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# The need to add motor evoked potential monitoring to somatosensory and electromyographic monitoring in cervical spine surgery

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## Abstract

Intraoperative neural monitoring (IONM), utilizing somatosensory evoked potentials (SEP) and electromyography (EMG), was introduced to cervical spine surgery in the late 1980's. However, as SEP only provided physiological data regarding the posterior cord, new motor deficits were observed utilizing SEP alone. This prompted the development of motor evoked potential monitoring (MEP) which facilitated real-time assessment of the anterior/anterolateral spinal cord. Although all three modalities, SEP, EMG, and MEP, are routinely available for IONM of cervical spine procedures, MEP are not yet routinely employed. The purpose of this review is to emphasize that MEP should now routinely accompany SEP and EMG when performing IONM of cervical spine surgery. Interestingly, one of the most common reasons for malpractice suits involving the cervical spine, is quadriparesis/quadriplegia following a single level anterior cervical diskectomy and fusion (ACDF). Previously, typical allegations in these suits included; negligent surgery, lack of informed consent, failure to diagnose/treat, and failure to brace. Added to this list, perhaps, as the 5th most reason for a suit will be failure to monitor with MEP. This review documents the value of MEP monitoring in addition to SEP and EMG monitoring in cervical spine surgery. The addition of MEP should minimize major motor injuries, and more accurately and reliably detect impending anterior cord deterioration that may be missed with SEP monitoring alone.

**Key Words:** Cervical surgery, electromyography, intraoperative monitoring, motor evoked potentials, neurological, somatosensory evoked potentials, spine surgery

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## Editorial Comments

At times, editorials provide guidance as to how to perform a procedure, or select patients for a specific operation. However, in this case, this editorial is focused on why it is essential that more and more spine surgeons utilize intraoperative motor evoked potential monitoring (MEP) to supplement the more commonly employed somatosensory evoked potentials (SEP) and electromyography (EMG). Even if one cannot recall an instance in which MEP helped avoid a neurological deficit, one can read the medicolegal literature to find a plethora of cases in which MEP were not performed and patients incurred major deficits (e.g. quadriplegia, paraplegia). With the availability of TIVA (total intravenous anesthesia), real-time MEP monitoring is feasible, and there is no "waiting". While some spine surgeons may think they have to perform cervical operations with the patient paralyzed in order to avoid motion during critical phases, those of us who perform these procedures with TIVA and MEP without paralysis think otherwise. Whether operating on the anterior or posterior cervical spinal cord, MEP provide critical and essential information regarding the status of the anterior or anterolateral cervical cord that may be missed by SEP. Those presuming that MEP are only important when dealing with anterior cervical disease are sadly mistaken; MEP can pick up changes and frequently do when both anterior or posterior cervical surgical procedures go awry.

Certainly, the evidence points to the value of SEP and MEP monitoring when operating on the spinal cord or spine. This is the principle I follow in my practice from the evidence in the literature and my own experience. Under optimal circumstances, patients should be transferred to a place where this technology is available or the patient and or family should be informed that the circumstances do not permit this technological addition to the surgery, and therefore, the risks will be higher of spinal cord damage.

However, I am fully aware that in different places one or both of these options may not be available.

Then what do they do? Are they guilty of malpractice? Say in a small community far from a neurological monitoring source? Or in another country? There is no set answer for all circumstances. Nevertheless, when given the option to include MEP, the answer should typically be in the affirmative.

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Editor, SNI: Spine

## INTRODUCTION

When performing cervical spine surgery, "real time" intraoperative neural monitoring (IONM) should now include not only somatosensory evoked potentials (SEP) and electromyography (EMGs), but also motor evoked potentials (MEP). While SEP classically monitor the posterior cord, MEP provide better information regarding the status of the anterior/anterolateral cord. When combined, SEP and MEP provide physiological coverage of essentially the entire cord, and thereby reduce the risk of incurring new neurological deficits without sufficient warning. This review progressively documents the "value added" of supplementing SEP/EMG IONM with MEP for cervical spine surgery.

## MEDICOLEGAL HISTORY FOR CERVICAL SPINE SURGERY

In the past, the most common reasons for malpractice suits involving the cervical spine included new postoperative neurological deficits (e.g., including quadriplegia) typically incurred during single level anterior cervical diskectomy and fusion (ACDF).[12,15,16] The allegations leading to the majority of these suits included; negligent surgery, lack of informed consent, failure to diagnose/treat, and failure to brace. Failure to adequately perform intraoperative neural monitoring (IONM)) may become the 5th most common reason for a suit. First and foremost, it will likely include the lack of MEP monitoring to supplement SEP and EMG IONM. Other shortcomings of IONM will probably include; failure to perform real-time intraoperative monitoring (e.g., a technician is alone in the operating room but there is no physician providing simultaneous interpretation during the actual surgery), failure to monitor MEP, SEP or EMG correctly, and failure to utilize the correct anesthetic to avoid the loss of potentials [Table 1].

### It is easier to confuse a jury than convince a judge: the crisis in medical malpractice

Insurance rates for medical malpractice are exorbitant, physicians practice defensive medicine, and both the patient and society pay a huge price. In 2002, Epstein explored different tort reform models to resolve the crisis in medical malpractice.[12] The evaluation included 36 cervical spine surgery malpractice cases (provided through Verdict Search, a medicolegal journal: East Islip, NY, USA); 20 cases were from California ($250,000 cap on pain and suffering), while 16 were from New York ("the sky's the limit"). The questions asked included; who sued? who was sued? who won? who lost?, and why? Common bases for suits included; failure to diagnose and treat (56%), lack of informed consent (64%), the evolution of new neurologic deficits (64%), and pain and suffering (72%). All six plaintiffs' verdicts (average, $4.42 million) and four of the nine settlements (average, $1.6 million) involved patients who were newly quadriplegic; these outcomes were appropriate. However, "no fault" on the part of the surgeon was noted by the author in five settled cases wherein the defendant surgeon did not deserve to lose. Alternatively, the author found "fault" in five defense verdicts rendered to 3 newly quadriplegic patients and to 2 others with new postoperative root injuries [Table 1].

**Table 1: Summary of sections**

| | |
|---|---|
| Medicolegal history for cervical spine surgery | The allegations leading to cervical spine surgery (most 1-level ACDF) included; negligent surgery, lack of informed consent, failure to diagnose/treat, and failure to brace. Failure to adequately perform intraoperative neural monitoring may become the 5th |
| It is easier to confuse a jury than convince a judge: the crisis in medical malpractice | In 2002, Epstein evaluated 36 cervical spine malpractice cases. Common bases for suits included; failure to diagnose and treat (56%), lack of informed consent (64%), the evolution of new neurologic deficits (64%), and pain and suffering (72%). All six plaintiffs' verdicts (average, $4.42 million) and 4/9 settlements (average, $1.6 million) involved quadriplegia were all deemed appropriate. However, 5/9 settled cases should not have been lost, while 5 defense verdicts should have favored the plaintiff (3 quadriplegias, 2 root deficits) |
| Tort reform and other malpractice models | Two tort reform models would likely work better than the present malpractice system; the American Medical Association National Specialty Societies Medical Liability Project with the Alternative Dispute Resolution Model, and the Selective No Fault Model |
| Cases involving quadriplegia following cervical spine Surgery | Using Verdict Search (medicolegal journal), Epstein identified 54 medicolegal cases of quadriplegia (1988-2008) attributed to; negligent surgery (47), lack of informed consent (23), failure to diagnose/treat (33), and failure to brace (15). There were 19 plaintiffs' verdicts (average US $5.9 million), 20 settlements (average US $2.8 million), and 15 defense verdicts ($0.00) |
| Review of medicolegal malpractice suits involving the cervical spine | Epstein used Verdict Search to identify 78 cervical spine surgical malpractice suits over 10-years. The 4 most common reasons for malpractice included; negligent surgery, lack of informed consent, failure to diagnose/treat, and failure to brace. Outcomes included; 22 plaintiffs' verdicts (average $4.0 million), and 26 settlements (average $2.4 million), and 30 defense verdicts (including 10 quadriplegic patients) |
| Anesthetic Considerations: Awake Intubation Protocols Utilizing Nasotracheal or Endotracheal Fiberoptic Intubation | Various anesthetic protocols involve fiberoptic awake nasotracheal (NT) vs. endotracheal intubation (ET) to avoid cervical manipulation during tube placement. NT intubation is typically preferred for anterior procedures (optimizes anterior access), while NT or ET may be used for posterior surgery. Additionally, NT intubation is more readily tolerated if intubation must be maintained postoperatively |
| Keeping patients intubated after multilevel OPLL Surgery (2002)<br>Maximizing Preoperative and IONM Utilizing Awake Fiberoptic Intubation and Positioning in Patients with Cervical Instability (2012) | Epstein designed a specific anesthetic protocol consisting of awake intubation/positioning, and keeping patients prophylactically intubated the first postoperative night following circumferential cervical surgery. Six major risk factors contributed to the need for continued intubation; repeated anterior surgery, operations over 10 hours, operations of 4 or >levels (including C-2), obesity, asthma, and >4 units of blood transfusions. For those exhibiting >3 major risk factors, extubation could be delayed a week, or lead occasionally to tracheostomy |
| Maximizing preoperative and IONM Utilizing awake fiberoptic intubation and positioning in patients with Cervical Instability (2012) | Continuous preoperative neurological monitoring for cervical spine surgery is best achieved utilizing topical anesthesia (oropharyngeal and/or transtracheal lidocaine) in order to perform awake fiberoptic intubation and self-positioning. Eleven of 14 patients with cervical instability in Malcharek *et al*., study safely/effectively underwent awake fiberoptic intubation and awake prone positioning |
| TIVA Total intravenous anesthesia | Anesthetic considerations for cervical surgery, typically dictated by the necessity for real time IONM (SEP, MEP, and EMG) typically requires the "balanced technique" or TIVA (total intravenous anesthesia). TIVA utilizes propofol and alfentanil, without inhalation anesthetics (e.g. nitrous oxide, flurane) to avoid interfering with intraoperative monitoring parameters |
| Value of SEP and MEP Monitoring to Avoid Hypotension Utilizing TIVA Anesthesia for Cervical Spine Trauma (2009) | Intraoperative MEP monitoring utilized in conjunction with TIVA anesthesia may signal intraoperative hypotension occurring during anterior cervical procedures for cervical spine trauma |
| Interaction of Total Intravenous Anesthetic Techniques with Intraoperative Monitoring and Patient Variables (Hypertension, Diabetes, Age, Weight) (2010) | Inhalation anesthesia more significantly decreases the waveforms for SEP, MEP; TIVA has less of an impact. Although halogenated agents and nitrous oxide depress MEP more than TIVA, less is known about the relationship between IONM and patients' hypertension, diabetes, age, and weight |
| Intraoperative Monitoring in Cervical Spine Surgery Evaluation of Intraoperative SEP Monitoring in 100 Cervical Operations (1993) | Epstein et al., performed real time SEP monitoring for 100 patients undergoing cervical spine surgery (1989-91); none developed new deficits. Alternatively, 3.7% of 218 previously unmonitored cervical cases developed quadriplegia (1985-1989) |

*Contd...*

**Table 1: Contd**

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|---|---|
| IONM Consisting of SEP During 508 Cervical Corpectomies (2006) | Khan et al., analyzed SEP monitoring of 508 cervical corpectomies. Significant changes occurred in 5.3%; new deficits were observed in 2.4%. SEPs detected impending or permanent deficits with a 77.1% sensitivity and 100% specificity |
| Neurophysiological Alerts (SEP, MEP, EMG) During Anterior Cervical Surgery (2006) | Of 1445 patients undergoing anterior cervical fusions using SEP, MEP and EMG monitoring, 267 (18.4%) cases showed minor (spontaneous, sustained EMG) or major (MEP/SSEP amplitude reduction) alerts. These were more frequent for corpectomies (28% increased risk) vs. diskectomies, CSM (30%), and trauma (76%) procedures |
| Value of IONM (SEP, MEP, EMG) in 246 Cervical Spine Operations (2007) | The sensitivity and specificity of SEP, MEP, EMG monitoring was assessed; 232 true negatives, 2 false negatives, 2 false positives, but 10 true positives (e.g., significant changes with new deficits). The sensitivity of monitoring was 83.3%; specificity was 99.2% |
| Predictive Value of IONM (SEP, MEP, EMG) in 1055 Cervical Spinal Operations (2008) | The IONM included; SEP (1055), MEP (26), and EMG (427) patients). SEP sensitivity was 52%, and specificity was 100%, MEP sensitivity was 100%, and specificity 96%, while EMG sensitivity was 46%, with a specificity of 73% |
| Combined 100% Sensitivity of SEP/MEP in Adult Spinal Deformity Cases (2009) | Quraishi et al., assessed IONM (SEP, EMG, MEP) in 102 spinal deformity/extensive thoracolumbar fusion cases. The overall combined sensitivity was 100%; SEPs in 101 (99%), EMGs in 89 (87%), and MEPs in 12 of 16 (75%) cases |
| Value of SEP and MEP In Avoiding Brachial Plexus Injury Attributed to Positioning Before Anterior Cervical Spine Surgery (2011) | During draping for surgery, SEP significantly deteriorated, and were followed by the loss of MEP; both returned once tape on the shoulders was removed |
| Value of somatosensory evoked potentials (SEP) and transcranial motor evoked potentials (MEP) Combined: 100% in Cervical Surgery (2012) | The relative sensitivities of SEP and MEP alerts in detecting impending neurological damage during 200 spinal operations using TIVA were 37.5% and 62.5%; together, they were 100%. Three SEP alerts were due to poor arm positioning (2 patients) and hypotension (1 patient), while 4 of 5 MEP alerts were due to hypotension, but 1 was attributed to cord compression by a bone graft |
| MEP warning thresholds (amplitude) for cervical cord compression (2012) | In 350 cases, Sakaki et al., correlated the levels of cervical spine surgery with outcomes and MEP loss (differentiating tracts, segments). Potentials lost in 11 cases were directly attributed to the levels of spinal surgery; 2 developed subsequent neurological sequelae. However for 43 cases in which MEP changes occurred below the level of surgery, there were no postoperative deficits |
| Compartment syndrome avoided by loss of SEP and MEP during cervical surgery (2012) | Bronson et al., described how early SEP and MEP loss during a 2-level ACDF led to the discovery of an infiltrated intravenous line that, once removed, allowed the swelling to resolve. In this case, IONM avoided the development of a compartment syndrome |
| Significant changes/loss of IONM (SEP, MEP, EMG) over 25 years in 12,375 Patients (2013) | Raynor et al., evaluated the efficacy of IONM (SEP, MEP, EMG) in 12,375 patients involving the cervical (29.7% (3671)), thoracic/thoracolumbar (45.4% (5624)), and lumbosacral (24.9% (3080)) spine. IONM changes/loss occurred in 406 instances in 386 (3.1%) of 12,375 patients due to; instrumentation ($n$=131), positioning ($n$=85), correction ($n$=56), systemic ($n$=49), unknown ($n$=24), and focal spinal cord compression ($n$=15) |
| Value of MEP and EMG monitoring in cervical diskectomy (2013) | The value and efficacy of "free running" MEP and EMG monitoring was assessed during 38 cervical diskectomy/fusions. Those demonstrating a 41% increase in TcMEP amplitude exhibited excellent postoperative results, while those with <11% increase in TcMEP amplitude had only fair results |
| MEP role in surgery for cervical spondylotic myelopathy (CSM) (2013) | As MEP monitor the corticospinal tracts for patients with CSM, Capone et al., correlated the preoperative and postoperative MEP with the clinical results of cervical spine surgery in 38 patients with CSM. They concluded that early surgery and lesser preoperative deficits correlated with better outcomes defined by improvement in MEP |
| Conclusion: MEP should become a routine addition to SEP/EMG intraoperative monitoring in cervical spine surgery | The recent literature supports the safety/efficacy and sensitivity/specificity of MEP monitoring. It also emphasizes that adding MEP to SEP/EMG IONM should provide maximal warnings of impending intraoperative injury and minimize new postoperative neurological deficits |

OPLL: Ossification of the posterior longitudinal ligament, EMG: Electromyographic monitoring, TcMEP: Transcranial electrical motor-evoked potential

## Tort reform and other malpractice models

In Epstein's 2002 study, although 6 different tort reform models were also identified, only two would likely work better than the present malpractice system.[12] These included; the American Medical Association National Specialty Societies Medical Liability Project with the

Alternative Dispute Resolution Model (SSMLP), and the Selective No Fault Model. These appeared to be the best models as they would both reimburse injured patients in a more timely fashion, would utilize malpractice panels that included the input of physicians (e.g., rather than trials), would cap damages, and eliminate physician liability (while setting up panels to review their performance) [Table 1].

### Cases involving quadriplegia following cervical spine surgery

In 2010, Epstein again utilized Verdict Search to identify patients across the US who developed quadriplegia following cervical spine surgery between 1988-2008.[15] During this period, when MEP were rarely performed and IONM consisted solely of SEP/EMG, 54 relevant malpractice suits involving quadriplegia were identified: These included 25 anterior cervical procedures, 22 posterior cervical operations, 1 circumferential procedure, and 6 cases in which the cervical operations were not defined. The four most significant reasons for suits included; negligent surgery (47 cases), lack of informed consent (23 cases), failure to diagnose/treat (33 cases), and failure to brace (15 cases). In this series, there were 19 plaintiffs' verdicts (average US $5.9 million, range US $540,000-$18.4 million), 20 settlements (average US $2.8 million, range US $66,500-$12.0 million), and 15 defense verdicts ($0.00). The average time to verdicts/settlements was 4.3 years, but in some instances extended beyond 11 years [Table 1].

### Review of medicolegal malpractice suits involving the cervical spine

In 2011, Epstein asked 4 major questions about medicolegal suits involving the cervical spine occurring predominantly before MEP accompanied routine SEP/EMG IONM; (1) What operations/neurologic deficits led to suits?, (2) Who was sued?, (3) What "malpractice" events prompted the suits?, and (4) What were the outcomes?[16] Verdict Search again was utilized to identify 78 cervical spine surgical malpractice suits over a 10-year period. Operations for 68 patients included; 48 anterior operations (1 to 4 level anterior diskectomy/fusions, 1-level corpectomy/fusion), 20 posterior surgery (7 fusions, 13 laminectomies with/without fusions), and 2 other operations/procedures. Eight patients never had surgery. New postoperative quadriplegic deficits led to suits in 41 patients, and were attributed to 21 anterior, and 20 posterior operations. Other injuries/lesser deficits were noted in 15 patients, while 22 had pain alone. The 4 most common malpractice events prompting cervical suits again included; negligent surgery, lack of informed consent, failure to diagnose/treat, and failure to brace. Interestingly, outcomes for these suits included; 22 plaintiffs' verdicts (average payout $4.0 million dollars), and 26 settlements (average $2.4 million dollars), and 30 defense verdicts (including 10 quadriplegic patients) [Table 1].

## ANESTHETIC CONSIDERATIONS: AWAKE INTUBATION PROTOCOLS UTILIZING NASOTRACHEAL OR ENDOTRACHEAL FIBEROPTIC INTUBATION

For patients undergoing anterior, posterior or circumferential cervical surgery, particularly for those with OPLL with marked cord compression, there are multiple intubation techniques that should now be performed under SEP, EMG, and MEP monitoring (patients are transiently sedated to obtain baseline MEP prior to intubation).[6-11,13,14] These protocols involve awake nasotracheal (NT) intubation vs. endotracheal intubation (ET) performed fiberoptically to avoid cervical manipulation during tube placement. The NT route is typically chosen for anterior procedures, to avoid extending the jaw inferiorly obscuring the operative field (e.g., particularly in more rostral (e.g., C3-C4) cases), and to facilitate maintaining postoperative intubation. For posterior procedures, NT intubation may still be utilized for ease of postoperative continued intubation, but endotracheal intubation (ET) is another option [Table 1].

### Keeping patients intubated after multilevel OPLL surgery (2002)

In patients under 65 years of age, multilevel OPLL is often treated with circumferential procedures including IONM (SEP and EMG as MEP were not yet routinely available/approved), multilevel anterior corpectomy/fusion, with immediate posterior fusion and often halo immobilization.[6-11,13,14] Epstein designed a specific anesthetic protocol for these patients that included awake intubation and positioning, and keeping patients prophylactically intubated at least the first postoperative night.[10] The study identified 6 major risk factors that potentially contributed to the need for continued intubation; repeated anterior surgery, operations lasting more than 10 hours, operations involving four or more levels (including C-2), obesity, asthma, and blood transfusions of more than 4 U (1000-1200 ml). For patients exhibiting three or more major risk factors, extubation was typically delayed for up to one week, or led occasionally to tracheostomy.

Whether on the first or subsequent postoperative days, anesthesiologists would test whether extubation was feasible.[10] First, they would let air out of the NT/ET balloon; if the patient could phonate, tracheal swelling around the NT/ET tube was minimal and the patient would likely tolerate extubation. Second, on the postoperative CT scan (obtained the night following surgery), if air could be seen around the NT/ET Tube, swelling was also likely minimal. Third, at the bedside, anesthesiologists would directly assess fiberoptically whether there was tracheal swelling both inside/outside (around) the NT/ET tube prior to extubation. Extubation was performed by an experienced anesthesiologist at the bedside who stood ready to reintubate fiberoptically if necessary. Notably, prior to extubation, typically drips utilized for sedation (e.g., typically Propofol (Diprivan- Fresenius Kabi USA, Lake Zurich, Illinois, USA, Remifentanil Abbott Laboratoties, Abbott Park, Illinois, USA) were halted to maximize adequate post-extubation spontaneous ventilation [Table 1].

### Maximizing preoperative and IONM utilizing awake fiberoptic intubation and positioning in patients with cervical instability (2012)

Continuous preoperative neurological monitoring for cervical spine surgery is best achieved utilizing topical anesthesia (oropharyngeal and/or transtracheal lidocaine) in order to perform awake fiberoptic intubation and self-positioning. In Malcharek *et al*., study, the safety and efficacy of awake fiberoptic intubation and awake prone positioning were evaluated in 14 patients with cervical instability.[23] Eleven patients were successfully intubated and positioning utilizing this technique, while it was unsuccessful in only 3 patients. The authors concluded that their anesthetic technique, therefore, maximized the ability to continuously perform IONM in patients at risk of inadvertent cervical injury with these two maneuvers [Table 1].

## TIVA TOTAL INTRAVENOUS ANESTHESIA

Patients undergoing NT or ET intubation for cervical pathology usually receive sedation (e.g., Versed) and local anesthetics to numb the airway (e.g., Lidocaine). Anesthetic considerations are typically dictated by the necessity for real time IONM including SEP, MEP, and EMG. This typically requires utilizing the "balance technique" or TIVA (total intravenous anesthesia), consisting of propofol and alfentanil, without inhalation anesthetics (e.g., nitrous oxide, flurane) to avoid interfering with intraoperative monitoring parameters. Advantages of TIVA include facilitation of a smooth induction, reliable/titratable maintenance, and the advantage of rapid emergence for immediate patient evaluation. For MEP monitoring it is also essential that paralytic agents are avoided, although they may transiently be utilized during the initial operative approach once MEP baselines have been recorded and adequately reproduced [Table 1].

### Value of SEP and MEP monitoring to avoid hypotension utilizing TIVA anesthesia for cervical spine trauma (2009)

Intraoperative MEP monitoring utilized in conjunction with TIVA anesthesia may signal intraoperative hypotension occurring during anterior cervical procedures for cervical spine trauma.[2] In Cann *et al*., case study, a young male with a cervical fracture undergoing an anterior cervical fusion developed abnormal MEP signaling a transient period of hypotension.[2] Fortunately this "pick up" allowed the surgeons to perform a wake-up test, confirmed normal function, and complete the operation without incurring any permanent neurological injury [Table 1].

### Interaction of total intravenous anesthetic techniques (TIVA) with intraoperative monitoring and patient variables (hypertension, diabetes, age, weight) (2010)

Deiner evaluated the interactions of IONM (SEP, EMG, MEP) with anesthetic techniques utilized in spinal surgery.[4] All three modalities, he acknowledged, have reduced the incidence of intraoperative/postoperative new neurological deficits. Notably, inhalation anesthesia more significantly decreases the waveforms (amplitude and increase latency) whereas intravenous anesthetics (TIVA) have less of an impact. Although studies have shown that halogenated agents and nitrous oxide depress MEP signals more than TIVA, less is known on the relationship between IONM and patient characteristics. In this study, however, certain patient characteristics warranted a more stringent TIVA regimen to avoid loss of potentials and the need for a Stagnara wake-up test. A history of hypertension and diabetes, but less so of advanced age and increased weight, increased the risk of failure to monitor, and were even more negatively impacted by inhalational agents [Table 1].

## INTRAOPERATIVE MONITORING IN CERVICAL SURGERY

### Evaluation of intraoperative SEP monitoring in 100 cervical operations (1993)

Epstein *et al*., prospectively evaluated the efficacy of real time intraoperative SEP (note: MEP monitoring was not yet approved) monitoring for cervical spine surgery in 100 patients (1989-91) and contrasted these with 218 previously unmonitored patients (1985-9).[6] At that time, SEP monitoring had already reduced the incidence of neurologic injury for scoliosis surgery from 4-6.9% to 0-0.7%. Cervical operations addressed disc disease, stenosis, spondylosis, and ossification of the posterior longitudinal ligament. Eight of 218 unmonitored patients became quadriplegic (3.7%) and one died (0.5%), while no morbidity/mortality occurred among the 100 SEP monitored patients. The reduction in neurologic deficits was attributed to: SEP detection of significant changes attributed to hypotension/vascular compromise, over-manipulation, or mechanical compression. These changes were immediately addressed with a variety of successful resuscitative maneuvers; reversal of hypotension, adjustment of operative positioning, release of distraction, cessation of manipulation, and/or removal of grafts [Table 1].

### IONM consisting of SEP during 508 cervical corpectomies (2006)

Khan *et al*., retrospectively analyzed the utility of intraoperative SEP monitoring during 508 cervical single/multilevel corpectomies (average age 55.7).[20]

Significant SEP changes were observed in 5.3% (27 of 508 patients) cases, while new postoperative deficits were observed in 2.4% of patients; deficits included 11 root injuries, and 1 instance of quadriplegia (SEP loss irreversible). SEP loss mostly signaled hypotension or deltoid (C5) paresis. SEPs detected impending or permanent neurological deficits with a 77.1% sensitivity and 100% specificity; if root deficits were excluded, both values were 100%. The authors concluded that the majority of SEP changes can be reversed, and result in no permanent deficit [Table 1].

### Neurophysiological alerts (SEP, MEP, EMG) during anterior cervical surgery (2006)

Lee *et al*., retrospectively evaluated 1445 patients undergoing anterior cervical diskectomy/corpectomy with fusion utilizing SEP, MEP and EMG monitoring.[21] In 267 (18.4%) cases, minor (spontaneous, sustained EMG) or major (MEP/SSEP amplitude reduction) alerts occurred, and were more frequent for those having corpectomies (28% increased risk) vs. diskectomies, CSM (30%), and trauma (76%) procedures. Eight cases were aborted due to sustained SEP/MEP amplitude loss, but resulted in no permanent deficits. The authors recommended the following maneuvers when such losses occurred; delaying or terminating surgery, infusion of methylprednisolone, and the wake up test [Table 1].

### Value of IONM (SEP, MEP, EMG) in 246 cervical spine operations (2007)

In a prospective study of 246 patients under cervical surgery (most with spinal stenosis), the sensitivity and specificity of multimodal intraoperative monitoring (MIOM) (SEP, MEP, EMG) was assessed.[5] Of these, 232 patients were true negatives, 2 were false negatives, 2 false positives, while 10 were true positives (e.g. developed significant changes and new postoperative neurological deficits). The sensitivity of MIOM was 83.3%, and was specific in 99.2% of cases [Table 1].

### Predictive value of IONM (SEP, MEP, EMG) in 1055 cervical spinal operations (2008)

In Kelleher *et al*., prospective series of 1055 (average age 55) cervical operations, they documented the frequency of significant IONM (sensitivity, specificity, positive predictive values (PPVs), negative predictive values (NPVs)) changes and correlated these with the incidence of new postoperative neurological deficits.[19]

The IONM included; SEP (1055 patients), MEP (26 patients) patients, and EMG (427 patients). New postoperative deficits were observed in 34 patients (3.2%): 21 fully resolved, 9 showed partial improvements, while 4 were permanent. SEP sensitivity was 52%, and specificity was 100% (PPV 100%/NPV 97%), MEP sensitivity was 100%, and specificity 96% (PPV 96%/NPV 100%), while EMG sensitivity was 46%, with a specificity of 73% (PPV 3%/NPV 97%). They concluded that IONM helped prevent neurological damage during cervical spine surgery [Table 1].

### Combined 100% sensitivity of SEP/MEP in adult spinal deformity cases (2009)

Quraishi *et al*., retrospectively assessed IONM (SEP, EMG, MEP) in 102 spinal deformity/extensive thoracolumbar fusion cases.[24] Intraoperatively, successful recordings included; SEPs in 101 (99%), EMGs in 89 (87%), and MEPs in 12 of 16 (75%) cases. The overall combined sensitivity was 100%. Five true positives (4.95%) were noted for 2-SEP, 2-EMG, and 1-MEP. No SEPs resulted in false positives, but there were 4 false negatives (sensitivity to 33%); there were no false negatives for MEPs [Table 1].

### Value of SEP and MEP in avoiding brachial plexus injury attributed to positioning before anterior cervical spine surgery (2011)

Janahangiri documented that intraoperative SEP and MEP monitoring during anterior cervical spine surgery helped avoid brachial plexus injuries.[18] During draping for surgery in a 43 year old, SEP significantly deteriorated, and were followed by the loss of MEP. Removal of the tape on the shoulders allowed both potentials to recover shortly thereafter. As demonstrated in this case, IONM allowed for the immediate identification of SEP/MEP changes, and a potential positioning-related deficit was avoided [Table 1].

### Value of somatosensory evoked potentials (SEP) and transcranial motor evoked potentials (MEP) combined: 100% in cervical surgery (2012)

Li *et al*., discussed the value of intraoperative somatosensory-evoked potential (SEP) and transcranial electrical motor-evoked potential (TcMEPs) IONM during 200 spinal operations performed utilizing TIVA (total intravenous anesthesia).[22] Alert criteria for SEP included; a 50% decrease in amplitude, a 10% increase in latency, a unilateral change, or an increase in stimulation threshold (>100 V for TcMEP). Three SEP alerts were attributed to poor positioning of the arm (2 patients) and hypotension (1 patient). Four of 5 TcMEP alerts were due to hypotension, but 1 was attributed to cord compression by a bone graft. When all alerts were addressed intraoperatively, thresholds returned to normal values, and patients experienced no deficits. Interestingly, the relative sensitivities of SSEP and TcMEP alerts in detecting impending neurological damage were 37.5% and 62.5%; together, they were 100%. Additionally, there were no false-positive or false-negative alerts. Furthermore, TIVA maximized SEP and TcMEP evaluation intraoperatively (e.g., improved the sensitivity and specificity of intraoperative neural monitoring; IONM) [Table 1].

### MEP warning thresholds (amplitude) for cervical cord compression (2012)

In 350 cases, Sakaki *et al.*, correlated the levels of cervical spine surgery with outcomes and MEP loss (differentiating tracts, segments).[26] Potentials lost in 11 cases were directly attributed to the levels of spinal surgery; 2 developed subsequent neurological sequelae. However, for 43 cases in which MEP changes occurred below the level of surgery, there were no postoperative deficits. Although the authors determined that raising the warning threshold by 30% of the control amplitude would likely have avoided both motor deficits, it would also likely have resulted in 106 (30.3%) false positives. They therefore concluded; "dividing the warning threshold on the basis of origin of amplitude changes could reduce false-positive cases and prevent intraoperative injuries" [Table 1].

### Compartment syndrome avoided by loss of SEP and MEP during cervical surgery (2012)

Bronson *et al.*, described a case in which SEP and MEP were lost indicating a compartment syndrome evolving during a 2 level ACDF.[1] These early changes led to the discovery of an infiltrated intravenous line that, once removed, allowed the swelling to resolve. Had these changes not occurred, the patient would likely have developed a compartment syndrome, requiring a fasciotomy to avoid neuromuscular damage [Table 1].

### Significant changes/loss of IONM (SEP, MEP, EMG) over 25 years in 12,375 patients (2013)

Raynor *et al.*, evaluated the efficacy of IONM (SEP, MEP, EMG) in 12,375 patients involving the cervical (29.7% (3671)), thoracic/thoracolumbar (45.4% (5624)), and lumbosacral (24.9% (3080)) spine.[25] Of these, 77.8% (9633) were primary, and 22.2% (2742) involved secondary/revision procedures. IONM changes/loss occurred in 406 instances in 386 (3.1%) of 12,375 patients. These were attributed to; instrumentation ($n$=131), positioning ($n$=85), correction ($n$=56), systemic ($n$=49), unknown ($n$=24), and focal spinal cord compression ($n$=15). IONM changes/loss were more common in revision (6.1%/167) vs. primary (2.3%/219) surgery, and data improved following interventions in 88.7% ($n$=360) vs. 11.3% ($n$=46) of cases respectively. For 93.3% of patients, data recovered, and patients had no permanent neurological sequelae; only 15 (6.7%) had permanent deficits. The authors concluded that IONM effectively limited permanent postoperative neurological deficits (e.g., the overall frequency of permanent neurological sequelae was 0.12%) [Table 1].

### Value of MEP and EMG monitoring in cervical diskectomy (2013)

Fotakopoulos *et al.*, assessed the prospective value and efficacy of "free running" MEP and EMG monitoring during cervical microdiskectomy/fusion for 38 patients with cervical radiculopathy attributed to disc herniations.[17] Those demonstrating a 41% increase in TcMEP amplitude exhibited excellent postoperative results, while those with 11% increase in TcMEP amplitude had only fair results [Table 1].

### MEP role in surgery for cervical spondylotic myelopathy (CSM) (2013)

As MEP monitor the corticospinal tracts for patients with CSM, Capone *et al.*, correlated the preoperative and postoperative MEP with the clinical results of cervical spine surgery in 38 patients with CSM.[3] Clinical assessment utilized the 18-point modified Japanese Orthopedic Association (mJOA) obtained preoperatively (7-15 days) and postoperatively (6-12 months). MEP were employed to monitor central motor conduction times (CMCT) in the following distributions; biceps, abductor digiti minimi, and tibialis anterior muscles bilaterally. Postoperatively, the mJOA score increased significantly (10.1 to 15.1), and the CMCT for the tibialis anterior muscles showed a slight but significant reduction (better results for those with lesser deficits). The authors concluded that early surgery for CSM patients with lesser preoperative deficits correlated with better outcomes defined by improvement in MEP [Table 1].

## CONCLUSION

### MEP should become a routine addition to SEP/EMG intraoperative monitoring in cervical spine surgery

This review emphasizes that, in the future, MEP should be routinely incorporated into the IONM protocol for cervical spine surgery. Overwhelmingly, the recent literature supports the safety/efficacy as well as sensitivity and specificity of MEP monitoring and emphasizes how adding MEP to SEP/EMG IONM should provide maximal warnings of impending intraoperative injury and thereby minimize postoperative neurological deficits. Furthermore, anesthetic TIVA protocols allow for effective MEP monitoring while markedly reducing anesthesia-related loss of potentials [Table 1].

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