

Intraoperative neurophysiological monitoring in spine surgery: indications, efficacy, and role of the preoperative checklist

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Spine surgery carries an inherent risk of damage to critical neural structures. Intraoperative neurophysiological monitoring (IONM) is frequently used to improve the safety of spine surgery by providing real-time assessment of neural structures at risk. Evidence-based guidelines for safe and efficacious use of IONM are lacking and its use is largely driven by surgeon preference and medicolegal issues. Due to this lack of standardization, the preoperative sign-in serves as a critical opportunity for 3-way discussion between the neurosurgeon, anesthesiologist, and neuromonitoring team regarding the necessity for and goals of IONM in the ensuing case. This analysis contains a review of commonly used IONM modalities including somatosensory evoked potentials, motor evoked potentials, spontaneous or free-running electromyography, triggered electromyography, and combined multimodal IONM. For each modality the methodology, interpretation, and reported sensitivity and specificity for neurological injury are addressed. This is followed by a discussion of important IONM-related issues to include in the preoperative checklist, including anesthetic protocol, warning criteria for possible neurological injury, and consideration of what steps to take in response to a positive alarm. The authors conclude with a cost-effectiveness analysis of IONM, and offer recommendations for IONM use during various forms of spine surgery, including both complex spine and minimally invasive procedures, as well as lower-risk spinal operations.

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EVEN in the most skilled hands, spine surgery carries an inherent risk of damage to critical neural structures with subsequent development of postoperative neurological deficits. To enhance the safety of spine surgery techniques, many surgeons use IONM. Although this technology cannot directly prevent intraoperative neurological injury, it has the potential to provide real-time feedback of critical neurological pathways to the surgeon. In select circumstances, this feedback may prevent or mitigate neurological injury. As evidenced by 1 large multicenter study, spinal operations for deformity correction that incorporate the feedback of an experienced neurophysiology team can have as much as a

50% lower rate of neurological deficits.⁴⁶ That said, there is no established consensus regarding the use of IONM in routine and complex spine surgery. Given the current state of the health care economy and changes in reimbursement practices, this issue has become particularly relevant when considering the use of IONM in lower-risk spinal procedures. To date, the routine use of IONM in all spine surgeries remains controversial and varies between centers.

There are few high-quality studies regarding the particular indications for IONM in spine surgery, which has led to the lack of firm consensus or evidence-based guidelines for safe and efficacious implementation of neuro-monitoring.^{19,22} Successful use of this technology requires fluid and coordinated 3-way communication between the neurosurgeon, anesthesiologist, and neurophysiologist.

The preoperative sign-in period serves as a critical time to integrate the separate goals of each member of the

Abbreviations used in this paper: CMAP = compound muscle action potential; EMG = electromyography; IONM = intraoperative neurophysiological monitoring; MEP = motor evoked potential; SCI = spinal cord injury; SSEP = somatosensory evoked potential.

operative team in an effort to coordinate communication during the ensuing procedure. The preoperative sign-in period includes a discussion of the appropriate anesthetic protocol, the surgeon's goals and concerns, and what actions will be taken in the setting of a change in signal amplitude, latency, or threshold.⁵⁰

At the authors' institution (Northwestern University), we have sought to incorporate a discussion of the role of IONM into the preoperative sign-in period. This discussion takes place prior to positioning of the patient and prior to IONM setup. The sign-in is always led by a surgeon and includes a discussion of the role of IONM in relation to the clinical goals of the ensuing case. Both the anesthesia and monitoring teams are expected to participate in this discussion and all questions are addressed. In particular, it is critical to discuss triggers for surgeon notification during the case. In this paper, we review modern techniques in neurophysiological monitoring, focusing on efficacy, limitations, and costs of utilization. Additionally, we review the available literature on operative checklist research and offer suggestions for incorporation of IONM into the preoperative sign-in period.

Literature Search Criteria

The terms "neurophysiological monitoring," "spine surgery," "somatosensory evoked potentials," "motor evoked potentials," "EMG," and "cost" were used as keywords to query the MEDLINE database. Both abstracts and full-text reports were reviewed, whereas case reports were excluded. Expert opinion was sought from academic spine surgeons specializing in minimally invasive techniques, deformity surgery, and intradural surgery, as well as neuroanesthesiologists and neuromonitoring specialists.

Somatosensory Evoked Potentials

Somatosensory evoked potentials are the most widely available and commonly used monitoring modality in spine surgery.³⁸ Initially described by Nash et al. in 1977,⁴³ distal stimulating electrodes are placed on the limbs, and ascending sensory signals are recorded via scalp or posterior neck electrodes. The most common sites for stimulation are the posterior tibial and peroneal nerves for the lower extremities, and median and ulnar nerves for the upper extremities.^{39,40,46} Somatosensory evoked potentials directly monitor the dorsal column-medial lemniscus pathway. As such, SSEPs do not directly monitor corticospinal activity. Accordingly, SSEPs may provide false negatives in the setting of focal corticospinal tract injury as is noted in anterior spinal artery syndrome. There have been several reports of paraparesis following anterior SCI, with preserved SSEPs intraoperatively.^{4,21,34,42,53}

Somatosensory evoked potentials are monitored continuously throughout surgery. Significant changes include amplitude decrease greater than 50% or increases in latency of more than 10% from baseline; these changes should be communicated to the surgeon. As a preliminary course of action, SSEP changes should prompt a search for correctable causes such as hypothermia, hypotension, use of halogenated anesthetics, and technical issues related to the IONM equipment. This trouble-shoot-

ing requires timely and effective communication between the anesthesiologist, surgeon, and neuromonitoring staff. If this investigation is unrevealing, consideration should be given to reversing any recent surgical maneuvers, particularly those temporally associated with the monitoring change, and assessing for improvement in SSEP signal.

Nuwer et al. in 1995⁴⁶ reported on results of a multicenter survey of members of the Scoliosis Research Society. This survey yielded 51,263 cases in which SSEPs were used as the sole mode of neuromonitoring, with a sensitivity of 92% and a specificity of 98% for new postoperative motor deficits. More recently, others have reported lower sensitivities ranging from 0% to 52%, with specificities ranging from 95% to 100% (Table 1).^{23,26,29,51,54,58,59}

A critical limitation of SSEP monitoring is the requirement for temporal summation. Readings are based on calculated averages and thus may take several minutes to change following an acute insult. In 2004, Hilibrand et al.²⁶ compared cases monitored using both MEPs and SSEPs and found that SSEP changes lagged behind MEP changes by an average of 16 minutes. Thus, a major concern of SSEP monitoring is that by the time monitoring changes become apparent, irreversible neurological injury may have already occurred. Additionally, SSEPs have a low sensitivity for detection of nerve root injury and thus may miss damage caused by aberrant pedicle screw placement or nerve root traction. These deficiencies limit the overall efficacy of SSEPs (Table 2) as a standalone monitoring tool; thus, SSEPs should be used primarily as an adjunct to other forms of monitoring.

Motor Evoked Potentials

Direct monitoring of the corticospinal pathway became possible with the work of Merton and Morton in 1980,⁴¹ who described transcranial magnetic stimulation of the motor cortex. This work allowed the development of transcranial MEP monitoring during spinal surgery with responses recorded either electromyographically via CMAPs or via epidural electrodes placed caudal to the region at risk (D-waves). Initially, transcranial MEPs had limited utility due to extreme sensitivity to volatile anesthetics. Work by Taniguchi et al. in 1993⁶¹ led to use of high-frequency (> 200 Hz) multipulse electrical stimulation at relatively low voltages, which showed improved reproducibility and anesthetic resistance relative to earlier techniques.⁶² These improvements, in conjunction with improvements in intravenous anesthetic protocols, led to the widespread use of transcranial MEPs for monitoring of motor pathways during spine surgery. Compound muscle action potential and D-wave recording will be discussed separately below.

Muscle MEPs

Electromyographic recording of transcranial MEPs with CMAPs (muscle MEPs) allows for assessment of the entire motor axis including motor cortex, corticospinal tract, nerve root, and peripheral nerve. Recordings are usually performed at multiple upper- and lower-extremity muscle groups. Langeloo et al.³¹ found a sensitivity of 100% when monitoring at 6 sites in a series of 145

Neurophysiological monitoring and spine surgery

TABLE 1: Significant studies reporting sensitivity and specificity of modern IONM techniques*

| Authors & Year | Type of Monitoring | No. of Cases | Types of Cases | Sensitivity (%) | Specificity (%) | Warning Criterion | Modalities Used |
|-------------------------|--------------------|--------------|-------------------------|-----------------|-----------------|-------------------|---|
| Nuwer et al., 1995 | SSEP | 51,263 | scoliosis | 92 | 98 | NA | NA |
| Hilibrand et al., 2004 | SSEP | 427 | cervical spine (mixed) | 25 | 100 | NA | NA |
| Gunnarsson et al., 2004 | SSEP | 213 | thoracolumbar deformity | 29 | 95 | NA | NA |
| Schwartz et al., 2007 | SSEP | 1,121 | scoliosis | 43 | 100 | NA | NA |
| Smith et al., 2007 | SSEP | 577 | ACDF | 0 | 99 | NA | NA |
| Kelleher et al., 2008 | SSEP | 1,055 | cervical spine (mixed) | 52 | 100 | NA | NA |
| Park et al., 2011 | SSEP | 29 | kyphosis | 25 | 96 | NA | NA |
| Calancie et al., 1998 | transcranial MEP | 32 | scoliosis | 100 | 100 | ↑threshold >100 V | NA |
| Langeloo et al., 2003 | transcranial MEP | 145 | scoliosis + kyphosis | 100 | 91 | ↓amplitude >80% | NA |
| Hilibrand et al., 2004 | transcranial MEP | 427 | cervical spine | 100 | 100 | ↓amplitude >60% | NA |
| Schwartz et al., 2007 | transcranial MEP | 1,121 | scoliosis | 100 | 100 | ↓amplitude >65% | NA |
| Hsu et al., 2008 | transcranial MEP | 172 | scoliosis | 100 | 97 | ↓amplitude >50% | NA |
| Kelleher et al., 2008 | transcranial MEP | 1,055 | cervical spine | 100 | 96 | not reported | NA |
| Park et al., 2011 | transcranial MEP | 29 | kyphosis | 75 | 84 | all or nothing | NA |
| Noonan et al., 2002 | multimodality | 134 | cervical spine | 100 | 95 | NA | SSEPs & neurogenic MEPs |
| Hilibrand et al., 2004 | multimodality | 427 | cervical spine | 100 | 100 | NA | SSEPs & transcranial MEPs |
| Schwartz et al., 2007 | multimodality | 1,121 | scoliosis | 100 | 100 | NA | SSEPs & transcranial MEPs |
| Quraishi et al., 2009 | multimodality | 102 | scoliosis + kyphosis | 100 | 84 | NA | SSEPs & either transcranial MEPs or spontaneous EMG |
| Hamilton et al., 2011 | multimodality | 108,419† | all forms | 43 | 98 | NA | for spinal cord deficit: SSEPs + transcranial MEPs |
| | | | | 13 | 99 | NA | for nerve root deficits: SSEPs + EMGs |
| | | | | 29 | 99 | NA | for cauda equina deficit: SSEPs + transcranial MEPs |

* ACDF = anterior cervical discectomy and fusion; NA = not applicable.

† Hamilton et al. report that 65% of reported cases used some form of neuromonitoring, but do not report what percentage used multimodality IONM.

consecutive patients, compared with a sensitivity of 88% when monitoring at only 2 sites. Because transcranial stimulation will induce movement, muscle MEPs preclude the use of neuromuscular blockade during surgery. It is absolutely essential to discuss this anesthetic concern preoperatively with the anesthesia providers. Additionally, muscle MEPs are only assessed periodically, in contrast to SSEPs that are assessed continuously throughout surgery. This represents a critical weakness of muscle MEPs and may lead to delayed recognition of neurological injury. Again, during the review of the preoperative checklist, a protocol for checking MEPs must be relayed to the neurophysiology team. This protocol ranges from only running MEPs at the surgeon's request, to periodic monitoring every set period of time.

A variety of different warning criteria are currently employed for interpretation of CMAP recordings. Ini-

tially, most authors described an all-or-none criterion by which only a complete loss of CMAPs is considered clinically significant. More recently, Langeloo et al.³¹ found that using a modified criterion of 80% decrease in amplitude at any single recording site yielded a sensitivity of 100%; however, they reported 10 false positives using this criterion and a specificity of only 91%. Calancie et al. in 1998⁸ reported a novel method of transcranial MEP interpretation, independent of amplitude. They assessed the minimum threshold stimulus required to generate distal CMAPs and found that an increase in threshold of more than 100 V yielded a sensitivity and specificity of 100% for postoperative motor deficits. Each of these criteria is considered valid, and the specific methodology used in any given case should be clarified preoperatively between the neurosurgeon and electrophysiologist.

Muscle MEPs are considered the gold standard for

TABLE 2: Summary of strengths and weakness of modern IONM techniques

| Type of Monitoring | Strengths | Weaknesses |
|--------------------|---|--|
| SSEP | <p>broadly available & relatively affordable</p> <p>allows continuous monitoring throughout case</p> <p>excellent specificity (approaching 100%)</p> <p>may be used w/ neuromuscular blockade</p> <p>warning criteria firmly established; decreased amplitude >50% or increased latency >10% considered significant</p> | <p>averaging of evoked responses leads to significant delays in signal change; may lag up to 16 mins behind transcranial MEP</p> <p>does not directly monitor corticospinal tract</p> <p>low sensitivity for motor deficit</p> <p>may remain unchanged w/ anterior spinal artery injury</p> |
| transcranial MEP | <p>excellent sensitivity for motor deficit, approaching 100%</p> <p>directly evaluates entire motor axis (cortex, corticospinal tract, nerve root, peripheral nerve)</p> <p>allows immediate assessment of corticospinal integrity following high-risk maneuvers</p> | <p>does not allow for continuous monitoring</p> <p>precludes use of neuromuscular blockade & causes patient movement</p> <p>highly sensitive to anesthetic effects</p> <p>theoretical risk of inducing seizures, although no cases have been reported</p> |
| D-wave | <p>correlates most accurately w/ long-term motor function following intramedullary spinal cord tumor resection</p> <p>can be recorded continuously & used w/ neuromuscular blockade</p> | <p>inaccurate in scoliosis surgery (27% false-positive rate)</p> <p>does not assess nerve root function</p> <p>epidural recording electrode must be placed over spinal cord, & thus D-waves can only be used above T10–11</p> |
| spontaneous EMG | <p>highly sensitive for nerve root injury</p> <p>provides constant feedback throughout case</p> <p>may be combined w/ SSEPs to improve specificity</p> | <p>high rate of false positives</p> <p>extremely sensitive to temperature changes (cold irrigation or use of cautery)</p> <p>precludes use of neuromuscular blockade</p> |
| triggered EMG | <p>high sensitivity for medial pedicle breach</p> <p>useful in minimally invasive surgery where anatomical landmarks may be challenging to visualize</p> <p>relatively easy to perform & interpret</p> | <p>optimal alarm criteria not firmly established</p> <p>may provide false-positive alarms if multiple passes have been made through pedicle or if operative field is bloody</p> <p>does not directly assess for neurological injury, only provides information regarding pedicle integrity</p> |

detection of new postoperative motor deficits, with reported sensitivities ranging from 75% to 100% and specificities ranging from 84% to 100% (Table 1).^{8,26,27,51,58} Additionally, CMAP monitoring has been shown to provide earlier detection of spinal cord ischemia compared with SSEPs and D-waves, which may allow timely reversal of injury.³⁶ Limitations of transcranial MEPs include sensitivity to volatile anesthetics as well; moreover, they cannot be continuously monitored throughout surgery. In addition, there is a theoretical risk of seizure induction secondary to transcranial stimulation, but there have been no reported cases of this induction in the literature (Table 2).

Direct Waves (D-Waves)

D-waves are generated via transcranial stimulation and monitored directly at the spinal cord level via placement of an epidural recording electrode caudal to the re-

gion at risk. In contrast to CMAP monitoring, D-waves are relatively resistant to anesthetic effects and permit the use of neuromuscular blockade for paralysis (Table 2).^{13,57,65} In general, a 20% decrease in D-wave amplitude is considered to be a preliminary warning, whereas a 50% reduction in amplitude is considered indicative of significant neurological injury.

D-waves are infrequently used during deformity surgery due to a reported 27% false-positive rate, which Ulkatan et al.⁶⁵ propose is due to rotation of the corticospinal tract relative to the recording electrode during spinal curvature correction. Additionally, the lack of nerve root and cauda equina monitoring with D-waves may limit their utility in these cases. Instead, the predominant clinical application of D-waves lies in intramedullary spinal cord tumor resection. Kothbauer et al.³⁰ initially reported in 1998 that D-waves were superior to CMAPs in prediction of long-term motor status following intramedullary

Neurophysiological monitoring and spine surgery

spinal cord tumor resection. Specifically, they found that patients with loss of CMAPs but preserved D-waves tended to have transient postoperative weakness that resolved by 1–2 month follow-up. In contrast, patients with loss of CMAPs as well as D-wave decrements greater than 50% were likely to have lasting motor deficit. Thus, use of D-waves allowed for safer, more aggressive resection than would otherwise have been possible. These findings were subsequently reproduced by Sala et al.,⁵⁷ and D-waves are currently believed to be the gold standard for motor pathway monitoring during intramedullary spinal cord tumor resection.¹³

Neurogenic MEPs

Neurogenic MEPs were originally developed in the early 1990s as an alternative means of motor monitoring that would bypass the complicated anesthetic requirements of transcranial MEPs. Neurogenic MEPs are generated via an epidural stimulating electrode placed rostral to the area at risk. Recordings are performed either at peripheral nerves or via an epidural recording electrode placed caudal to the region at risk. However, they have subsequently become controversial due to studies questioning whether neurogenic MEPs are truly monitoring motor signals.^{48,49,63,67} Initially, neurogenic MEPs were believed to represent descending motor activity, but Toleikis et al. in 2000⁶³ performed collision studies suggesting that they instead represented antidromic dorsal column signal. These findings correlated with a report by Minahan et al.⁴² of 2 cases of postoperative paraparesis and normal sensory examination with preserved SSEPs and neurogenic MEPs intraoperatively. As such, current consensus is against the use of neurogenic MEPs as the sole method of motor pathway monitoring.^{13,22,39}

Spontaneous EMG

Spontaneous or free-running EMG is widely used as a means of monitoring selective nerve root function during spinal cord surgery. During spinal cord instrumentation and pedicle screw placement, postoperative radiculopathy is more likely than SCI, making spontaneous EMGs optimal for these procedures.²⁴ No stimulation is required for this technique, and continuous recordings are made from preselected muscle groups based on the nerve roots at risk. One muscle group per nerve root is generally considered adequate, but due to the high risk of C-5 palsy during cervical spine surgery, many surgeons prefer monitoring 2 muscle groups at this level, namely deltoid and biceps.^{5,18,28} At baseline, a healthy nerve root should have no muscle activity, that is, either a flat line or silence if audio feedback is equipped. During surgery, irritation of the nerve root due to traction or thermal injury will result in spikes or bursts of activity termed neurotonic discharges. With increasing degree of mechanical injury, amplitude and frequency of these discharges will increase and trains of activity may be observed.^{5,23,47} As with other forms of EMG monitoring, neuromuscular blockade is prohibited. In contrast to transcranial MEPs in which motor function is only assessed periodically, spontaneous EMG allows continuous feedback throughout the entire procedure.

Spontaneous EMG recordings are sensitive to temperature changes, and common causes of false spontaneous EMG activation include irrigation with cold water, and use of cautery devices. Gunnarson et al.²³ reported spontaneous EMG activation at least once in 77.5% of 213 consecutive lumbosacral cases, which resulted in a sensitivity of 100%, but a specificity of only 23.5%. These results correlate with other studies of spontaneous EMG reporting high sensitivity and low specificity.^{5,28,54} The low specificity, however, may reflect the fact that spontaneous EMG is providing constant feedback to the surgeon, leading to alterations in surgical technique that may prevent a new neurological deficit and thus deceptively elevating the rate of false positives.

Triggered EMG

Triggered EMG was initially described by Calancie et al. in a porcine model in 1992⁹ as a means of assessing accuracy of pedicle screw placement. Triggered EMG relies on the concept that intact cortical bone should electrically insulate a well-placed pedicle screw from the adjacent nerve root. In contrast, with a medial pedicle breach, the pedicle screw would be relatively poorly insulated. Thus, by electrically stimulating the pedicle screw directly, and electromyographically assessing the lowest threshold voltage at which CMAPs are generated, one can assess the likelihood of medial pedicle breach. With the increasing prevalence of spinal instrumentation and fusion, triggered EMG has emerged as a popular means of preventing neurological injury in these cases.^{33,52,55,56} Triggered EMG has particular utility in minimally invasive spine surgery, in which visualization of anatomical landmarks is limited. In such cases, stimulation of pedicle taps and K-wires may be used to evaluate for accurate screw trajectory. Notably, in the setting of preoperative nerve root deficit, nerve conduction may be impaired, requiring higher thresholds for stimulation. Nerve conduction can be assessed intraoperatively by direct stimulation of the nerve root at low voltages and assessing for generation of CMAPs.

Several major studies have attempted to establish warning criteria for pedicle perforation in the lumbar spine, but consensus has yet to be reached. In 2007, Raynor et al.⁵⁵ reported results of more than 4800 consecutive lumbar pedicle screw placements, with triggered EMG results compared with postoperative CT scans in each case. The authors found that with a threshold of more than 8.0 mA, there was a 99.5%–99.8% likelihood of intraosseous screw placement (95% CI), but the high false-positive rate at this threshold may lead to unnecessary delays in surgical time and revision of adequately placed screws. More recently, Parker et al.⁵² reported results for 2450 consecutive lumbar screw placements and found that by using a threshold cutoff of less than 5 mA, they were able to maintain an acceptable sensitivity of 43.4% for medial screw breach, while limiting the number of false positives.

Fewer studies have been performed to evaluate triggered EMG efficacy for thoracic pedicle screws. Raynor et al.⁵⁶ reported using rectus abdominis CMAP record-

ings for 677 consecutive thoracic pedicle screw placements. These authors found that above a threshold of 6.0 mA, 100% of screws were intraosseous. For screws with a threshold below 6.0 mA, 6 (28.5%) of 21 screws were found to be medial breaches. Thus, the authors recommended using a threshold of less than 6.0 mA as a warning criterion for likely pedicle perforation.

The primary limitation of triggered EMG lies in the high rate of false-positive alarms. Common causes of false-positive monitoring include multiple passes within the same pedicle resulting in diminished pedicle integrity, and a wet field that may result in direct current conduction to the adjacent nerve root. Of note, most major studies on triggered EMG simply report rates of pedicle perforation, and there is a paucity of data on clinical correlation with these findings. Further studies are required to delineate the efficacy of triggered EMG in predicting true neurological compromise. Nonetheless, triggered EMG is an invaluable tool for improving safety in both minimally invasive and complex spine cases.

Combined Multimodality IONM

Multimodality monitoring has the potential to compensate for limitations of each individual monitoring modality and has become standard practice for a variety of spinal procedures. A combination of SSEP and MEP monitoring has long been used in scoliosis surgery for combined monitoring of ascending and descending pathways. The addition of spontaneous EMG and triggered EMG can enhance detection of nerve root injuries. Several studies have reported combined sensitivities and specificities approaching 100% for combined multimodal neuromonitoring (Table 1).^{16,26,54} More recently, Hamilton et al. in 2011²⁴ reported on rates of new neurological deficits in more than 100,000 patients operated on by members of the Scoliosis Research Society. For cases using multimodal neuromonitoring (mostly a combination of SSEPs with transcranial MEPs or EMG), sensitivity was reported as 43% for detection of new spinal cord deficit, 13% for new nerve root deficit, and 29% for new cauda equina deficit. These relatively poor results were in stark contrast to previously published reports and have generated significant debate on the sources of this discrepancy.^{17,45} This discussion is mostly speculative due to the nonspecific nature of the Scoliosis Research Society survey and the lack of data on IONM methodology in their study.

Several explanations have been proposed. First, the study does not specify how cases were classified in which a positive alarm led to a change in surgical approach. It is possible that many of these cases were actually true positives in which monitoring prevented a postoperative deficit, but they may have been incorrectly labeled as false positives due to the absence of postoperative deficit. Second, it is unclear whether a neurophysiologist team was present in all reported cases, and some have hypothesized that either surgeon-directed monitoring or automated monitoring may have led to the low sensitivities.^{17,45} Finally, the lack of standardization in warning criteria for a positive alarm may have led to inconsistencies in data across multiple institutions. Nonetheless, this study high-

lights the need for future prospective studies on the efficacy of multimodality neuromonitoring.

Operative Checklists and Checklist Science

Although the scientific literature on preoperative checklists remains incomplete, several studies to date have addressed the value of surgical checklists. In 2009, Haynes et al.²⁵ studied the incorporation of the WHO's surgical safety checklist at 8 international hospitals and found a 30% reduction in surgical complications relative to historical rates. Although these findings make a strong argument for the use preoperative checklists, critics have questioned the generalizability of these results to higher-income countries with better-developed health care infrastructure. More recently, Calland et al.¹⁰ assessed the efficacy of surgical checklists by randomizing 47 laparoscopic cholecystectomies to either use or not use the preoperative checklist. No significant difference was found in patient outcomes or case times between the 2 groups, but the authors reported a decrease in subjective participant-reported levels of comfort, communication, and team efficiency.

In perhaps the most ambitious study to date on surgical checklists, Ziewacz et al.⁶⁸ developed a pilot checklist for management of operating room crises. The authors identified 12 frequent operative crises including massive hemorrhage, air embolus, and ventricular tachycardia/fibrillation, and developed evidence-based protocols that they incorporated into a series of comprehensive checklists. Participants completed 8 simulation scenarios, 4 with the use of a checklist and preoperative education on how to properly use the checklist, and 4 without the checklist. The authors found a 6-fold decrease in major deviation from evidence-based management guidelines in the group that used the crisis checklists. Although these results have yet to be correlated with a live clinical scenario, they offer a glimpse of the potentially pivotal role of operative checklists. These findings may be the most generalizable to neuromonitoring in spine surgery; development of a specific protocol to address changes in neuromonitoring signal may lead to a more systematic and standardized approach to these scenarios.

One critical barrier to checklist implementation is the persuasion of the surgical team and the operating room staff to commit to the process. Conley et al.¹² studied the process of implementing a surgical checklist in 5 Washington state hospitals and found that failure to persuasively explain why and how to use the checklist led to increased levels of frustration, and in some cases, complete abandonment of the protocol. This study highlights the critical role that surgeons, as leaders in the operating room, may play in encouraging a commitment to checklist implementation.

Neuromonitoring and the Preoperative Sign-In

As discussed above, the lack of standardization in neuromonitoring practices may contribute to inconsistency in the effectiveness and utility of neuromonitoring during spine surgery. As such, the preoperative discussion

Neurophysiological monitoring and spine surgery

is a critical juncture for clarification of the goals and technique of monitoring in the case at hand. To this extent, we present a list of fundamental questions to be addressed by the neurosurgical, anesthesia, and electrophysiology teams prior to surgery. A summary of these questions can be found in Table 3.

At the authors' institution, we have attempted to incorporate a discussion of neuromonitoring into the preoperative sign-in. This discussion takes place prior to positioning of the patient and setup of IONM equipment. It is institutional policy that an attending surgeon be present for the sign-in for all nonemergency cases. In an emergency setting, it is the responsibility of the attending surgeon to ensure that a resident with an appropriate level of training and experience is available. The surgical team leads the preoperative sign-in in all circumstances. Critical points for discussion include the goals of the surgery, special equipment required for the procedure, high-risk portions of the case, and potential complications. Although the degree of formality of the process is dependent on the specific team involved, it is the surgeon's responsibility to ensure that all critical issues are discussed and that all team members remain engaged in the process.

With regard to neuromonitoring, the discussion should initially focus on what forms of neuromonitoring are indicated in the case at hand. This discussion should be driven by the perceived likelihood of neurological injury as well as identification of anatomical structures at highest risk. In cases in which spinal cord deficits are most likely, SSEPs and transcranial MEPs are most likely to be indicated. If a posterior approach is being used, SSEPs may be sufficient, but anterior approaches most likely warrant transcranial MEPs due to the risk of anterior spinal artery syndrome. In cases in which nerve root deficits are of concern, spontaneous EMG and triggered EMG monitoring may be of value.

After selection of appropriate monitoring modalities, anesthetic requirements should be discussed. If transcranial MEPs are being used, halogenated anesthetics are contraindicated, and total intravenous anesthesia generally results in optimization of signal acquisition. Use of any form of EMG monitoring precludes the use of neuromuscular blockade. If paralytics are used, monitoring should be performed only after adequate reversal, that is, 3 or more twitches on train-of-4 testing.^{39,47,55,56}

Establishment of appropriate warning criteria is critical. For SSEP monitoring, a decrease in amplitude of more than 50% or an increase in latency of more than

10% is widely considered to be optimal. For other modalities such as muscle MEPs and triggered EMG, however, consensus has yet to be reached. Lower requirements for positive alarm criteria may improve sensitivity, but this must be balanced against the increased rate of false positives, which may contribute to unnecessary delays and changes in surgical plan. At the author's institution, for muscle MEPs, we consider a decrease in CMAP amplitude of more than 50% to be significant. For triggered EMG, we consider a threshold value of 5 mA to be indicative of possible pedicle breach. As with all monitoring, the specific methodology should be clarified with the electrophysiologist prior to each case.

It is the role of the neurosurgeon to establish a clear plan for responding to a positive alarm. Initial investigation should be directed at common sources of false-positive monitoring, including hypotension, hypothermia, and use of halogenated anesthetics. For SSEP and transcranial MEP monitoring, placement of the stimulating and recording electrodes should be verified, because migration or fall-out of leads may cause significant variation in signal amplitude. If this investigation is unrevealing or if true neurological injury is suspected, the surgeon should consider reversing any recent high-risk maneuvers and assessing for improvement in signal amplitude or latency. With triggered EMG, low stimulation thresholds should prompt investigation for medial screw deviation. During open spine surgery, this can be accomplished by manual palpation of the medial pedicle wall. In minimally invasive surgery, assessment may be difficult and screw removal and replacement may be necessary.

Finally, rapid development of new spine surgery techniques, including minimally invasive technologies, can present new challenges for coordination in the operating room. When new techniques are used in the operating room, it is the responsibility of the surgeon to discuss how IONM will be used during the case. This is especially critical during cases in which the anatomy will only be "seen" through the use of fluoroscopy or O-arm. For example, Smith et al.⁶⁰ report a 6.2% rate of pedicle breach, and a 3.7% rate of severe breach (> 3 mm) during percutaneous placement of lumbar pedicle screws despite the use of intraoperative fluoroscopic guidance. As such, in cases using minimally invasive techniques or other new technologies, an understanding of how IONM will be implemented throughout the case is critical.

Cost-Effectiveness of IONM and Recommendations for Use

Despite the marked advancements in neuromonitoring technology, there have been no prospective studies with a high level of evidence performed to validate the efficacy of IONM. Use of IONM is driven largely by surgeon preference and medicolegal concerns. There is a need for prospective studies to establish standardized criteria for use of neuromonitoring; in this report, we present general guidelines for IONM based on the available literature. Use of IONM should largely be dictated by the complexity of the surgical procedure and the assumed risk of new neurological injury. For scoliosis surgery,

TABLE 3: Summary of important IONM-related questions to include in the preoperative checklist

1. What monitoring modalities are most appropriate for the case at hand? What types of neurological deficits are most likely?
2. What anesthesia protocol will optimize acquisition of neuromonitoring signals? Is total intravenous anesthesia indicated? Can paralytics be used?
3. What alarm criteria will be used for each monitoring modality?
4. What actions will be taken in the setting of a positive alarm?
5. Are new techniques involved? How will they be implemented?

the general consensus is that combined monitoring with SSEPs and transcranial MEPs represents the minimum standard of care. In many cases, triggered EMG may be added for additional nerve root monitoring following instrumentation. Nuwer et al.⁴⁶ compared the results from their 1995 survey of the Scoliosis Research Society to prior data from the same group collected before the widespread use of neuromonitoring.³⁷ These authors found a decreased rate of neurological deficits in the newer data and attributed this to the use of SSEP monitoring. While the authors admit that it is impossible to assess the validity of this assumption, they estimate that if SSEP monitoring prevents 1 deficit in every 200 cases, then the cost of preventing 1 new neurological deficit with SSEP monitoring is \$120,000. This amount is significantly less than even the first-year health care costs of a newly paraplegic patient (<http://www.spinalcord.uab.edu>; Table 4).¹⁴

For other forms of spine surgery there are varying levels of evidence. As a specific case example, with intramedullary spinal cord tumor resection the evidence appears to support addition of D-wave monitoring because this correlates most accurately with long-term motor function.^{30,57} However, this form of monitoring is likely not appropriate for other spine cases. Although many would consider IONM to be the standard of care for cervical decompression surgery, not all surgeons agree on this. For instance, in 2012, Traynelis et al.⁶⁴ published a series of 720 consecutive cases of cervical decompression performed without IONM with no new postoperative deficits. Based on CPT codes, the authors estimate the average cost per case (assuming a 4-hour case length) as follows: SSEP, \$941.82; transcranial MEP, \$1114.77; combined SSEP and transcranial MEP, \$1423.27. Based on these estimates, the authors propose that the cost saved by not using combined SSEP and transcranial MEP in these 720 cases is \$1,024,754. In light of the continually rising costs of health care, this study has raised questions over which cases can be safely performed without neuromonitoring. That said, the use of SSEPs and transcranial MEPs in routine cervical spine decompression and fusion cases is well supported by the scientific literature.³⁵ Reports investigating IONM during instrumented anterior cervical surgery suggest a strong role for IONM in alerting the surgical team about neurological changes that may occur during positioning or due to hemodynamic changes during the case.^{6,32} Devlin and colleagues¹⁵ have suggested that IONM is a useful adjunct during surgery

for cervical spondylotic myelopathy. Likewise, Garcia et al.²⁰ described the successful use of SSEPs during posterior cervical laminoplasties.

Intraoperative neurophysiological monitoring during lumbar surgery, particularly routine lumbar spine procedures such as uncomplicated decompression and discectomy, is controversial. Although authors of some series have suggested that monitoring in all cases is beneficial, it is not entirely clear whether IONM truly affected the already low neurological complication rates.^{1,66} In revision cases, the higher risk of neurological injury supports the use of neuromonitoring.²⁴ Likewise, instrumentation and fusion is associated with a higher risk of nerve root injury, and use of spontaneous EMG or triggered EMG may enhance safety.^{2,3,7,11} In all cases, the experience and skill level of the surgeon should be factored into decision making.

Finally, although use of IONM remains unsupported by prospective studies with a high level of evidence, many surgeons believe it is critical for high-risk cases. The medicolegal implications of neural injury can be significant. In these circumstances, the documentation of the electrophysiology technician can be critical. This documentation provides the surgeon with a timeline of when intraoperative events occurred. Equally, if even more critical, they can demonstrate what steps were taken by the surgeon at the time of an intraoperative event.

To conduct a more complete cost-benefit analysis of IONM, future prospective studies must clarify the rate at which IONM prevents neurological injury. From this information, one could calculate the socioeconomic cost of injury prevented by IONM and compare it to the actual cost of monitoring. By doing so, one could develop a predictive model to assess the financial viability of IONM for various forms of spinal surgery. Given the current state of health care economics, this would be an invaluable tool for assessing which cases warrant use of IONM.

Conclusions

Intraoperative neurophysiological monitoring is a rapidly evolving field with the potential to greatly improve the safety of spinal surgery. A thorough appreciation of the strengths and weaknesses of each monitoring modality is critical for the optimal use of IONM. Preoperative discussion between the neurosurgeon, anesthesiologist, and electrophysiologist is an essential component of safe IONM usage, and topics should include anesthetic requirements for IONM, alarm criteria to be used, and steps to be taken in response to a positive alarm. Further prospective studies are needed to establish the true efficacy of IONM, but when used properly, IONM represents a powerful tool for improving outcomes in spine surgery.

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TABLE 4: Average health care and life expenses attributable to SCI*

| Type of SCI | First-Yr Costs Following SCI (\$) | Subsequent Annual Costs (\$) |
|-------------|-----------------------------------|------------------------------|
| C1–4 | 775,567 | 138,923 |
| C5–8 | 500,829 | 56,905 |
| paraplegia | 283,388 | 28,837 |
| incomplete | 228,566 | 16,018 |

* From the National Spinal Cord Injury Statistical Center (<http://www.spinalcord.uab.edu>).

Neurophysiological monitoring and spine surgery

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