



Intraoperative neuromonitoring in spine deformity surgery: modalities, advantages, limitations, medicolegal issues – surgeons' views

Mirza Biscevic¹

Aida Sehic²

Ferid Krupic³

- In spine deformity surgery, iatrogenic neurologic injuries might occur due to the mechanical force applied to the spinal cord from implants, instruments, and bony structures, or due to ischemic changes from vessel ligation during exposure and cord distraction/compression during corrective manoeuvres.
- Prompt reaction within the reversible phase (reducing of compressive/distractive forces) usually restores functionality of the spinal cord, but if those forces continue to persist, a permanent neurological deficit might be expected.
- With monitoring of sensory pathways (dorsal column–medial lemniscus) by somatosensory-evoked potentials (SSEPs), such events are detected with a sensitivity of up to 92%, and a specificity of up to 100%.
- The monitoring of motor pathways by transcranial electric motor-evoked potentials (TceMEPs) has a sensitivity and a specificity of up to 100%, but it requires avoidance of halogenated anaesthetics and neuromuscular blockades.
- Different modalities of intraoperative neuromonitoring (IONM: SSEP, TceMEP, or combined) can be performed by the neurophysiologist, the technician or the surgeon. Combined SSEP/TceMEP performed by the neurophysiologist in the operating room is the preferable method of IONM, but it might be impractical or unaffordable in many institutions. Still, many spine deformity surgeries worldwide are performed without any type of IONM. Medicolegal aspects of IONM are different worldwide and in many cases some vagueness remains.
- The type of IONM that a spinal surgeon employs should be reliable, affordable, practical, and recognized by the medicolegal guidelines.

Keywords: intraoperative neuromonitoring; motor potentials; neurological deficit; safety; spinal deformity; medicolegal issue

Cite this article: *EFORT Open Rev* 2020;5:9-16.

DOI: 10.1302/2058-5241.5.180032

Introduction

Expectations of patients undergoing correction surgery for spinal deformity have been shifting toward the ideal spine shape. In most cases, surgeons can meet those expectations with new surgical techniques, improved spinal implants, perioperative care, safer anaesthesia, invention of cell saver, etc. Unfortunately, with more extensive surgeries, the intraoperative risk of spinal cord injury increases. This neurologic injury may occur due to direct mechanical force applied to the spinal cord (implants, instruments, bony structures), or due to indirect ischemic changes (vessel ligation during exposure, cord distraction/compression during corrective manoeuvres). Quick identification of impending spinal cord injury opens the window of opportunity to the surgeon and anaesthesiologist to act before the injury becomes irreversible. Therefore, the monitoring of gross motor and sensory function in spine deformity surgery is extremely important, especially when correcting spine deformities in the paediatric population presenting with additional neurological risk: neglected rigid kyphoscoliosis, congenital spine anomalies, revision spine surgeries, marfanoid patients with lordoscoliosis, etc.¹ Surgeons should understand the rationale and the clinical basis for intraoperative neuromonitoring (IONM), interpret the monitoring alerts, and utilize them for a better surgical outcome.² In addition to a surgeon, the neuromonitoring team is composed of clinical neurophysiologist, anaesthesiologist, and monitoring technician.³

The simplest and the oldest way of detecting gross motor function deficit is the Stagnara wake-up test. It is

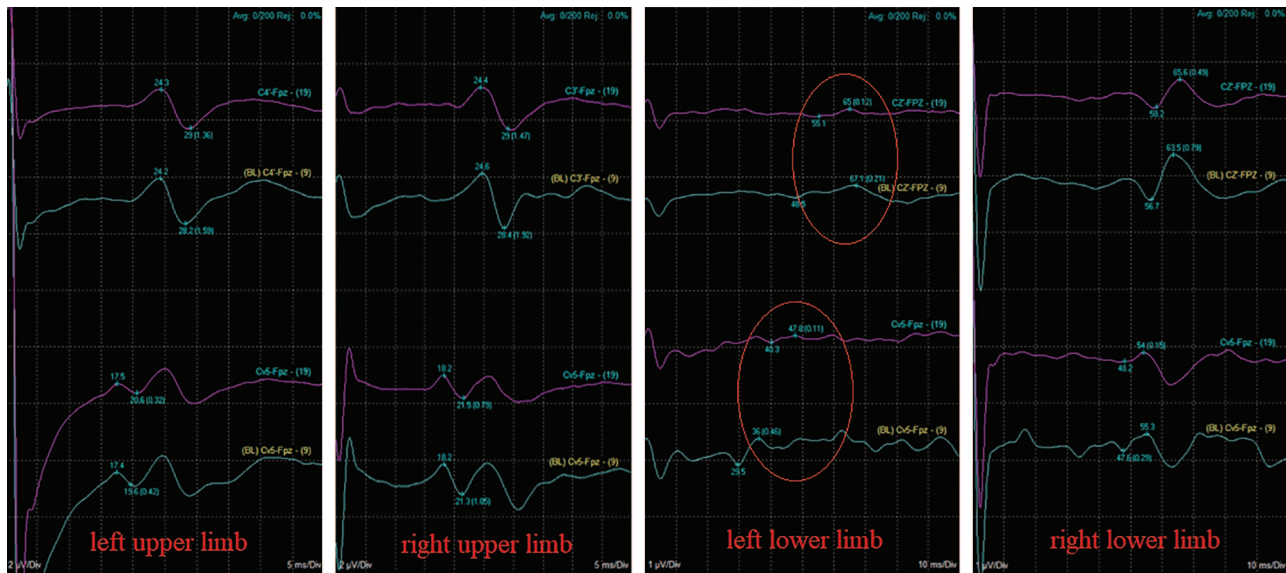


Fig. 1 Normal and altered somatosensory-evoked potentials (SSEPs): SSEP loss on left lower limb, concomitant to transcranial electric motor-evoked potential (TceMEP) loss (see Fig. 2.); blue line – baseline SSEP, purple line – SSEP during osteotomy; upper lines represent cortical, lower lines cervical responses; latency 27% (29.5 to 40.3 msec) of cervical response after stimulation of posterior tibial nerve; reduction of amplitude in left lower limb 76% (0.46 to 0.11) – red circles; rest of figure represents normal SSEPs.

based on intraoperative reduction of anaesthesia and asking the patient to move his/her limbs. This test is considered to be almost 100% accurate, while the limitations are mental disability, young age and pre-existing motor deficit. Its drawbacks are the risk of self-extubation, loss of intravenous lines, positioning on the operating table, air embolism, as well as potential psychological stress. Nowadays this test may be used only when neurophysiological recordings are unavailable or fail to return after excluding all technical, anaesthetic and surgical factors and when there is a problem of obtaining an IONM signal, as with patients suffering from thoracic myelopathy.⁴

The most commonly utilized IONM techniques include, but are not limited to: somatosensory-evoked potentials (SSEPs), transcranial electric motor-evoked potentials (TceMEPs) and electromyography (EMG).⁵ The aim of this review article is to present the clinical importance of IONM, its different technical modalities, its advantages, limitations, and legal issues.

Somatosensory-evoked potentials

The monitoring of somatosensory spinal pathways (dorsal column–medial lemniscus) is based on sub/cortical responses to continuous electrical stimulation of peripheral nerves (e.g. tibial, peroneal, ulnar/median nerve). Although sensory deficit is less debilitating than motor deficit, the monitoring of sensory pathways gives an insight into the function of motor pathways too, since the

ischemic or mechanic injury usually affects both pathways. This, the most common type of IONM, which is easy to implement, and has no contraindications. It may be sufficient for the posterior spine approach in spine deformity surgery as it has the range of sensitivity of 25–92%, and specificity of 96–100%.⁶

Latency increase of more than 10% and reduction of amplitude more than 50% in comparison to the baseline signals are highly suggestive of neurologic impairment.⁷ Halogenated or nitrous-oxide-based agents influence SSEP amplitude and latency, but SSEPs are generally more resistant to anaesthetics than MEPs.² Sevoflurane and desflurane may be used as long as the minimal alveolar concentration (MAC) of the inhaled agents is kept stable below 0.7%. The controlled intravenous application of sedatives and analgesics (midazolam, fentanyl/ketamine) along with N₂O also allows recording of stable SSEP parameters.^{8,9} Muscle relaxants do not affect SSEPs, in fact they might enhance the SSEP signal by decreasing electric noise by eliminating muscle artifacts (Fig. 1).

SSEP recording requires signal averaging, which results in a time lag before data interpretation (1–20 min). Therefore, an injury can be irreversible before it is even detected.² Further limitations of SSEPs are the monitoring of patients with pre-existing neurologic deficit (myelopathy, spinal cord tumour, peripheral neuropathy), or situations with the intraoperative isolated motor pathway or nerve root injury, which can be detected only by MEP or EMG type of recording.

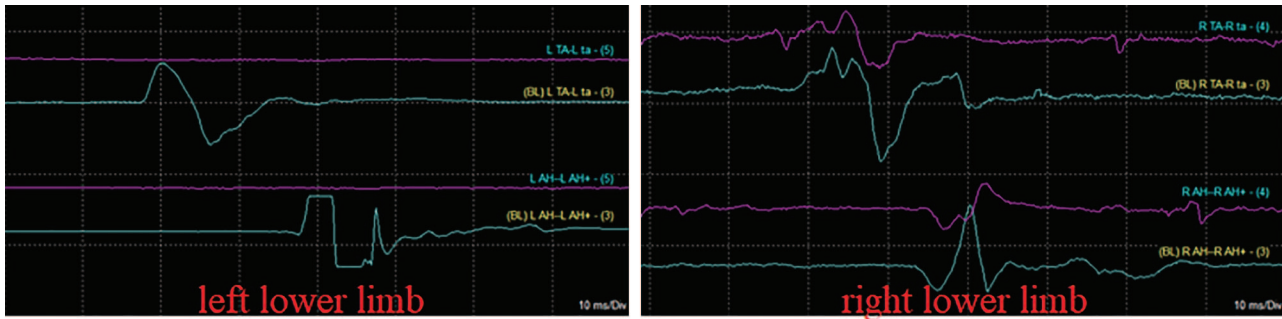


Fig. 2 Normal and altered motor-evoked potentials (MEPs): upper lines represent response of tibialis anterior, lower lines of abductor hallucis muscles; no response in both left lower limb muscles on the left side, normal response on the right side.

Motor-evoked potentials

MEPs directly monitor the function of the motor pathways in the anterior/central portions of the spinal cord and the nerve roots. These are very sensitive indicators of the corticospinal tract injury, and have proven to be very sensitive indicators of the spinal cord ischemia during spinal deformity correction.⁶ Spinal cord motor function monitoring is based on muscle responses to intermittent stimulation of the motor cortex in real time.

Transcranial stimulation as single high voltage or multiple small stimuli of the motor cortex can be magnetic, and, more commonly in the operating room, electric (TceMEP). Recording sites are at the end muscle, preferably muscles rich in corticospinal tract innervations such as distal limb muscles. Electromyography signals – compound motor action potential (CMAP) – are typically acquired through needle electrodes inserted bilaterally into the upper limbs as control to determine systemic, anaesthesia and positioning-related changes¹⁰ (abductor digiti minimi, the first dorsal interosseous or abductor pollicis brevis), and lower limbs (vastus lateralis, anterior tibialis, gastrocnemius medialis, abductor hallucis). TceMEP signals should have an amplitude $\geq 50 \mu\text{V}$ to be considered as a ‘monitorable’. A higher number of channels on the lower extremities provide a more reliable picture in the case of developing changes that do not necessarily affect all recording channels to the same degree. Unilateral or bilateral, reproducible decrease in TceMEP amplitude from the baseline greater than 60% should be considered as a ‘significant warning criteria’ in spine deformity surgery.¹¹ Since MEPs are much more unstable than SSEPs, other authors rather employ an interval of 50–80% amplitude reduction instead of a ‘cut off’ value (Fig. 2).¹²

MEP has high sensitivity (75–100%) and specificity (84%–100%)⁶ but it requires avoidance of halogenated anaesthetics (halothane, sevoflurane, isoflurane, etc.), and neuromuscular blockades (vecuronium, rocuronium etc.). Ketamine-based anaesthesia allows for appropriate

MEP recordings, but total intravenous anaesthesia (TIVA) with propofol is preferred.¹³

D-wave is subtype of MEP where the recording site is on the spinal cord. It is used together with other modalities of IONM in various spinal procedures,¹⁴ mostly in spinal cord tumour procedures,¹⁵ and in neurophysiological assessment of injured spinal cords.¹⁶ In scoliosis surgery its usage is not the primary method of choice due to low sensitivity (27%),¹⁷ absence of D-wave at the baseline, undeveloped neural system in children, and long-term injury of the spinal cord.

Electromyography

EMG is a type of ‘real-time’ neuromonitoring modality, mostly employed in detecting nerve root injuries during minimally invasive spine surgery, transpoas approaches, screw placements or decompressions.² Free-running EMG modality does not require stimulation, and it can be recorded continuously from preselected muscle groups based on the nerve roots at risk. If the nerve root is irritated, continuous electrical activity in the myotome is noted with 100% sensitivity, but only 23.5% specificity. An abnormal free-running EMG response during the spine procedure may or may not be associated with a clinical deficit, while normal response is predictive of the preserved nerve root.¹⁸ Extensive nerve root manipulation or impingement will elicit an increased activity, while an accidental cut of the nerve root will manifest as the absence of recorded electrical signal: ‘silence’.

Triggered EMG modality records the electrical activity of a certain muscle after stimulation (triggering) in the proximity of the corresponding nerve root. In application, bone has high impedance requiring a high threshold to stimulate the adjacent nerve. If the pedicle cortex is intact, high stimulation is necessary to evoke CMAP. When there is perforation of osseous pedicular wall, direct stimulation of a pedicular screw can activate the adjacent nerve root and evoke CMAP in the appropriate myotome at lower stimulus intensities than would be expected with the

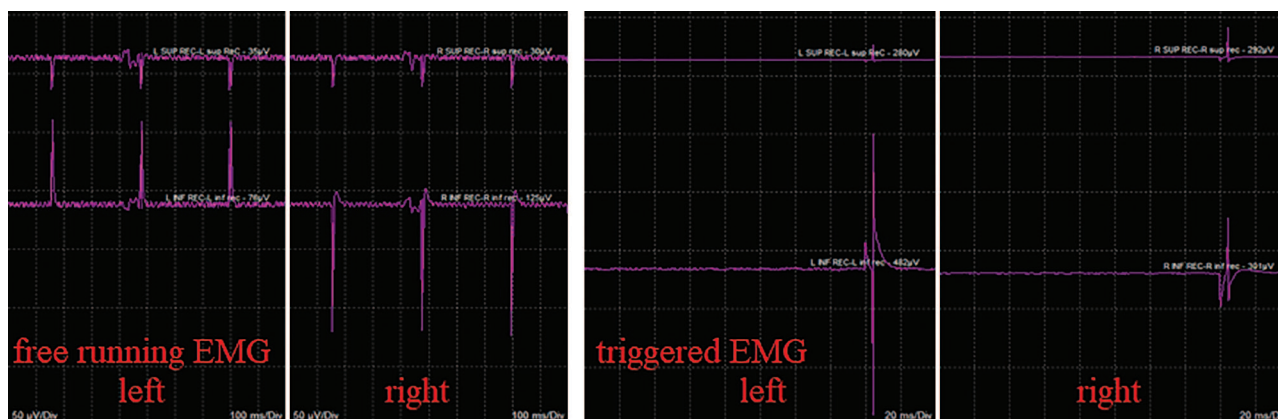


Fig. 3 Free-running and triggered electromyography (EMG); two purple lines on the left side show free-running EMG recorded in the upper and lower parts of the rectus abdominis muscle; right side – adequate response in left inferior rectus abdominis muscle after triggering of T10 left pedicle, indicating that there is no breach of pedicle.

imperforated pedicle cortex.¹⁹ A positive EMG response at or below a constant current of < 6–10 mA may be an indication of inspection, redirection, or removal of the instrument or implant.²⁰ Lall et al summarize data from few studies concluding that triggered EMG has a high rate of false-positive alarms, without clinical correlation.⁶ Both trigger and free-running EMG requires total avoidance of neuromuscular blockade (Fig. 3).

Multimodality intraoperative neuromonitoring

In general, 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. In cases in which spinal cord deficits are most likely (spine deformity surgery, intradural tumours), multimodal IONM is highly recommended. After selection of the appropriate monitoring modality, the anaesthesiologist should adjust anaesthetic agents to allow the best obtainable IONM recordings.²¹ If transcranial MEPs are being used, halogenated anaesthetics are contraindicated, and TIVA will optimize signal acquisition. MEPs and any form of EMG monitoring preclude the use of neuromuscular blockade.

Although several false-negative results have been reported with SSEP, just one article has reported false-negative MEPs during an operation.²² When SSEPs and MEPs are combined in spine deformity surgery, the sensitivity to detection of permanent motor and sensory neurologic injury during spinal deformity surgery is 99.6–100%,²³ and the specificity is 84–100%.⁶ But, false-negative results can still be found even with a combined IONM. Diab et al reported a group of 1301 adolescent idiopathic scoliosis

(AIS) patients; all were monitored using both SSEPs and MEPs. One patient had no changes identified during the combined monitoring, but he still awoke with a spinal cord injury that resolved spontaneously within three months (Table 1).²⁴

Vitale et al established a consensus-based ‘Checklist for the response to IONM changes’. After announcement to the OR personnel (stop the unnecessary conversation and traffic in the room, summon attending anaesthesiologist and senior neurophysiologist, anticipate the need for imaging – C/O arm, etc.) and checking of electrodes, neck and limb positions, the anaesthesiologist will optimize mean arterial pressure, haematocrit, oxygenation, and pH. The next step would be discussion with the anaesthesiologist about anaesthetic agents (neuromuscular blockade, MAC, etc.) and discussion with the whole team about the actions prior to the signal loss. Accordingly, reversal actions would be tackled (removing of traction or other correcting forces, removing rod/screws, examine spinal cord for compression – osteotomy site, intraoperative imaging – malpositioned screws). Continuation of SSEP and/or TceMEP signal degradation indicates a wake-up test, steroid protocol, and consultation with a college (completing or staged surgery).¹¹ The same algorithm is generally accepted.²⁵

Postoperative neurological deficit after spine deformity surgery is also possible. Its incidence is 0.01%, mostly appearing during the first 24 hours. Forty-one per cent of affected patients experience complete neurologic recovery, 26% partial, and 33% no recovery.²⁶ None of the monitoring techniques are able to predict a delayed-onset paraplegia that appears after the surgery. Postoperative imaging studies should be conducted to discover the cause of the neurologic deficit (epidural haematoma, misplaced screw, spinal cord ischemia secondary to excessive tensioning, etc.) without any unnecessary delay. Early decompression may improve the neurologic outcome for

Table 1. Advantages, limitations, alarm criteria, anaesthetic requirements, sensitivity and specificity of SSEP, MEP and EMG neuromonitoring

	Monitoring	Advantages	Limitations	Alarm criteria	Anaesthetic requirements	Sensitivity	Specificity
SSEP	Functional integrity of sensory pathways	Continuous monitoring: firm warning criteria More recording sites, more reliable result. Generally better resistance of anaesthetics than MEP	Signal averaging results in time delay: injury can be irreversible before detection Influence of halogenated and nitrous-oxide-based agents	Latency increase > 10%, signal decrease > 50%	Intravenous anaesthesia, eventually dexmedetomidine	25–92%	96–100%
MEP	Functional integrity of motor pathways	Real-time monitoring, instant, no averaging Reliable even after posterior myelotomy More sensitive to ischemia Less sensitive to electrical noise	Requires total intravenous anaesthesia without neuromuscular blockade Movements Contraindicated in seizures and pace makers Wide warning criteria	Signal decrease > 50–75%	Total intravenous anaesthesia, no halogenated agents or neuromuscular blockade	75–100%	84–100%
EMG	Functional integrity of peripheral nerves	Constant feedback, Combined with SSEP improved specificity, Easy performance and interpretation	High rate of false positives Very sensitive on temp. changes and cautery Triggered EMG: only insight in pedicle integrity	No firm alarm criteria	Avoidance of neuromuscular blockade	Free-running: 100% Triggered: 99.5%	Free-running: about 23% Triggered: low
Multimodal IONM	All of the above	Both modalities together improve sensitivity and specificity: most reliable	Highly trained personnel Technical requirements Cost	Avoidance of each of the above-mentioned limitations with adjusted anaesthetic protocols will provide sensitivity of 100% and specificity of 84–100%.			

Note. SSEP, somatosensory-evoked potentials; MEP, motor-evoked potentials; EMG, electromyography; IONM, intraoperative neuromonitoring.

the patient with a new onset of neurologic deficit in the acute postoperative period. Conversely, if no abnormality is identified on computed tomography (CT) or magnetic resonance imaging (MRI) scan, the patient should be closely observed with a supportive treatment.¹⁹

Who can carry out neuromonitoring?

Monitoring services during a surgery may be provided by a variety of personnel with different education, annual volume, work per case, and types of cases.²⁷ Technologists acquire the intraoperative data and relay the information to the surgeon, anaesthesiologist, neurologist, neurophysiologist, or another professional for interpretation. Interpretation may be carried out in the operating room or by remote internet consultation (telemedicine) on a continuous or intermittent basis, but no more than three cases can be followed simultaneously. Surgeons should understand the qualifications and roles of the personnel responsible for data acquisition and the interpretation of intraoperative neurophysiological data monitoring.²⁸

Finally, an appropriate standard of care relating to IONM is difficult to devise because of national variance with regard to qualifications of neurophysiologic, technical and professional personnel, different levels of training and certification, and anaesthesia protocols²⁹ and IONM service availability. According to a web-based survey among surgeons in Canada on their attitude to the interpretation of IONM, most of the interpretation is performed

by either technologists or by surgeons themselves. Most surgeons would prefer professional oversight by the neurologist or neurophysiologist at the doctoral level. There appears to be a shortage of qualified personnel and a lack of Canadian guidelines for the performance of this task.³⁰ A survey from 2011 of 117 French spinal surgeons showed that only 36% had neurophysiological monitoring available (public healthcare facilities, 42%; private facilities, 27%).³¹ In the article by Siller et al from 2019, based on a survey in German-speaking countries (Germany, Austria, Switzerland), about 76% of neurosurgical and 15% of orthopaedic spine centres utilize IONM. The main modalities were MEP and SSEP, and the main indications were scoliosis and intradural spinal tumour surgeries. IONM utilization was low in spine surgeries for degenerative, traumatic, and extradural tumour diseases. A more frequent IONM use, however, was mainly limited due to the shortage of skilled staff and restricted reimbursement.³²

Authors' view

Apart from the patient's safety, IONM encourages surgeons to achieve better curve correction, and reduces his/her stress. In the US and other developed countries, multimodal IONM in spine deformity surgery is a standard of care and obligatory, but worldwide many surgeons perform spine surgeries without any type of IONM.

Some IONM devices have 'surgeon-directed MEP mode', where a surgeon can easily set up the system, and

monitor the signals during the surgery.³³ Interpretation of MEPs that represent a gross motor function of the lower limbs, in relation to the current action of the surgeon or anaesthesiologist, is not a problem for a high-volume spine surgeon. There are some reports about IONMs monitored by surgeons,^{30,31,33} although there was some criticism, especially of the statement 'Whatever the monitoring technique used, it remains preferable to the absence of monitoring'.³⁴

We have done our best to discover legal aspects of IONM in different countries, but there is no common approach. Medicolegal aspects of IONM are different worldwide and in many cases some vagueness remains. Finally, the surgeon and/or hospital responsible for the IONM services must be sure that each provider has adequate training and experience, consistent with the national legislation.

Discussion

A fear of complications, especially neurological ones, is experienced by both patients and physicians. Prior to surgery, the complication rate can be diminished by optimizing factors such as general condition, anaemia, pulmonary function, etc. During surgery, proper monitoring of cardiopulmonary, urinary and spinal cord functions can additionally decrease the overall complication rate. Neuromonitoring recognizes functional changes in the spinal cord, usually in the reversible phase, when prompt reaction prevents a neurological complication. If distractive/compressive forces persist, neurologic deficit may be expected.^{35–37}

In the pre-IONM era, the rate of permanent paraplegia was 0.4% according to the Scoliosis Research Society's database from 1975,³⁸ while in the IONM era the reported incidence of major neurologic injury is from 0.4% to 1.9%. This can be explained by different methodologies of the mentioned studies and more aggressive surgeries nowadays. In the article by Schwartz et al from 2007, there was no permanent neurological deficit in a group of 1121 MEP/SSEP-monitored scoliosis surgeries, although the relevant signal changes were noted in 3.4% surgeries.³⁹ IONM significantly decreases risk in spinal surgeries, and today it is the standard of care in the US and many other developed countries. Multimodal IONM is accurate and comfortable for spine surgeons, but it may be unaffordable to many of them. The monitoring of MEP alone is a safe, simple and feasible modality in spine deformity surgeries, but multimodal IONM is a superior method.⁴⁰ If the choice is to be made between MEP and SSEP, the former is a better option.⁴¹ The surgeon-directed MEP type of IONM allows the surgeon to perform it alone with minimal engagement during the surgery. Everything else requires the surgeon's ability to interpret the amplitudes and

correlate them with the situation in the operative field and anaesthesia parameters.³³ It should not be the first solution for serious spinal surgeries since experienced neuro-monitoring teams had fewer than one-half as many neurologic deficits per 100 cases compared to teams with relatively little monitoring experience.²⁷ However, surgeon-directed MEP is a better option than no IONM, disregarding its limitations and consequences.

The average four-hour spine case SSEPs costs US\$942, and Tce-MEPs US\$1115, and US\$1423 in combination.⁴² Except the costs and duration of anaesthesia due to MEP/SSEP setting, IONM has no adverse effects. Large retrospective reviews have revealed the incidence of tongue lacerations to be about 0.2%,⁴³ and seizures 0.03% related to IONM.⁴⁴ On the other hand, IONM was significantly associated with increased home discharge and lower risk of neurologic complications, while hospital charges and length of hospitalization were not affected by IONM.⁴⁵

IONM is also utilized for other spine surgery indications: tethered cord, injured spinal cord, intramedullary tumours, extramedullary tumours, minimally-invasive surgery, cervical myelopathy, as well in other fields of surgery: cranial, vascular, cardiothoracic, etc. It is helpful in preventing perioperative peripheral nerve injury (PPNI) due to excess mechanical pressure and torsion of the limbs and neck. Prone patient positioning is designed to achieve optimal exposure and operative conditions; however, it might be potentially harmful due to over-prolonged contact with the operating table frames.^{10,46,47} Most commonly observed are positioning brachial plexopathies with a risk of 6.2% in Labrom et al's study,⁴⁸ and 3.6% in Schwartz et al's study.⁴⁹ Repositioning the arm(s) or shoulder(s) resulted in nearly immediate improvement of amplitude of SSEP, resulting in postoperative neurologically intact patients.⁴⁹

Finally, combined SSEP/MEP modality performed until the wound closure⁵⁰ has the highest reliability in spine deformity surgeries,^{6,11} and should be the IONM option that surgeons insist on. Perioperatively, close follow-up, especially in the first 48 hours, and prompt action if needed is also mandatory.²⁶ Maintaining a high quality of practice with correct application, and an appropriately trained team is critical.⁵¹

Conclusion

Patient selection, preoperative planning, surgical technique and diligent IONM with frequent perioperative neurologic examination are the key points in prevention of neurodeficit in spine deformity surgeries. The type of IONM that the spinal surgeon employs should be reliable, affordable, practical, and recognized under the relevant national law. Combined SSEP/MEP performed by the neurophysiologist is the preferable method of IONM in surgeries of paediatric spine deformities.

AUTHOR INFORMATION

¹Department of Orthopedics, General Hospital Sarajevo, Bosnia and Herzegovina.

²Department of Intraoperative Neurophysiologic Monitoring, SMS, Louisville, Kentucky, USA.

³Department of Orthopedics, Sahlgrenska Academy at University of Gothenburg, Sweden.

Correspondence should be sent to: Mirza Biscevic, General Hospital Sarajevo, Kranjceviceva 13, 71000 Sarajevo, Bosnia & Herzegovina.
Email: info@dr.biscevic.ba

ICMJE CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest relevant to this work.

FUNDING STATEMENT

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

LICENCE

© 2020 The author(s)

This article is distributed under the terms of the Creative Commons Attribution-Non Commercial 4.0 International (CC BY-NC 4.0) licence (<https://creativecommons.org/licenses/by-nc/4.0/>) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed.

REFERENCES

- Gavaret M, Pesenti S, Pennaroli D, et al.** Intraoperative neuromonitoring in pediatric spinal deformity surgery: risk factors analysis about 1048 cases. *Clin Surg* 2019;2455:1–7.
- Park JH, Hyun SJ.** Intraoperative neurophysiological monitoring in spinal surgery. *World J Clin Cases* 2015;3:765–773.
- Sung-Min K, Seung Hyun K, Dae-Won S, Kwang-Woo L.** Intraoperative neurophysiologic monitoring: basic principles and recent update. *J Korean Med Sci* 2013;28:1261–1269.
- Girardi FP, Boachie-Adjei O, Rawlins BA.** Safety of sublaminar wires with Isola instrumentation for the treatment of idiopathic scoliosis. *Spine (Phila Pa 1976)* 2000;25:691–695.
- Tamaki T, Kubota S.** History of the development of intraoperative spinal cord monitoring. *Eur Spine J* 2007;16:S140–S146.
- Lall RR, Lall RR, Hauptman JS, et al.** Intraoperative neurophysiological monitoring in spine surgery: indications, efficacy, and role of the preoperative checklist. *Neurosurg Focus* 2012;33:E10.
- Devlin VJ, Schwartz DM.** Intraoperative neurophysiologic monitoring during spinal surgery. *J Am Acad Orthop Surg* 2007;15:549–560.
- Strahm C, Min K, Boos N, Ruetsch Y, Curt A.** Reliability of perioperative SSEP recordings in spine surgery. *Spinal Cord* 2003;41:483–489.
- Langeron O, Lille F, Zerhouni O, et al.** Comparison of the effects of ketamine-midazolam with those of fentanyl-midazolam on cortical somatosensory evoked potentials during major spine surgery. *Br J Anaesth* 1997;78:701–706.
- Biscevic M, Sehic A, Biscevic S, et al.** Kyphosis: a risk factor for positioning brachial plexopathy during spinal surgeries. *Acta Orthop Traumatol Turc* 2019;53:199–202.
- Vitale MG, Skaggs DL, Pace GI, et al.** Best practices in intraoperative neuromonitoring in spine deformity surgery: development of an intraoperative checklist to optimize response. *Spine Deform* 2014;2:333–339.
- Langeloo DD, Lelivelt A, Louis Journée H, Slappendel R, de Kleuver M.** Transcranial electrical motor-evoked potential monitoring during surgery for spinal deformity: a study of 145 patients. *Spine (Phila Pa 1976)* 2003;28:1043–1050.
- Stecker MM.** A review of intraoperative monitoring for spinal surgery. *Surg Neurol Int* 2012;3:S174–S187.
- Costa P, Peretta P, Faccani G.** Relevance of intraoperative D wave in spine and spinal cord surgeries. *Eur Spine J* 2013;22:840–848.
- Kothbauer KF.** Neurosurgical management of intramedullary spinal cord tumors in children. *Pediatr Neurosurg* 2007;43:222–235.
- Costa P, Faccani G, Sala F, Montalenti E, Giobbe ML, Deletis V.** Neurophysiological assessment of the injured spinal cord: an intraoperative approach. *Spinal Cord* 2014;52:749–757.
- Ulkatan S, Neuwirth M, Bitan F, Minardi C, Kokoszka A, Deletis V.** Monitoring of scoliosis surgery with epidurally recorded motor evoked potentials (D wave) revealed false results. *Clin Neurophysiol* 2006;117:2093–2101.
- Leppanen RE.** Intraoperative monitoring of segmental spinal nerve root function with free-run and electrically-triggered electromyography and spinal cord function with reflexes and F-responses: a position statement by the American Society of Neurophysiological Monitoring. *J Clin Monit Comput* 2005;19:437–461.
- Butler JS, Lenke GL.** The incidence and management of acute neurologic complications following complex adult spinal deformity surgery. In: Vialle LR, ed. *AO spine masters series: adult spinal deformities*. Vol. 4. New York: Thieme Medical Publishers, 2015:68–77.
- Glassman SD, Dimar JR, Puno RM, Johnson JR, Shields CB, Linden RD.** A prospective analysis of intraoperative electromyographic monitoring of pedicle screw placement with computed tomographic scan confirmation. *Spine (Phila Pa 1976)* 1995;20:1375–1379.
- Sloan TB, Heyer EJ.** Anesthesia for intraoperative neurophysiologic monitoring of the spinal cord. *J Clin Neurophysiol* 2002;19:430–443.
- Modi HN, Suh SW, Yang JH, Yoon JY.** False-negative transcranial motor-evoked potentials during scoliosis surgery causing paralysis: a case report with literature review. *Spine (Phila Pa 1976)* 2009;34:E896–E900.
- Chen B, Chen Y, Yang J, et al.** Comparison of the wake-up test and combined TES-MEP and CSEP monitoring in spinal surgery. *J Spinal Disord Tech* 2015;28:335–340.
- Diab M, Smith AR, Kuklo TR; Spinal Deformity Study Group.** Neural complications in the surgical treatment of adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)* 2007;32:2759–2763.
- Bjerke BT, Zuchelli DM, Nemani VM, Emerson RG, Kim HJ, Boachie-Adjei O.** Prognosis of significant intraoperative neurophysiologic monitoring events in severe spinal deformity surgery. *Spine Deform* 2017;5:117–123.
- Auerbach JD, Kean K, Milby AH, et al.** Delayed postoperative neurologic deficits in spinal deformity surgery. *Spine (Phila Pa 1976)* 2016;41:E131–E138.
- Nuwer MR, Dawson EG, Carlson LG, Kanim LE, Sherman JE.** Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. *Electroencephalogr Clin Neurophysiol* 1995;96:6–11.
- Skinner SA, Cohen BA, Morledge DE, et al.** Practice guidelines for the supervising professional: intraoperative neurophysiological monitoring. *J Clin Monit Comput* 2014;28:103–111.

- 29. Dormans JP.** Establishing a standard of care for neuromonitoring during spinal deformity surgery. *Spine (Phila Pa 1976)* 2010;35:2180–2185.
- 30. Norton JA, Aronyk KE, Hedden DM.** Interpretation of surgical neuromonitoring data in Canada: a survey of practising surgeons. *Can J Surg* 2015;58:206–208.
- 31. Gavaret M, Jouve JL, Pereonc Y, et al.** Intraoperative neurophysiologic monitoring in spine surgery: developments and state of the art in France in 2011. *Orthop Traumatol Surg Res* 2013;99:S319–S327.
- 32. Siller S, Raith C, Zausinger S, Tonn JC, Szelenyi A.** Indication and technical implementation of the intraoperative neurophysiological monitoring during spine surgeries: a transnational survey in the German-speaking countries. *Acta Neurochir (Wien)*. 2019;161:1865–1875.
- 33. Bisevcic M, Bisevcic S, Ljuca F, Smrke BU, Ozturk C, Tiric-Campara M.** Motor evoked potentials in 43 high risk spine deformities. *Med Arch* 2014;68:345–349.
- 34. Deletis V, Mac Donald DB, Sala F, Fernandez Conejero I.** Comments on: ‘Intraoperative neurophysiologic monitoring in spine surgery. Developments and state of the art in France in 2011’ written by M. Gavaret et al. published in *Orthop Traumatol Surg Res* 2013;99:S319–S327. *Orthop Traumatol Surg Res* 2014;100:353–354.
- 35. Hong JY, Suh SW, Lee SH, et al.** Continuous distraction-induced delayed spinal cord injury on motor-evoked potentials and histological changes of spinal cord in a porcine model. *Spinal Cord* 2016;54:649–655.
- 36. Jarvis JG, Strantzis S, Lipkus M, et al.** Responding to neuromonitoring changes in 3-column posterior spinal osteotomies for rigid pediatric spinal deformities. *Spine (Phila Pa 1976)* 2013;38:E493–E503.
- 37. Shah PA.** Transcranial motor evoked potential monitoring outcome in the high-risk brain and spine surgeries: correlation of clinical and neurophysiological data – An Indian perspective. *Ann Indian Acad Neurol* 2013;16:609–613.
- 38. MacEwen GD, Bunnell WP, Sriram K.** Acute neurological complications in the treatment of scoliosis: a report of the Scoliosis Research Society. *J Bone Joint Surg Am* 1975;57:404–408.
- 39. Schwartz DM, Auerbach JD, Dormans JP, et al.** Neurophysiological detection of impending spinal cord injury during scoliosis surgery. *J Bone Joint Surg Am* 2007;89:2440–2449.
- 40. Hong JY, Suh SW, Modi HN, Hur CY, Song HR, Park JH.** False negative and positive motor evoked potentials in one patient: is single motor evoked potential monitoring reliable method? A case report and literature review. *Spine (Phila Pa 1976)* 2010;35:E912–E916.
- 41. Dong CC, MacDonald DB, Janusz MT.** Intraoperative spinal cord monitoring during descending thoracic and thoracoabdominal aneurysm surgery. *Ann Thorac Surg* 2002;74:S1873–S1876.
- 42. Traynelis VC, Abode-Iyamah KO, Leick KM, Bender SM, Greenlee JD.** Cervical decompression and reconstruction without intraoperative neurophysiological monitoring. *J Neurosurg Spine* 2012;16:107–113.
- 43. Schwartz DM, Sestokas AK, Dormans JP, et al.** Transcranial electric motor evoked potential monitoring during spine surgery: is it safe? *Spine (Phila Pa 1976)* 2011;36:1046–1049.
- 44. Macdonald DB, Skinner S, Shils J, Yingling C; American Society of Neurophysiological Monitoring.** Intraoperative motor evoked potential monitoring: a position statement by the American Society of Neurophysiological Monitoring. *Clin Neurophysiol* 2013;124:2291–2316.
- 45. George J, Das S, Egger AC, Chambers RC, Kuivila TE, Goodwin RC.** Influence of intraoperative neuromonitoring on the outcomes of surgeries for pediatric scoliosis in the United States. *Spine Deform* 2019;7:27–32.
- 46. Hazarika A, Rath GP.** Modified prone positioning for dorsal spine surgery in a patient with postural deformity due to spasticity of lower limbs. *J Clin Anesth* 2014;26:582–584.
- 47. Kamel I, Barnette R.** Positioning patients for spine surgery: avoiding uncommon position-related complications. *World J Orthop* 2014;5:425–443.
- 48. Labrom RD, Hoskins M, Reilly CW, Tredwell SJ, Wong PK.** Clinical usefulness of somatosensory evoked potentials for detection of brachial plexopathy secondary to malpositioning in scoliosis surgery. *Spine (Phila Pa 1976)* 2005;30:2089–2093.
- 49. Schwartz DM, Drummond DS, Hahn M, Ecker ML, Dormans JP.** Prevention of positional brachial plexopathy during surgical correction of scoliosis. *J Spinal Disord* 2000;13:178–182.
- 50. Buckwalter JA, Yaszay B, Ilgenfritz RM, Bastrom TP, Newton PO; Harms Study Group.** Analysis of intraoperative neuromonitoring events during spinal corrective surgery for idiopathic scoliosis. *Spine Deform* 2013;1:434–438.
- 51. Minahan RE.** Intraoperative neuromonitoring. *Neurologist* 2002;8:209–226.