

Utility and Interpretation. Properly administered, the wake-up test should be 100% accurate in detecting gross motor changes.[5] While the limitations of the test prevent it from assessing fine motor changes, it will alert the surgeon to the most clinically significant injuries. Interpretation is fairly straightforward. A patient unable to move both upper and lower extremities is usually not sufficiently awake to permit assessment. If the patient is responsive and able to move facial muscles but not the extremities, global ischemic injury, or cervical spine injury cannot be discounted.[6] Absence of global injury, time, and well-managed anesthesia should permit for a successful test.

Conclusion. The wake-up test was a valuable addition to the intraoperative armamentarium of the spinal surgeon at the time of introduction. Although limited, and potentially missing devastating injuries, the information provided by the wake-up test permits intraoperative decision-making. Further, drawbacks of the wake-up test include the following: one time measure of function as opposed to continuous, risk of air embolism, self extubation, recall for event,[7] self-induced contamination, positional changes resulting in neural compression, and lack of nerve root injury information. With each performance of the wake-up test its related risks multiply and interperformance reliability declines; hence, multiple wake-ups are rarely performed. A change in examination, even if suspected to be because of the anesthetic effect, forces the surgeon to consider altering surgical plan.

In 1995, Nuwer *et al*[8] showed that an independent factor in reducing postoperative neurodeficits when using SSEP was the performance of a wake-up test as adjunct. Others have suggested that the test's value is indirect, as anesthesia is reduced, blood pressure is increased perhaps improving spinal cord perfusion.[7]

No longer generally considered a viable stand-alone IOM technique, the wake-up test gains new life as a supplement to other testing methods. If another IOM test such as SSEP or MEP demonstrates abnormality, a normal wake-up test can reassure the surgeon that no permanent neurologic injury has occurred.[9–11]

Somatosensory-Evoked Potentials. Somatosensory-evoked potentials (SSEPs) were first used clinically in the 1980s[12,13] and by 1986, SSEPs were deemed both reliable and reproducible.[14] In 1991, 78% of surgeons surveyed were using SSEPs for deformity surgery, albeit with a reported false negative of as high as 28%.[15]

Applicable Anatomy and Methodology. Anatomy assessed, in addition to the cerebral cortex and mixed peripheral nerve, is the posterior columns of the spinal cord. The posterior columns subserve proprioception rather than pain and temperature. Proprioceptive loss, while not as debilitating as motor deficit, can have significant impact on daily living. SSEP IOM is sensitive to focal posterior column and global spinal cord injury suggesting it is a good surrogate for other neural pathways. However, there are situations when a motor injury might not be demonstrated on SSEP monitoring. For example, anterior vascular territory injury without concomitant posterior vascular changes might not be addressed by SSEP monitoring.

For SSEP monitoring, electrodes are placed on the distal limbs and scalp. A small electrical current is given distally and recordings are made along the pathway and at the scalp. The posterior tibial nerve, at the medial malleolus, is a frequent stimulation site due to accessibility and reliability of data.[5] Alternatives include peroneal and sural nerves. Upper extremity monitoring of median nerves permits comparison to the lower extremities and alarms the surgeon to brachial plexus injury during preoperative positioning and anesthesia initiated changes intraoperatively.[16]

Scalp electrodes provide useful cortical and subcortical data.[7] Cortical recordings are easier to record with more noise immunity, whereas subcortical recordings are less attenuated by anesthetic agents.[17] Subcortical recordings require neuromuscular blocking agents to reduce muscle-related noise. In ideal situations, SSEPs can require 5 minutes[18] to detect change. Change is defined by a comparison to initial baseline values best acquired immediately after incision,[19] which permits stabilization of anesthesia and core temperature.[5]

SSEP latency changes of 7% to 14% and amplitude changes of 45% to 50% can occur without postoperative neurologic sequelae.[9,20,21] Amplitude changes of greater than 50% and latency increases of 10% are considered abnormal[8,15,22] with amplitude changes being slightly more sensitive to onset of injury.[23] SSEP changes are assumed significant after alternative causes for monitoring changes have been addressed (*i.e.*, technical faults, hypothermia, and hypotension).[24–26]

Avoiding Performance Obstacles. Indirect sources of SSEP change include hypotension, hypothermia, IV sedation, and halogenated inhalational anesthetics. Anesthetic effects appear to be dose related and nitrous oxide can act as a supplemental agent to permit reduction of the primary agent.[5] However, at greater than 50% concentration, nitrous oxide can actually enhance negative effect of primary anesthetic agents on SSEPs.[27] Muscle relaxation can permit quieter and more reliable recordings, and MAP should be maintained above 60 mm Hg to prevent significant cortical changes on SSEPs.[5]

Ability to initiate IOM can be affected by neurologic disorders such as neuromuscular scoliosis or cerebral palsy.[28,29] Further, in contrast to the findings in idiopathic scoliosis, recovery of the trace, or return to baseline values, in neuropathic scoliosis was associated with a 50% to 60% risk of neurologic impairment when using the 50% amplitude change rule.[30]

Utility and Interpretation. The risk that SSEPs may fail to provide information on functional integrity of the motor pathways is lower for procedures where the cord integrity is expected to be affected in its entirety.[28] For example, spine curvature correction in scoliosis surgery is expected to stretch all neural and vascular components such that the dorsal column can serve as a reasonable proxy for motor pathways.[28] SSEP IOM is more sensitive to motor changes due to mechanical injury than vascular injury in animal studies when the injury affects the entire cord.[31] In a porcine model, temporal loss of signal related to mechanical *versus* ischemic injury is 2 and 20 minutes, respectively.[31] Postoperative paraparesis with normal SSEPs is commonly the result of anterior spinal artery syndrome. Anterior spinal artery syndrome selectively affects the anterolateral columns of the spinal cord with preservation of posterior columns.[28]

Many cases in which SSEPs provide false negative results are purely motor deficits or nerve root related, some SSEPs do not directly monitor.[32–40] Mixed nerve SSEPs may not be adequate to detect injuries involving individual nerve[41–43] as might occur in pedicle screw placement. Gundanna *et al*[44] showed that in 186 patients (888 screws) screw misplacement (5 patients, 8 screws) causing radiculopathy and requiring reposition might be associated with no change in SSEPs.

Conclusion. SSEPs continue to be the most frequently used intraoperative monitoring method to assess the integrity of the dorsal column,[28] but cannot be relied on to monitor motor function directly. Reports of postoperative paraparesis in absence of intraoperative SSEP signal change underscores this important limitation.[7,34,45–50] SSEP IOM, unlike the isolated snap shot of the wake-up test, introduced continuous monitoring. SSEP dependability falls off when applied to patients with preexisting neurologic conditions (Table 1). The flaws of SSEP monitoring continue to be its need for summation, and thereby potential to delay presentation of key data, and its lack of motor pathway information in all but the most global of injuries. Individual nerve root injury is not effectively monitored by SSEPs. Missed nerve root or isolated motor pathway injuries are not failures of the modality but rather injuries outside SSEP monitoring capability, and highlight the need for alternative or adjunct monitoring approaches.

Motor-Evoked Potentials. Motor pathway monitoring with transcranial MEPs (tcMEPs) with spinal cord signal (D-wave),[59–62] and muscle compound motor action po-

Table 1. IOM Modality Capability to Monitor Neural Axis: (NAA) Neural Axis Abnormality

Modality	N	TP	FP	TN	FN	Spec	Sens	Path	Author	Notes
SSEP	60,366	72%	1.6%		28%			IS	Dawson *et al*[15]	Survey
SSEP	220	43%						IS, neoplasm	Dinner *et al*[14]	
SSEP			0.983%		0.063%				Nuwer *et al*[8]	
SSEP	186				2.7%				Gundanna *et al*[44]	Nerve root injury
SSEP + tcMEP	672	1.8%	0.6%	97%	0.6%				Iwasaki *et al*[51]	
SSEP + nMEP	134		4.5%		0			AIS	Noonan *et al*[52]	
SSEP + nMEP	500	0.004%	0.014%		0	98.6%	100%	IS	Padberg *et al*[53]	
tcMEP	100				0	91%	100%	IMSCT	Kothbauer *et al*[54]	
SSEP + tcMEP + EMG	217		1.38%	92.6%	0.46%	98.5%	92.3%	Spinal deformity	Eggspuehler *et al*[55]	
SSEP + tcMEP + EMG	1017	6.49%	0.79%	91.9%	0.79%	99%	89%		Sutter *et al*[56]	
tEMG	1078					94%	86%		Raynor *et al*[57]	<8 mA
tEMG	1078					99%	36%		Raynor *et al*[57]	<4 mA
tEMG	1078					100%	8%		Raynor *et al*[57]	<2 mA
SSEP + MEP	177				0			NAA, AIS	El-Hawary *et al*[53]	

SSEP indicates somatosensory-evoked potentials; tcMEP, transcranial motor-evoked potentials; nMEP, spinal cord MEP's; EMG, electromyography; tEMG, triggered electromyography; Sens, sensitivities; Spec, specificities; IMSCT, intramedullary spinal cord tumors; TP, true positive; FP, false positive; TN, true negative; FN, false negative; IS, idiopathic scoliosis; AIS, adult idiopathic scoliosis.

tential (CMAP)[63–65] was introduced in 1986. Merton and Morton[66] initial single stimulus work was instrumental to the development of tcMEPs but wide spread use was significantly hampered due to the effects of volatile anesthetics.[67] Introduction of high frequency multipulse stimulation technique permitted MEP recording under some forms of anesthesia.[68,69] Advances in anesthesia, specifically total intravenous anesthesia (TIVA), have made MEPs easier to obtain.[70]

Applicable Anatomy and Methodology. MEPs monitor corticospinal track activity *via* stimulation at the level of the motor cortex or spinal cord and are selective for motor pathways, albeit only monitor 4% to 5% of motor neuron pool.[67] MEP monitoring relies on intervening thalamic synapses to prevent antidromic firing of spinal sensory tracts.[7] The stimulation site for tcMEP is the cerebral cortex. MEP end point data are ascertained from the spinal cord (D-wave) or from the end muscle (CMAP) and while not mutually exclusive have strengths and weaknesses attributable to each (Table 2) .

Stimuli are presented as single high voltage or multiple small stimuli. Train stimulus is preferable because it permits reduced voltage application, and thus diminished muscle reactivity. There is no clear consensus on the optimal parameters of the short train stimuli.[28] Sources of stimulation include magnetic and electrical. For magnetic tcMEP, a coil over the cortex provides the stimulation.[82] Electrical stimulus of the motor cortex is provided by subdermal electrodes.[83] Types of electrodes include cup, needle, and corkscrew. Although occasionally associated with scalp edema and unreliable recordings, corkscrew electrodes are preferable given low impedance and secure positioning in the scalp.

Peripheral data are commonly electromyographic (EMG) *via* CMAP. The CMAP is best monitored at sites rich in corticospinal track innervation such as the distal limb muscles.[64] Common recording sites are abductor pollicus brevis, or adductor hallucis brevis with viable alternatives of long forearm flexors and extensors in the upper extremity[68] and tibialis anterior in the lower extremity.[28] Although there does not appear to be any monitoring advantage to increasing the number of monitored muscles,[28] increased muscle group testing might provide benefit in identifying positioning-related injury.

Table 2. Comparison of D-Wave *Versus* CMAP Utility When Used as Part of tcMEP Monitoring

IOM Function	CMAP	D-Wave
Reflection of entire motor system	X[71]	
Delineates laterality	X	
Lower false positive rate in scoliosis surgery	X	27% false +[72]
Can monitor lowest sacral roots including sphincter	X[73,74]	D-wave difficult to aquire below midthoracic levels[75]
Less sensitive to halogenated anesthetics		X[70]
Can be recorded with neuromuscular blockade		X
Causes little or no movement during application and can be performed continuously		X
Valuable for IMSCT resection	X	X
Absent in 20% of patients with IMSCT or postradiative myelopathy		X[76]
Provides earliest warning of vascular cord compromise	X[77–79]	
May be effective for spinal cord embolisation procedures	X[80]	
Requires epidural catheter placement		X
Data acquisition potentially inhibited by dural adhesions and scar		X
Sensitive to muscle ischemia	X[81]	
May be more predictive of motor outcome with resection of IMSCT		X

IMSCT indicates intramedullary spinal cord tumor; IOM, intraoperative neuromonitoring; CMAP, compound motor action potential; tcMEP, transcranial motor-evoked potentials.

An alternative to CMAP monitoring is recording at the spinal cord itself (D-wave). The D-wave is the initial wave associated with direct conduction of corticospinal neurons.[84] The advantages and disadvantages of CMAP *versus* D-wave recordings have been described (Table 2).[7,85] CMAPs are a reflection of the entire motor system[85] and may be more sensitive to ischemic changes.[81] Further, CMAPs have a large associated amplitude and reliable latency. However, amplitude morphology and latency can be unreliable with difficult to titrate anesthesia. Further, although mitigated by train stimuli, patients can have significant movement from stimulation for CMAPs requiring brief cessation of surgical activity. Because patient movement during CMAP recording can affect surgeon desire to perform testing, frequency of testing is reduced. The less frequently the test is performed, the less sensitive it becomes for early neurologic change. As opposed to myogenic recordings, D-wave recordings benefit from complete muscle relaxation with the advantage of elimination of patient movement. Recordings are assessed in 1 of 3 ways as follows: percentage reduction in amplitude, all or none, and threshold.

Avoiding Performance Obstacles. MEP reliability diminishes in isolated patient populations with antecedent neurologic deficit. Further, although MEP monitoring is considered to be a safe venture,[75] relative contraindications include epilepsy, cortical lesion, skull defect (*e.g.*, fontanelle or prior craniectomy), proconvulsantmedication, cardiac pacing, and implantable device.[86]

Anesthesia can have a significant impact on synaptic junctions necessitating careful attention to pharmacology during surgery. While inhalational anesthetics and muscle relaxants can be used for induction, use must be curtailed immediately thereafter. Inhalational anesthetics reduce the effectiveness of cranial stimulation and muscle relaxants inhibit data acquisition at the muscle end point. Initially, a balanced regiment of nitrous oxide, narcotic, and propofol was recommended,[5] but there has been a shift toward use of TIVA inclusive of propofol, ketamine, and more recently, dexmedetomidine, to obtain MEPs,[70] particularly in children below 18 years old.[87] Even when TIVA is applied appropriately, MEPs may not be successfully generated in all patients.[88] Another anesthetic effect not yet extensively studied is "anesthetic fade" or increased voltage demand to elicit MEP. Anesthetic fade significantly correlates with increasing case length and does not indicate impending neurologic deficit.[89]

Utility and Interpretation. In 1121 patients with idiopathic scoliosis, a 65% decrease in MEP amplitude always predicted postoperative motor deficit, whereas SSEPs only picked up a change 43% of the time.[18] Perhaps equal importance, SSEP warnings lag behind tcMEP warnings by an average of 5 minutes.[18,90,91] MEPs have been demonstrated to be more sensitive to detecting spinal cord ischemia[92,93] when not diminished by hypothermia and hypoperfusion.[94] With the exception of anterior spinal artery syndrome, motor signals tend to deteriorate progressively providing a time window for response and perhaps reversal.[28] Anterior spinal artery syndrome is thought to result in abrupt deterioration of motor signals because it is an acute, commonly irreversible, process. Although highly sensitive tcMEPs do not monitor 96% of motor neuronal activity and could fail to detect an injury affecting complex coordinated motor activity.[95]

MEP monitoring during resection of IMSCT correlates well with motor outcomes.[54] A 20% change in D-wave can be considered a warning[96] while a 50% decrement[54,97] should be regarded with urgency. Because of significant overlap of myotomal innervation, it is unlikely that muscle MEPs can provide enough information about nerve roots to demonstrate intraoperative root lesion.[28]

Conclusion. MEP monitoring provides a repeatable snap shot that permits immediate assessment of spinal cord function after high-risk maneuvers such as correction. This is contrary, and superior, to SSEPs which require 3 to 5 minute summation before warning of potentially irreversible changes.

Maneuvers to improve response rate continue to be developed. Tetanic facilitation of MEP muscle groups immediately before transcranial stimulation shows promise, as does spatial stimulation.[87,98] Spatial facilitation consists of facilitatory stimuli within the receptive field of the withdrawal reflex of the recorded muscle before a transcranial stimulus is delivered.[87]

An alternative, or adjunct, to tcMEPs showing some promise is the H-reflex. Loss of H-reflex, or significant amplitude reduction, correlates with neurologic motor outcome and is less impacted by anesthesia effects than MEPs.[28,67,99] H-reflex can be recorded in some patients in whom SSEPs and MEPs cannot.[95] Although false positives are known to occur, H-reflex monitoring provides information about the integrity of both afferent and efferent connections and alerts the surgeon to disruption of this pathway. It is assumed that when the motor pathways are injured, the subsequent hyperpolarization of the α-motoneurons will result in a significant decrease in the amplitude of the H-reflex.[28]

MEP monitoring is linked to few untoward effects[75] and has clear advantages but still requires that other monitoring methods such as SSEPs or EMG be used to provide optimal information.[67]

Neurogenic MEP. An additional modality developed to address the limitations of SSEP monitoring is nMEP.[85,100] Initially thought a viable supplement to SSEPs for motor pathway monitoring it has been discredited to some extent by collision studies that demonstrated descending and ascending sensory information appeared no different than nMEPs.[101] Subsequent to collision studies clinical reports surfaced to support the hypothesis that nMEPs monitor dorsal column integrity only.[49]

Applicable Anatomy and Methodology. nMEP waveforms are ascertained from an electrode placed over the spinal cord in either direct epidural[36,100,102] or percutaneous[37,85] manner. Electrodes are placed rostral to the surgical site. Recording sites are commonly the spinal cord itself (D-wave) or peripheral muscle (CMAP). The D-wave is the initial wave associated with direct conduction of corticospinal neurons.[84]

nMEP stimulation appears to cause whole spinal cord stimulation without selectivity. nMEPs are largely mediated by dorsal column antidromic activity rather than motor tracts.[49,101,103–105] While elevated stimulation levels in cats demonstrate motor recruitment to occur at the ventral roots, low intensity stimulation only shows electrical activity in the dorsal roots, suggesting exclusive sensory antidromic activity.[106] In 2001, Minahan *et al*[49] reported on 2 cases where SSEP and nMEP signals were unchanged throughout surgery, as well as on subsequent testing, but the patients were found to have postoperative motor deficits. This finding was replicated by Luk.[107]

Avoiding Performance Obstacles. Direct cord stimulation as in nMEPs simplifies anesthetic considerations unless CMAP recordings are to be made. As opposed to CMAP recordings, complete muscle relaxation should be applied for D-wave recordings so as to reduce muscle reactivity.

Conclusion. Increasing neurophysiologic and clinical evidences suggest that nMEPs, while cheaper and easier to perform than tcMEP, do not provide as accurate motor system monitoring. According to the senior authors experience, nMEPs are frequently less reliable than tcMEP in the setting of spinal deformity surgery.

General consensus at present regards nMEP data as antidromic sensory information.[71] Even in light of these findings a survey of 39 spine centers primarily in the United States, conducted in 2002, demonstrated that nMEP was the preferred technique for motor monitoring at 15 of the centers.[108] nMEP monitoring has not been entirely discredited as a stand-alone monitoring tool; rather, users are cautioned not to rely on NMEP as a sole indicator of motor function.[71]

Spontaneous EMG. Postoperative radiculopathy is a more common complication than postoperative myelopathy, particularly when employing segmental instrumentation.[41,42,109–112] Expansion of the clinical application of segmental spinal instrumentation has been the driving force behind the development of selective nerve root monitoring.[71]

Initial IOM for nerve root continuity for segmental instrumentation focused on dermatomal SSEPs to assess nerve root function *via* individual dermatomal field stimulation.[113–116] However, recordings are actually a product of mixed nerve stimulation, with multiple nerve root contribution, and further are highly susceptible to the suppressive effects of general anesthesia.[71,117] Because, dermatomal SSEPs require prolonged signal averaging to acquire reproducible data,[118] a nerve root injury might go unnoticed until irreversible injury has occurred. Real-time assessment of nerve root function would be more ideal.

History of EMG clinical applications, and its specificity for the motor system led to introduction of sEMG recordings in the 1990s.[10,119] While EMG supramaximal stimulation in the laboratory results in responses and amplitudes that correlate well with numbers of functioning axons present, intraoperative EMG uses submaximal stimulation and provides highly complicated polyphasic responses with variable onset latencies and response amplitudes.[118] Although stimulus threshold can provide some quantitative information regarding nerve function[119–121] responses tend to be all or none.

sEMG myotomes are preselected to coordinate with operative levels. Padberg and Thuet[71] discuss the methodology of sEMG. Briefly, continuous electrical activity to a myotome is recorded and observed. When a nerve root is excessively manipulated or impinged on a burst of activity is noted.[122–125] With more severe nerve manipulation and stretch of a nerve root train activity is noted. One would generally note silence if the nerve root is cleanly severed.[126] Distal recording sites are typically paired intramuscular needle or wire electrodes inserted after induction but before surgery.[118] Neurotonic discharges will frequently occur in the setting of a normal nerve when cold irrigation is applied to the surgical field.[118] Most outcomes studies have reported an increased sensitivity to nerve root issues when sEMG has been employed.[71]

Triggered EMG. Introduced in an animal model in 1992,[127] the clinical application of tEMG grew rapidly. It was postulated that a high stimulus intensity tEMG would demonstrate intact cortex of a pedicle hole through which a screw was to be passed. In application, bone has high impedance requiring high threshold to stimulate the adjacent nerve. When tEMG requires high stimulation, it demonstrates integrity of the pedicle cortex and lack of perforation.[118] Direct stimulation of a misplaced pedicle hole, with breech, can activate the adjacent nerve root and evoke a CMAP in the appropriate myotomes at lower stimulus intensities than would be expected with and imperforate pedicle cortex.[124,128–133] Clinical correlation in human population was quickly established.[128,132,133]

tEMG will provide data on a pathway from pedicle screw or tract to distal site and can be used in the thoracic spine operations if rectus abdominis or intercostals musculature are monitored as the distal recording site.[134,135] Stimulating current is gradually increased to determine the threshold at which stimulating signal generates CMAP in corresponding muscle group.[127,136]

Table 3. IOM Modality Capacity to Achieve Baseline Data Such That IOM Can be Used

Modality	Baseline Achieved (%)	Pathology	Patient Age	N	Notes	Study
MEP	94.8		Adult	341	BUE	Chen *et al*[169]
MEP	39–66		Adult	341	BLE, 39% if prior neurological deficit	Chen *et al*[169]
SSEP	98		Adult	341	BUE	Chen *et al*[169]
SSEP	93		Adult	341	BLE	Chen *et al*[169]
MEP	82.2	Motor/sensory compromise	Adult			Costa *et al*[93]
SSEP	62.5	Motor/sensory compromise	Adult			Costa *et al*[93]
MEP	39–63	Cerebral palsy	Pediatric			Deletis and Sala[28]
SSEP	82	Cerebral palsy	Pediatric			Deletis and Sala[28]
MEP	78		$<$18 yr	134	Temporal facilitation	Frei *et al*[87]
MEP	96		$<$18 yr	134	Temporal + spatial facilitation	Frei *et al*[87]
tcMEP	96		Adult	716		Tamaki *et al*[51]
SSEP	97.8	Idiopathic scoliosis	Adult	1168		Forbes *et al*[155]
SSEP	84		Adult	320		Lubicky *et al*[21]
SSEP/tcMEP	69			100		Weinzierl *et al*[143]
SSEP	70			30	Prospective	Luk *et al*[109]
SSEP	72	NM scoliosis	Adult	101		Ashkenaze *et al*[29]
SSEP	73				Single site	Owen *et al*[170]
SSEP	96				Multiple site	Owen *et al*[170]
SSEP	85	Neural axis abnormality		41		El-Hawary *et al*[53]
SSEP	98.5	AIS		136		El-Hawary *et al*[53]
MEP	82.6	Neural axis abnormality		41		El-Hawary *et al*[53]
MEP	100	AIS		136		El-Hawary *et al*[53]
SSEP	82	Mild CP		39		DiCindio *et al*[148]
MEP	63	Mild CP		39		DiCindio *et al*[148]
nMEP	100	AIS		466		Komanetsky *et al*[103]
SSEP	93.2	AIS		466		Komanetsky *et al*[103]
nMEP	50.8	Neural axis abnormality		38		Wilson *et al*[104]
tcMEP	94			34		Calancie *et al*[83]

SSEP indicates somatosensory-evoked potentials; tcMEP, transcranial motor-evoked potentials; nMEP, spinal cord MEP's; IOM, intraoperative neuromonitoring; NM, neuromuscular; CP, cerebral palsy; BUE, bilateral upper extremity; BLE, bilateral lower extremity; AIS, adult idiopathic scoliosis.

The stimulator for tEMG is typically a hand held bipolar or monopolar device used by the surgeon.[118] Threshold sensitivity and specificity for placement of 4857 screws showed increasing specificity with decreasing mA threshold, but was associated with a drastic concomitant fall off in sensitivity (Table 1).[136] Generally, stimulus thresholds of less than 4 to 6 mA are suggestive of cortical bony perforation by pedicle instrumentation when the adjacent nerve root is healthy.[128,132,133]

tEMGs will provide reliable information during partial NM blockade. Blockade of less than 80% will permit adequate screw testing with thresholds comparable to nonparalyzed patients.[137] Stimulus intensities required to evoke CMAP response from direct electrical stimulation of the nerve root are higher in the presence of preexisting axonometric radiculopathy[121,133] and chronically compressed nerves may have enhanced sensitivity to the effects of neuromuscular blockade.[121,57] If there is some question as to degree of stimulation required, the nerve root can be stimulated directly for comparison to implant stimulation.[121] An individual patient approach is advocated and includes reevaluation of any outlier in a specific patient regardless of threshold.[7]

Multimodality Intraoperative Monitoring. SSEPs are the most common modality employed, but are not always a sufficient proxy for all cord function.[28] Failing to recognize the limitations of SSEPs can have dire consequences.[46,48,49] It has been shown that no single modality sufficiently monitors all spinal cord pathways.[28,55,92,138–141] If the goal of IOM is to detect the onset of deficit for both sensory and motor pathways, then no single IOM approach meets the goal[5]; however, a combination of testing methods might.

MIOM uses all electrophysiological techniques that can provide intraoperative information about the neural structures at risk.[67] MIOM permits assessment of both ascending and descending pathways concurrently,[142] providing a certain degree of redundancy since many types of intraoperative injuries will compromise both motor and sensory pathways.[143] Redundancy is of great value when technical factors such as electrical interference or anesthetic limitations reduce effectiveness of 1 monitoring modality (Table 3).[7]

In scoliosis surgery, there is a higher risk of misdirection of instrumentation due to abnormal spine curvature and rotation, and higher risk of neural injury due to increased proximity of spinal cord to the concave wall of scoliotic spine.[7] Further, scoliosis surgery often requires significant correction that can place the cord at risk from mechanical and vascular injury.[7] In addition to scoliosis surgery, IMSCT resection can benefit from the data provided by IOM.

Because of the high rates of false positives,[144] SSEP monitoring alone during tumor resection may result in unjustifiable cessation of resection precluding the possibility of complete resection.[28] Even when SSEPs warn of true positives the delay required for data acquisition and averaging might result in resection to a point of no return where another modality might have provided data that prevented irreversible injury. From a monitoring standpoint, it is these procedures that appear to be most eventful.[145] During resection of IMSCTs risk of disparate injury to motor and sensory tracts is higher because of direct tract manipulation. In multiple cases[85] of MIOM for intramedullary tumor midline myelotomy resulted in loss of SSEP[45,11] while MEP was maintained and guided resection. SSEPs can assist with location selection for midline myelotomy while MEP will assist with delineation of the edge of the tumor perhaps permitting more aggressive safe tumor resection.

While tcMEP CMAP monitoring seems adequate to assess the functional integrity of motor pathways in most spinal surgeries,[146,147] this is not likely the case in IMSCT.[28] Transcranial MEP D-wave monitoring has proven an invaluable addition to IMSCT resection, and may prove useful for scoliosis surgery as well. In more than 100 cases, a 50% preservation of D-wave, even with complete loss of tcMEP CMAP, will only result in transient paraplegia.[54,97,11] Patients with transient paresis subsequent to less than 50% D-wave reduction recovered completely within hours to weeks.[97] If D-wave is lost during surgery paraplegia is usually permanent.[148] In patients whom are already paraplegic before surgery D-waves can not be recorded caudal to the lesion site.[149] If D-wave can not be ascertained for surgery, due to extreme desynchronization that can occur with IMSCT, a 50% drop in tcMEP CMAPs can be tolerated.[28] Patients who are impaired neurologically at the outset of surgery likely benefit less from IOM than those without deficit and further it is the preoperative neurologic status appears to be the major factor affecting outcome.[28]

Asazuma compared outcomes over a 37-year period of resection of IMSCTs and demonstrated improved outcomes when microscope and neuromonitoring are employed.[150] Combination of IOM and microdissection seems to permit greater resection, which is known to improve outcome for ependymomas. Sala *et al*[97] assessed a shorter time frame reducing variables to assess MIOM for IMSCT resection and showed that although there is no short-term outcome benefit, a long-term benefit in neurologic outcome can be demonstrated.

The use of D-wave in IMSCT surgery shows clear potential and its utility should also be assessed further for scoliosis surgery as a possible adjunct. While not mutually exclusive, strengths and weakness of D-waves should be weighed against those of CMAP recording (Table 2) and be considered for simultaneous use.

When MIOM methods have been employed, there has not been a reported case of false-negative monitoring.[28] A 2007 survey of 180 surgeons demonstrated the availability to be 95% for SSEP, sEMG 67%, stimulated EMG 61%, and MEP only 41%.[151] Although consensus continues to develop for use of IOM in appropriate settings individual neurologic and orthopedic surgeons continue to face limited availability of each modality.

IOM Interpretation:

SSEP

- Latency change of greater than 10% concerning.
- Latency change rarely if ever occurs as a primary finding.[7]
- Stability of latency in setting of SSEP amplitude loss should not be reassuring.[152,153]
- Upper extremity change can suggest brachial plexus injury if lower extremity findings are unchanged.
- Lower extremity SSEP change without concomitant upper SSEP change may be concerning for injury.
- Lower and upper extremity change might suggest global change such as hypotension.
  i. Even small changes in BP can affect evoked potential monitoring[148,154–157] inducing a normotensive state can normalize monitoring.[158,159]

A corrective measure approach is acronym TIP (time, irrigation, pressure).[28]

MEP with CMAP.

- Interstimulation[160] wave variability is expected.[161,162]

Table 4. Potential Approach to IOM Changes

Initial MIOM change		
	Localization	
		Does the monitoring change correlate to the level being manipulated (*i.e.*, normal IOM for upper extremity)?
	Timeline	
		Was a recent higher risk maneuver performed?
	Monitor leads	
		Have the leads become detached?
	Blood pressure	
		Have changes in MAP been corrected?
	Temperature	
		Is the patient hypothermic?
	Anesthetic level	
		Any recent changes (*i.e.*, propofol bolus)?
Follow-up action		
	Radiographic assessment	
		Structural alignment changes?
	Implant	
		Well positioned?
	Direct visualization	
		Hematoma?
		Bone fragments?
		Dural buckling?
		Other compressive forces (*i.e.*, gel foam, disc *etc.*)?
Secondary action		
	Correction	
		Eliminate, reduce corrective forces
	Positioning	
		Reposition the patient, flip supine and reassess IOM
	Implant	
		Remove?
	Stop point	
		Determine safe stop point vs. immediate cessation
Follow-up to wake-up test		
	Postoperative	
		ICU for observation
		Stat MRI
		Consider exploring prior site (*i.e.*, anterior exposure and implants)

IOM indicates intraoperative neuromonitoring; MIOM, multimodality intraoperative neuromonitoring; MAP, mean arterial pressure; MRI, magnetic resonance imaging; ICU, intensive care unit.

Table 5. IOM Techniques and Individual Capabilities and Limitations

Modality	Anatomy	Not Addressed	Anesthetic Concerns	Temporality	Risks
Wake-up test	Gross motor function	Nerve roots, sensation	Only short acting reversible agents should be employed	1 point, difficult to repeat	Self extubations, missed focal deficit, delayed warning
SSEP	Ascending pathways: dorsal column proprioception and vibration	Focal motor pathway injury, nerve roots	Muscle relaxants helpful, volatile anesthetics inhibit, balanced by <50%. NO dose-related barbiturate inhibition	3–5 min summation	Missed focal motor and nerve root injury. Delay to warning during summation
tcMEP	Anterior spinal grey of descending pathways: 4%–5% of CTS pool	Sensation, complex motor movement	TIVA best, limited muscle relaxant (CMAP)	1 point, easily repeated	Concern for pt movement
nMEP	Whole cord with significant antidromic dorsal column component	Nerve roots, possibly no true motor data	Inhaled anesthetics acceptable however no muscle relaxant if CMAP recording	1 point, easily repeated	Possible lack of true motor data
sEMG	Nerve root: assessment in selected myotomes	Sensation, anterior descending motor pathways	No muscle relaxants, inhalational anesthetic OK	Continuous	
tEMG	Nerve root: stimulator (pedicle/screw) to end muscle	Sensation, anterior descending motor pathways	No muscle relaxants, inhalational anesthetic OK	1 point, easily repeated	Concern for pt movement

SSEP indicates somatosensory-evoked potentials; tcMEP, transcranial motor-evoked potentials; nMEP, spinal cord MEP's; sEMG, spontaneous electromyography; tEMG, triggered electromyography; CMAP, compound motor action potential.

- One can follow amplitude reduction[147,163] with 65% being a reasonable threshold amount of reduction.[18]
- All or none phenomenon correlates well with clinical outcome in the setting of IMSCT.[54]
- When CMAP and D-wave are used in intramedullary tumor a change in one or both measures was noted in all cases of postoperative deficit.[54]
- Loss of tcMEP during intramedullary tumor resection: If D-wave is normal this correlates well with good long-term motor outcome.

Medical-Legal Issues. To date, IOM use is not supported by class one evidence and consequently the use of IOM should be considered in many situations optional and has not been universally accepted as standard of care.[28] Further, a consensus group formed of a consortium of surgeons, neurologists, neurophysiologists, and anesthetists concluded in 2006 that although there is enough evidence to make recommendations for use of IOM/MIOM, there is not enough to establish legally binding guidelines.[164] The value of IOM is becoming increasingly clear in certain settings where a relatively high risk of neurologic injury exists and individual surgeons should be aware of the implications for use.

The surgeon should know the record keeping capacity of the IOM team in reference to what data are kept and for what periods following surgery.[165] The IOM log should be ideally stored, logged, and printed throughout the surgical procedure along with intraoperative log entries and reference points to demarcate surgical actions at the time of IOM changes as well as reactions, both anesthetic and surgical.[71] As a legal document, IOM records should include patient demographic data, medical and surgical history, and should be meticulously complete.[71]

Conclusion

Current use of IOM is mostly dictated by surgeon preference and technical availability. The surgeon must understand the role of IOM and the possibility of neurologic deterioration despite IOM because even in the most ideal scenarios IOM does not eliminate all adverse neurologic events (Table 4).[8] One of the first considerations for requesting IOM is the incidence and magnitude of possible deficit.[5] In most types of spine surgery, the incidence of deficit is either so low or the complications of the injury so insignificant that IOM is not warranted.[5]

Given known risk of neurologic compromise during complex spinal surgery, IOM has been developed to inform the surgeon of onset of impairment (Table 5). The goal of IOM is to permit change of intraoperative strategy to minimize or reverse deficit. The advent of IOM also potentially permits more aggressive maneuvers than might otherwise have been undertaken such as deformity correction or tumor resection.

Combination of SSEP and MEP monitoring provides assessment of entire spinal cord functionality in real time. The wake-up test can continue to serve as a supplement to these methods when needed. MIOM may prove to be useful in preservation of neurologic function where an alteration of approach is possible.

IOM cannot replace a deep knowledge of spinal cord neurovascular anatomy, nor can it be a surrogate for lack of technical skill.[28] Indication for use includes improved outcomes where risk of injury to neural elements is weighed against IOM theoretical risks. When using IOM, one must be aware of the possibility of increased OR time, added cost, alteration in anesthetic technique, and the impact of false positives as well as false negatives. IOM should only be applied if a change in approach or intraoperative strategy is possible. IOM is a potentially valuable tool for optimization of outcome in complex spinal surgery.

■ Key Points

- Current use of IOM is mostly dictated by surgeon preference and technical availability.
- The surgeon must understand the role of IOM and the possibility of neurologic deterioration despite IOM because even in the most ideal scenarios IOM does not eliminate all adverse neurologic events.
- In most types of spine surgery, the incidence of deficit is either so low or the complications of the injury so insignificant that IOM is not warranted.
- The goal of IOM is to permit change of intraoperative strategy to minimize or reverse deficit.
- The advent of IOM also potentially permits more aggressive maneuvers than might otherwise have been undertaken such as deformity correction or tumor resection.
- IOM cannot replace a deep knowledge of spinal cord neurovascular anatomy, nor can it be a surrogate for lack of technical skill.
- IOM should only be applied if a change in approach or intraoperative strategy is possible.
- Intraoperative neuromonitoring is a valuable tool for optimization of outcome in complex spinal surgery.

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