Intraoperative Neurophysiological Monitoring in Spinal Lesions Surgeries

Mostafa Mohy El Deen, Atef El Kelany, Sherif Abd El Raaof, Ahmed Esam Nasr Mohamed

Department of Neurosurgery, Faculty of Medicine, Zagazig University, Egypt.

Corresponding author: Ahmed Esam Nasr Mohamed

E-mail: ahmedelzorokany@gmail.com

Conflict of interest: None declared.

Funding: No funding sources

Abstract

Although relatively infrequent, neurological injury is a much dreaded complication in spine surgery and has the potential to result in serious postoperative motor and sensory deficits. In recent years, an increase in the utilization of intraoperative neurophysiological monitoring (IONM) has been noted in an effort to avert these neurological complications. This technology allows intraoperative assessment of spinal cord function through real-time feedback from sensory tracts, motor tracts, and individual nerve roots. Currently, the most commonly employed IONM techniques for spinal procedures include (1) somatosensory sensory evoked potentials (SSEPs), (2) motor-evoked potentials (MEPs), and (3) spontaneous and triggered electromyography (EMG). Despite advancements in the understanding of IONM and the popularity of this technique in modern spine surgery, controversies still exist regarding its effectiveness and the necessity for its use in routine spinal procedures. Also, as modern health care shifts toward value-based systems, questions arise as to the exact cost-effectiveness of IONM.

Keywords: Intraoperative ,neurophysiological monitoring, spinal lesions surgeries

Tob Regul Sci.™ 2023 ;9(1): *7727 - 7739*

DOI: doi.org/10.18001/TRS.9.1.546

Introduction

Although relatively infrequent, neurological injury is a much dreaded complication in spine surgery and has the potential to result in serious postoperative motor and sensory deficits. In recent years, an increase in the utilization of intraoperative neurophysiological monitoring (IONM) has been noted in an effort to avert these neurological complications. This technology allows intraoperative assessment of spinal cord function through real-time feedback from sensory tracts, motor tracts, and individual nerve roots [1].

Currently, the most commonly employed IONM techniques for spinal procedures include (1) somatosensory sensory evoked potentials (SSEPs), (2) motor-evoked potentials (MEPs), and (3) spontaneous and triggered electromyography (EMG) [2].

Despite advancements in the understanding of IONM and the popularity of this technique in modern spine surgery, controversies still exist regarding its effectiveness and the necessity for its use in routine spinal procedures. Also, as modern healthcare shifts toward value-based systems, questions arise as to the exact cost-effectiveness of IONM [3].

Types of Neurophysiological Monitoring

There are different techniques, which complement each other, depending on whether any of the following parameters have been checked [4]:

Integrity of the motor pathway. Usually measured with motor evoked potentials (MEPs) or with direct wave recording (D waves) with epidural electrodes.

Functional integrity of the sensory pathways. Usually performed with somatosensory evoked potentials (SSEPs).

Integrity of nerve routes. Monitored by spontaneous or stimulated electromyogram (EMG).

The combination of several procedures (multimodal monitoring) will optimize recording, since the isolated use of each could lead to false negatives (Table 2) [5].

Table (1): Strengths and weaknesses of the different types of monitoring [5].

Type of Monitoring	Strengths	Weaknesses
SSEP	Allows continuous monitoring throughout the surgery Does not preclude the use of neuromuscular blockade	Its interpretation requires temporal summation, which can delay the detection of a signal change by up to 16 minutes Unable to detect motor changes Individual nerve root function is not effectively monitored by SSEPs
tcMEP	Allows monitoring of the entire motor pathway (cortex, corticospinal tract, nerve root, peripheral nerve) Sensitive in the detection of postoperative motor deficits Sensitive for detecting spinal cord ischemia	Does not allow for continuous monitoring Precludes use of neuromuscular blockade Highly sensitive to inhalational anesthetics, demanding rigid anesthetic protocols
Spontaneous EMG	Sensitive for nerve root injury Provides real-time information	Sensitive to temperature changes

	about nerve root function throughout surgery May be combined with SSEPs to improve specificity	High rate of false positive alarms Precludes use of neuromuscular blockade
Triggered EMG	High sensitivity for medial pedicle wall breach Useful in minimally invasive surgery where anatomical landmarks may be challenging to visualize Relatively easy technique	Accepted set thresholds not firmly established Less sensitive for thoracic pedicle screws than for lumbar pedicle screws High rate of false positive alarms

Somatosensory Evoked Potentials (SEPs)

In theory, SEPs can be obtained by stimulating almost all peripheral sensory nerves. However, bilateral median or ulnar SEPs for the upper extremities and bilateral tibial or peroneal SEPs for the lower extremities are used in most cases. Bilateral median or ulnar SEPs are obtained by stimulating bilateral wrists and recorded with the following hemispheric montages: C3'-Fz (right median or ulnar nerve); C4'-Fz (left median or ulnar nerve) [6].

Bilateral peroneal or tibial SEPs are obtained by stimulating bilateral ankles and recorded with a midline montage of Cz'-FPz' (Cz', right and left tibial or peroneal nerve; reference, FPz') according to the international 10–20 electroencephalography system. Stimulation intensities are usually around 10–20 mA but depend on the patient's neural condition [7].

Unlike MEPs, SEPs do not elicit the patient's truncal movement; therefore, continuous acquisition of SEP waves is possible at regular intervals. Compared to MEPs, SEPs are hardly affected by the muscle relaxant used during intubation, and a meaningful waveform can be obtained even before the muscle relaxant effect disappears. After confirming the baseline waveform, sequentially obtained waveforms are compared to that acquired at baseline in terms of amplitude, latency, and morphology [8].

The consensus for alarm criteria has been established for decades. The most critical and definite alarm criterion is the sudden disappearance of the waveform, which could be evidence of neural transection. In addition to this criterion, the other current alarm criterion is as follows: latency prolongation > 10% or amplitude reduction > 50%, compared to the baseline values [9].

If this alarm criterion is exceeded, the postoperative prognosis is likely to be poor; therefore, if deterioration of SEPs is observed near the alarm level during surgery, it is recommended to inform the surgeon and anesthesiologist of this situation and to look at the surgical site in advance [10].

Moreover, IONM professionals should always be alert to confirm the cause of the electrophysiological changes and differentiate them from possible various artifacts or technical errors. For example, if the latency of SEPs is continuously delayed from the beginning of the surgery and exceeds 10% of the baseline value, it may be because the surgical site has been exposed to cold conditions for a long time or because the blood pressure is constantly decreasing for certain reasons [11].

In this case, IONM professionals should communicate with the anesthesiologist to check the patient's body temperature or blood pressure. If hypothermia or hypotension is confirmed, correction of the condition can result in the return of the SEP parameters to their baseline values in some cases. Multimodal monitoring with a combination of MEPs and D waves has been recommended in spinal cord tumor (SCT) surgery for favorable long-term outcomes [12].

The sensitivity and specificity of the test used to predict postoperative motor deterioration in SCT surgery are known to be lower in SEPs than in MEPs. Although SEPs do not directly reflect the neurophysiological function of the corticospinal tract, SEPs are monitored to enhance the specificity of IONM in combination with MEPs [13].

Moreover, there have been reports of cases in which postoperative motor deterioration was observed, even though only SEP was significantly changed without MEP change. SEP mapping is sometimes used to find the midline of the spinal cord to reduce the possible neural insult during myelotomy in intramedullary spinal cord tumor (IMSCT) surgery [8].

Motor Evoked Potentials (MEPs)

Motor evoked potentials (MEPs) can be obtained in several ways, such as through transcranial electrical stimulation (TES), epidural stimulation, and subcortical stimulation. However, TES-MEPs are usually used in SCT removal surgeries where craniotomy is not required [14].

Transcranial Electrical Stimulation-Motor Evoked Potentials (TES-MEPs)

TES-MEPs can be obtained from any muscle in the extremities. It is recommended that TES-MEPs be recorded in at least two muscles within one extremity for precise monitoring. Identifying differences in MEP responses of different muscles within one extremity helps to discriminate artifacts during monitoring. In the case of a patient suspected of postoperative motor deterioration of the right lower limb after surgery, it is recommended to monitor MEPs of two or more muscles of the right lower limb and compare them with those of the left side [15].

Train stimuli consisting of 5–7 square-wave stimuli with a 1–4 ms interstimulus interval are used rather than a single stimulus because of the muscle MEP's build-up effect. For stimulation, the interhemispheric montage of C1/C2 or C3/C4 is commonly used so that simultaneous bilateral stimulation is possible. Unlike SEPs, MEP waves are not obtained by averaging, so that the responses may appear slightly different for each stimulus [16].

Particularly, in patients whose baseline MEP amplitude is not large, even a small change can affect the reliability of the examination; therefore, these characteristics should be carefully considered and tested with a real-time interpretation by a skilled IONM professional. The absolute alarm criterion for persistent postoperative motor deterioration (PMD) in IMSCT surgery is still the presence/absence criterion [17].

The loss of muscle MEPs indicates postoperative motor impairment with a specificity of approximately 90% during IMSCT. The current consensus for MEP alarm criterion in SCT surgery is > 80% amplitude reduction compared to the baseline value. A less conservative standard is used in brain surgery, where 50% reduction is considered the alarm level, but some institutions set it to 50%–70% or more than 80% in spinal surgery [18].

Unlike that of SEP, latency is not included in the alarm criterion for MEP. During MEP monitoring, examiners should be aware of the effects of muscle relaxants. Even in the case of total intravenous anesthesia, the baseline wave must be acquired by considering the half-life and dose of the muscle relaxant used for safe and easy intubation. For example, if the baseline values are smaller than the original value taken while the muscle relaxant effect remains, it can be interpreted as a false negative even if a serious neural insult occurs during surgery [11].

The pooled sensitivity of MEPs was 90% and specificity was 82% according to a meta-analysis of 13 previous studies on IMSCT. Other than amplitude reduction, threshold elevation is considered as another sensitive early warning sign. Empirical alarm consensus has been set at ≥ 100-V threshold elevation for spinal cord monitoring. This means that the need to increase the stimulation intensity to obtain an amplitude similar to that of the previous waveform suggests a neural insult. If the waveform is not obtained even with an elevated simulation intensity of ≥ 100 V, postoperative motor weakness is expected [19].

The increase in stimulation intensity can only be noticed by an examiner who continuously monitors the surgery. Depending on the examiner, if the amplitude of an MEP is reduced, or the threshold intensity increases, not only the simulation intensity but also the duration of stimulus, or the number of trains can be modulated to obtain the waveform appropriately [4].

In addition to unexpected outcomes, such as false negative/positive outcomes, adverse effects have been reported for TES-MEPs, and there have been safety concerns regarding the risk of inducing seizures by TES. However, the occurrence rate is very low (5 out of 15,000 cases) and the reported duration of seizure is very brief, within a few seconds [16].

There are also non-neurological adverse effects, such as bite injury resulting in tongue/lip laceration, or tooth breakage, which can be prevented by using soft bite blocks. Hair loss, or minor scalp burns around the stimulation site have also been rarely reported [20].

Direct Wave (D-Waves)

D-waves are generated by direct activation of the corticospinal tract from the primary motor cortex. Unlike muscle MEPs, D-waves are recorded at the spinal cord by placing a recording electrode in the epidural or subdural space. The response of the TES is recorded in the muscle through synapses of the vertically oriented excitatory interneurons in muscle MEPs, whereas the D-wave directly reflects the activation of the motor neuron axon, so it is relatively less affected by anesthetics with muscle relaxation effect. Thus, unlike muscle MEPs, it is useful to obtain semiquantitative data on the functional integrity of the corticospinal tract [10].

A wire-type recording electrode with two metal wrappings 1.5–2 cm apart from each other at the end is used for recording. In general, the recording electrode is placed at the planned spinal level, usually 2–4 levels below the lowest level of SCT, in an aseptic manner by a surgeon. The recording electrode itself cannot specify the left-right direction of the recording, and as the interhemispheric montage (C1–C2 or C3–C4) is used to obtain muscle MEPs, differential recording from the left or right corticospinal tract is not possible [21].

Below the T10 bony level, the corticospinal fiber is not sufficient; therefore, it is not a recommended location for obtaining sufficient waveforms of D-waves. D-waves are elicited by a single pulse stimulus, whereas muscle MEPs are obtained by train stimuli. Unlike muscle MEPs, D-waves have the advantage of relatively continuous monitoring without eliciting the patient's movement, because it can obtain a stable waveform with a single pulse stimulus of small intensity [22].

In IMSCT surgery, > 50% reduction in the amplitude of a D-wave is considered a significant change. D-waves are helpful in predicting the postoperative prognosis accurately, especially when muscle MEPs have deteriorated. When there is amplitude reduction or threshold increment of muscle MEPs with D-wave amplitude reduction less than 50%, it is suggested to transiently move surgical manipulation to a different area, make warm irrigation or correct hypotension, and the postoperative motor deficit is not predicted [23].

When the muscle MEPs are lost with D-wave amplitude reduction less than 50%, transient motor deficit is predicted, so that it is recommended to stop surgery transiently and/or improve spinal cord blood flow through local irrigation with papaverine. Nevertheless, if the muscle MEPs do not reappear, it is recommended to abandon surgery in selective cases. When muscle MEPs were lost with significant D-wave changes, it is recommended to stop surgery immediately since the permanent motor deficit is predicted. If the D-wave does not recover, abandonment of surgery is recommended [13].

The preserved D-wave is predictive of a favorable motor outcome, even when MEPs or SEPs are lost during IDEM tumor resection. D-waves demonstrated a higher sensitivity (100%) than muscle MEPs (62.5%) or SEPs (37.5%) in IDEM tumors. Although D-wave monitoring is limited because of a lack of approval regarding the use of epidural recording electrodes and a lack of approved cost codes in Korea, it is a necessary modality for precise neurophysiological monitoring [12].

Electromyographic Recording

a. Spontaneous EMG

Spontaneous EMG does not require stimulation, enabling continuous recording. It is performed on pre-selected muscle groups. One muscle group per nerve root is sufficient, but in cervical surgery, some prefer to monitor 2 groups. In the baseline situation, a healthy root should not show muscular activity. During surgery, any root irritation (traction, electrocoagulation, etc.) will cause neurotonic discharges. The amplitude and frequency of these shocks will increase in relation to the damage received by the root. The disadvantages are: muscle relaxants (MB) must not be used. It is a technique that is very sensitive to thermal changes (cold serum, electro-scalpel). False positives are also given [24].

b. Stimulated EMG

Described by Calancie et al. in 1992. Based on the fact that a recording will be achieved if we stimulate a pedicle screw, even at low voltage, if it contacts the root [25]. Some highlight that the stimulus should be increased to 20 mA if there is no EMG response at a lower intensity. Stimulus trains have recently been used to detect whether the screw is touching or is near the medulla [26].

The disadvantages are that it appears that relocation of a screw could result in false positives. Similarly, if MB has been used, at least 30 min should be waited before provoking the EMG. This modality is of special interest in minimally invasive surgery, which depends on the quality of the radiological equipment. It goes without saying that any preoperative root damage to the problem roots must be established. If there is a risk of root damage, spontaneous, or stimulated EMG can be useful for roots S1 and L5. All spinal roots can now be monitored without problems [27].

Combined Procedures (Multimodal Monitoring)

These seek to compensate for weaknesses, or limitations of procedures used in isolation. The combined use of spontaneous and stimulated EMG increases the detection of root damage. Gavaret et al. use the combination of SSEPs, neurogenic MEPs, and D waves for spinal deformity surgery [28, 29].

Kaliya-Perumal et al. suggest that, for pedicle screws, palpation, radioscopy, and provoked EMG should be combined. This significantly reduces the number of reinterventions [30].

Indications for Monitoring

IONM is a useful procedure principally for: thoracolumbar spine deformity surgery (not so much for lumbosacral surgery); medullary tumor surgery, both intra and extramedullary; prevention of neurological damage while positioning the patient and herniated thoracic disc. It has also been pointed out that it does not make sense for pre-existing medullary lesions and in revision surgeries with abnormal reference potentials. In degenerative cervical spine surgery, some support its use, whereas for others, it is of little use, as very few true positives are identified [31].

In cervical disc surgery without myelopathy, some papers support the use of MEPs and SSEPs. Weinzierl et al. indicate that the loss of MEPs indicates a motor deficit, that unaltered MEP indicates preservation of the motor pathway, and that changes in MEPs may or may not coincide with a motor deficit [32].

Others point out that indications in spinal surgery can be: cranio-cervical junction, spinal cord procedures, including cauda equina, spinal deformity correction, vertebral fracture surgery, spinal tumor resections, and anterior cervical discectomy. Thus, the routine use of IONM in all spinal surgeries remains controversial [30].

Modification of Anesthesia

It is important to highlight that, if IONM is decided, anesthetic techniques must be adapted, which is not without drawbacks. There are publications contraindicating the use of many anesthetics, mainly neuromuscular blockers and halogenated anesthetics (HA) (both fundamental in general anesthesia with orotracheal intubation). This is in addition to the influence that these recommendations may have on the anesthetic procedure and its safety [33].

Thus, HA are contraindicated, since both SSEPs and MEPs are affected, MEPs being much more sensitive. However, there are publications that allow their use at low doses (<0.5 minimum alveolar concentration) [34].

MB should be excluded from use in any EMG or MEP modality. If they were to be used, monitoring should be undertaken with a 100% train of 4. For this reason, their use should be restricted to the time of orotracheal intubation, using very low doses, or reversing their effect. Due to these limitations, the suggested gold standard would be total intravenous anesthesia based on propofol and remifentanil. Although both drugs barely alter IONM, their use has certain limitations [2].

Thus, hemodynamic control may be more unstable than with HA. There is a greater risk of intraoperative awakening, especially in obese patients. This constitutes a serious complication, forcing level of consciousness monitoring, which, in turn, is distorted by a lack of muscle relaxation and stimulation of potentials [35].

Remifentanil allows early anesthetic induction and early neurological assessment. Propofol, however, can lead to prolonged awakenings. In addition, the fact that sedoanalgesia is mainly based on these 2 drugs, requires a higher plasma concentration, with the risk of overdose and side effects, such as hyperalgesia syndrome (opioid-induced hyperalgesia), and propofol infusion syndrome (rare but lethal) [36].

Therefore, although it is important to provide adequate conditions for correct neurophysiological monitoring, it is also necessary to find anesthetic levels that allow adequate hemodynamic control and anesthetic depth [33].

Not all patients are equally sensitive to drugs, nor do they need the same intensity of stimulation. For this reason, the exclusion of some drugs which, at low doses, allow correct IONM in some patients may be premature, there being the possibility of defining the pharmacological levels admissible for obtaining an adequate recording at the start of surgery [34].

Methodology of Action

This is not limited to the intervention but begins beforehand. Before the surgical procedure, ideally, an anesthesiologist, neurophysiologist, and surgeon should establish a common plan of action, defining which monitoring techniques to use and how to use them. Thus, consensus should be reached on [20]:

The type of monitoring for each case, based on expected neurological deficits.

The type of anesthesia, dose, and other factors according to the risk/benefit.

The start of monitoring (premobilization or preoperative).

If medullary deficits are anticipated, combined SSEP and MEP recording would be advisable.

Alarm and response criteria.

If new techniques are used, defining the mode of action.

Some have proposed monitoring without a neurophysiologist, although recent reviews consider this possibility less reliable than when carried out by experienced neurophysiologists. It is the role of the surgeon to establish a clear plan of action in the event of any alarm. The first thing to be discounted are false positives, which include: hypotension, hypothermia, use of HA, or migration of stimulation, and recording electrodes. Once discounted, real neurological damage must be considered, reverting any risky maneuver and ensuring recovery of the amplitude or latency of the lost signal (Table 2) [21].

Table (2): Alarm criteria in spinal IONM [21].

Type	Criteria
SSEP	Decrease in amplitude >50% Increase in latency >10%
MEP	Not defined Decrease in amplitude >50%
Stimulated EMG	Not defined Threshold value of 5 mA

EMG: electromyogram; IONM: intraoperative neurophysiological monitoring; MEP: motor evoked potential; SSEP: somatosensory evoked potentials.

The Use of IONM During Deformity Surgery

IONM in spinal deformity surgery has been well described in numerous studies. Since the introduction of SEP monitoring in the 1970s, the rate of neurological injuries in scoliosis surgery has been significantly reduced [37].

Nuwer et al. reported the results of a survey conducted by the Scoliosis Research Society (SRS), in which members were asked to submit surgical data on outcomes of operated patients, including the use of IONM. SSEP monitoring was used in 51,263 of 97,586 spinal cases (53%) with a reported sensitivity of 92%, specificity of 98.9%, while positive predictive value (PPV) and negative predictive value (NPV) were 42% and 99.9%, respectively. The authors' findings were strongly in support of SSEP monitoring during scoliosis procedures [38].

Nevertheless, false-negative SSEP changes have been reported in several studies, thus raising many concerns as to the use of SSEP as the singular tool for neuromonitoring. To address this issue, multimodal IONM (MIONM) was introduced in complex procedures [39].

Bhagat et al., in a large retrospective review of 354 consecutive patients who underwent spinal deformity surgery, demonstrated the superiority of combined MIONM over either single modality in early detection of impending neurological injuries. The overall sensitivity and specificity of combined SSEPs and MEPs in this study were found to be 100% and 99.3%, respectively, strongly supporting its use [40].

The Use of IONM During Degenerative Lumbar Surgery

Although IONM is commonly used during spinal deformity in the modern era, its use in degenerative lumbar surgery, especially in uncomplicated procedures, remains controversial. Supporters of IONM point out its value in detecting spinal nerve root injuries with high sensitivity and specificity, especially in revision and instrumented fusions cases [41].

Despite advancements, the topic of monitoring spinal nerve root function remains controversial. Additionally, although numerous studies have supported the use of IONM in lumbar fusion surgery, it is still unclear whether the improved detection of crisis events intraoperatively translates to a decreased rate of postoperative neurological deficits [42].

The Use of IONM During Spinal Tumor Surgery

The value of IONM in detecting neurologic injuries during resection of spinal cord tumors has been well described. In 2007, Sutter et al. published the results of 109 patients who were monitored with MIONM during surgical treatment for intradural spinal tumors of various types. The authors found high sensitivity and specificity of 92% and 99%, respectively, for predicting adverse neurological outcomes [43].

Forster et al., in a retrospective study of 203 patients undergoing intradural tumor removal, reported IONM changes in 47 patients (23.2%). In this series, SSEP monitoring showed a sensitivity of 94.4% and a specificity of 96.8% in detecting postoperative deficits, whereas the sensitivity and specificity of MEPs monitoring was 95.0% and 98.9%, respectively. Both authors concluded that MIONM is an effective method for spinal cord monitoring during surgery for spinal tumors [44].

Similar results were reported by Harel et al. in their retrospective review of 41 patients with IDEM spinal tumors. When their study group was compared to that of a historical cohort of 70 patients, the authors demonstrated the utility of MIONM in predicting neurological injury with sensitivity, specificity, and positive and negative predicted values of 75%, 100%, 100%, and 97%, respectively. Both studies demonstrated high accuracy for MIONM in predicting neurological adverse events in resection of IDEM [45].

Finally, in a retrospective study, Costa et al. reported the results of 103 patients operated for spinal cord pathologies that included intramedullary, extramedullary tumors, as well as cervical myelopathy. Intraoperative monitoring was obtained with MIONM including SSEP and MEP. In this study, D-wave was obtained in 97 of the cases. The authors showed that the presence of a persistent and stable D wave was predictive of a good functional outcome, even in the absence of MEP signals during surgery [46].

No Conflict of interest.

References:

1. Daniels AH, Hart RA, Hilibrand AS, et al. Iatrogenic spinal cord injury resulting from cervical Spine surgery. Glob Spine J 2017;7:84S-90S.

2. Laratta JL, Shillingford JN, Ha A, et al. Utilization of intraoperative neuromonitoring throughout the United States over a recent decade: an analysis of the nationwide inpatient sample. J Spine Surg 2018b;4:211–9.
3. Ajiboye RM, D'oro A, Ashana AO, et al. Routine use of intraoperative neuromonitoring during ACDFs for the Treatment of spondylotic myelopathy and radiculopathy is questionable. Spine (Phila Pa 1976) 2017;42:14–9.
4. MacDonald DB, Dong C, Quatrale R, et al. Recommendations of the International Society of Intraoperative Neurophysiology for intraoperative somatosensory evoked potentials. Clin Neurophysiol 2019;130:161–79.
5. Liu LY, Callahan B, Peterss S, et al. Neuromonitoring Using Motor and Somatosensory Evoked Potentials in Aortic Surgery. J Card Surg 2016;31:383–9.
6. Muzyka IM, Estephan B. Somatosensory evoked potentials. Handb Clin Neurol 2019;160:523–40.
7. Macerollo A, Brown MJN, Kilner JM, et al. Neurophysiological Changes Measured Using Somatosensory Evoked Potentials. Trends Neurosci 2018;41:294–310.
8. Park J, Park YG. Intraoperative neurophysiological monitoring in spinal cord tumor surgery. J Intraoperative Neurophysiol 2021;3:10–5.
9. Rijs K, Klimek M, Scheltens-de Boer M, et al. In Reply to the Letter to the Editor Regarding "Intraoperative Neuromonitoring in Patients with Intramedullary Spinal Cord Tumor: A Systematic Review, Meta-Analysis, and Case Series." World Neurosurg 2019;127:664.
10. Taskiran E, Brandmeier S, Ozek E, et al. Multimodal intraoperative neurophysiological monitoring in spinal cord surgery. Turk Neurosurg 2017;27:436–40.
11. MacDonald DB. Overview on criteria for MEP monitoring. J Clin Neurophysiol 2017;34:4–11.
12. Ghadirpour R, Nasi D, Iaccarino C, et al. Intraoperative neurophysiological monitoring for intradural extramedullary spinal tumors: Predictive value and relevance of D-wave amplitude on surgical outcome during a 10-year experience. J Neurosurg Spine 2019;30:259–67.
13. Park T, Park J, Park YG, et al. Intraoperative neurophysiological monitoring for spinal cord tumor surgery: Comparison of motor and somatosensory evoked potentials according to tumor types. Ann Rehabil Med 2017;41:610–20.
14. Cantone M, Lanza G, Vinciguerra L, et al. Age, height, and sex on motor evoked potentials: Translational data from a large italian cohort in a clinical environment. Front Hum Neurosci 2019;13.
15. Shigematsu H, Miyabayashi T, Kawasaki S, et al. Transcranial electrical stimulation motor-evoked potentials rescue from postoperative neurological deficit due to inadequate neck position for the case of lumbar surgery with asymptomatic cervical stenosis. Eur Spine J 2022.
16. Li XJ, Lenke LG, Thuet E, et al. Prone Position–Induced Quadriceps Transcranial Motor Evoked Potentials Signal Loss—A Case Report. Spine Deform 2018;6:627–30.
17. Sala F, Skrap B, Kothbauer KF, et al. Intraoperative neurophysiology in intramedullary spinal cord tumor surgery. Handb Clin Neurol 2022;186:229–44.

18. Muramoto A, Imagama S, Ito Z, et al. The cutoff amplitude of transcranial motor evoked potentials for transient postoperative motor deficits in intramedullary spinal cord tumor surgery. Spine (Phila Pa 1976) 2014;39.
19. Schwartz D, Sestokas A, Dormans J, et al. Transcranial electric motor evoked potential monitoring during spine surgery: is it safe? Spine (Phila Pa 1976) 2018.
20. Yoshida G, Imagama S, Kawabata S, et al. Adverse Events Related to Transcranial Electric Stimulation for Motor-evoked Potential Monitoring in High-risk Spinal Surgery. Spine (Phila Pa 1976) 2019;44:1435–40.
21. Tobert DG, Bailey TL, Spiker WR. Evolving Indications for Neuromonitoring in Spinal Surgery: What and When to Monitor. Oper Tech Orthop 2019;29.
22. Scibilia A, Terranova C, Rizzo V, et al. Intraoperative neurophysiological mapping and monitoring in spinal tumor surgery: Sirens or indispensable tools? Neurosurg Focus 2016;41.
23. Dikmen PY, Halsey MF, Yucekul A, et al. Intraoperative neuromonitoring practice patterns in spinal deformity surgery: a global survey of the Scoliosis Research Society. Spine Deform 2021;9:315–25.
24. Nunes RR, Bersot CDA, Garritano JG. Intraoperative neurophysiological monitoring in neuroanesthesia. Curr Opin Anaesthesiol 2018;31:532–8.
25. Calancie B, Lebwohl N, Madsen P, et al. Intraoperative evoked emg monitoring in an animal model: A new technique for evaluating pedicle screw placement. Spine (Phila Pa 1976) 1992;17:1229–35.
26. Shaw KA, Murphy JS, Devito DP. Accuracy of robot-assisted pedicle screw insertion in adolescent idiopathic scoliosis: is triggered electromyographic pedicle screw stimulation necessary? J Spine Surg 2018;4:187–94.
27. Henderson L, Tsirikos AI. Intraoperative neurophysiological monitoring in spinal deformity surgery. Orthop Trauma 2017;31:425–32.
28. Eager M, Shimer A, Jahangiri FR, et al. Intraoperative neurophysiological monitoring (IONM): Lessons learned from 32 case events in 2069 spine cases. Neurodiagn J 2011;51:247–63.
29. Hilibrand AS, Schwartz DM, Sethuraman V, et al. Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. J Bone Jt Surg 2004;86:1248–53.
30. Kaliya-Perumal AK, Charng JR, Niu CC, et al. Intraoperative electromyographic monitoring to optimize safe lumbar pedicle screw placement - a retrospective analysis. BMC Musculoskelet Disord 2017;18.
31. Harel R, Knoller N, Regev G, et al. The value of neuromonitoring in cervical spine surgery. Surg Neurol Int 2014;5.
32. Weinzierl MR, Reinacher P, Gilsbach JM, et al. Combined motor and somatosensory evoked potentials for intraoperative monitoring: Intra- and postoperative data in a series of 69 operations. Neurosurg Rev 2017;30:109–16.
33. Martin DP, Bhalla T, Thung A, et al. A preliminary study of volatile agents or total intravenous anesthesia for neurophysiological monitoring during posterior spinal fusion in adolescents with idiopathic scoliosis. Spine (Phila Pa 1976) 2014;39:E1318–24.

34. Sloan TB, Toleikis JR, Toleikis SC, et al. Intraoperative neurophysiological monitoring during spine surgery with total intravenous anesthesia or balanced anesthesia with 3 % desflurane. J Clin Monit Comput 2015;29:77–85.
35. Trifa M, Krishna S, D'Mello A, et al. Sugammadex to reverse neuromuscular blockade and provide optimal conditions for motor-evoked potential monitoring. Saudi J Anaesth 2017;11:219–21.
36. Subramanian A, Wanta BT, Fogelson JL, et al. Time to extubation during propofol anesthesia for spine surgery with sufentanil compared with fentanyl: A retrospective cohort study. Spine (Phila Pa 1976) 2014;39:1758–64.
37. Thirumala PD, Cheng HL, Loke YK, et al. Diagnostic accuracy of somatosensory evoked potential monitoring during scoliosis fusion. J Clin Neurosci 2016;30:8–14.
38. Nuwer MR, Dawson EG, Carlson LG, et al. Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. Electroencephalogr Clin Neurophysiol Evoked Potentials 2017;96:6–11.
39. Thirumala PD, Crammond DJ, Loke YK, et al. Diagnostic accuracy of motor evoked potentials to detect neurological deficit during idiopathic scoliosis correction: A systematic review. J Neurosurg Spine 2017;26:374–83.
40. Bhagat S, Durst A, Grover H, et al. An evaluation of multimodal spinal cord monitoring in scoliosis surgery: a single centre experience of 354 operations. Eur Spine J 2015;24:1399–407.
41. Chen Y, Wang BP, Yang J, et al. Neurophysiological monitoring of lumbar spinal nerve roots: A case report of postoperative deficit and literature review. Int J Surg Case Rep 2016;30:218–21.
42. Shilian P, Zada G, Kim AC, et al. Overview of intraoperative neurophysiological monitoring during spine surgery. J Clin Neurophysiol 2016;33:333–9.
43. Sutter M, Eggspuehler A, Grob D, et al. The validity of multimodal intraoperative monitoring (MIOM) in surgery of 109 spine and spinal cord tumors. Eur Spine J 2007;16.
44. Forster MT, Marquardt G, Seifert V, et al. Spinal cord tumor surgery - Importance of continuous intraoperative neurophysiological monitoring after tumor resection. Spine (Phila Pa 1976) 2012;37.
45. Harel R, Schleifer D, Appel S, et al. Spinal intradural extramedullary tumors: the value of intraoperative neurophysiologic monitoring on surgical outcome. Neurosurg Rev 2017;40:613–9.
46. Costa P, Peretta P, Faccani G. Relevance of intraoperative D wave in spine and spinal cord surgeries. Eur Spine J 2013;22:840–8.