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The Spine Journal 000 (2019) 1−8

THE SPINE JOURNAL

Clinical Study

# Utility of motor evoked potentials to diagnose and reduce lower extremity motor nerve root injuries during 4,386 extradural posterior lumbosacral spine procedures

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Received 4 March 2019; revised 21 August 2019; accepted 26 August 2019

**Abstract**

**BACKGROUND CONTEXT:** Motor evoked potentials (MEPs) have excellent sensitivity for monitoring the functional integrity of the lateral corticospinal tract of the spinal cord. The sensitivity for nerve root function, however, is not as well established; consequently, MEPs are often not utilized for posterior extradural spine procedures distal to the conus. Spontaneous electromyography (sEMG) and somatosensory evoked potentials (SSEPs) are often included for these procedures, but their limited sensitivity has been well documented. Given the risk of motor nerve root injuries during spine procedures, and specifically increased vulnerability of the L4 and L5 nerves, the sensitivity of MEPs was evaluated for diagnostic accuracy and therapeutic impact.

**PURPOSE:** To determine the diagnostic sensitivity of MEPs during lumbosacral spine procedures and the potential therapeutic impact of the resolution of MEP alerts.

**STUDY DESIGN:** A total of 4,386 posterior extradural lumbosacral spine procedures utilizing multimodality intraoperative neuromonitoring (IONM) with sEMG, SSEPs, and MEPs were abstracted from a multi-institutional database. All cases took place between October 2015 and October 2017. No external funding was provided.

**OUTCOME MEASURES:** Sensitivity and specificity, as well as positive and negative likelihood ratios for new postoperative neurologic deficits were calculated for each modality individually as well as when combined (multimodality).

**PATIENT SAMPLE:** Age 18 and older

**METHODS:** Data entered in the electronic medical record were analyzed. Alerts to sEMG activity, decreases in SSEP amplitude, or decreases in MEP amplitude were documented as well as the status of the alerts at closure: resolved or unresolved. The presence of an sEMG alert or an unresolved MEP or SSEP alert at closure was considered a positive diagnostic result, and these results were assessed relative to presence of new immediate onset neurologic deficits as documented in the electronic record.

FDA device/drug status: Not applicable.

Author disclosures: ***WBW***: Nothing to disclose. ***EAT***: Nothing to disclose. ***JSH***: Consulting: Depuy Spine (JJ) (D), Globus (B). ***WCW***: Nothing to disclose. ***AFC***: Royalties: Nuvasive (C), RTI (B); Consulting: Nuvasive (E), Alliance (C), ATEC (C), Spinal Elements (C); Speaking and/or Teaching Arrangements: Mazor (B). ***KAP***: Royalties: K2M (C); Stock Ownership: Mazor/Medtronic (E); Private Investments: SpinalCyte (F); Consulting: Medtronic (C), MiRus (B), KUROS (A), K2M (B), Misonix (B), Stryker Spine (C); Speaking and/or Teaching Arrangements: K2M (D), Mazor Robotics (C), Medtronic (C), Stryker Spine (B); Scientific Advisory Board/Other Office: KUROS (B). ***TE-Z***: Nothing to disclose. ***TS***: Nothing to disclose. ***JC***: Nothing to disclose. ***AKS***: Stock Ownership: SpecialityCare (D); Speaking and/or Teaching Arrangements: American Society of Neurophysiological Monitoring - Honoraria (A).

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https://doi.org/10.1016/j.spinee.2019.08.013
1529-9430/

**RESULTS:** The sensitivity and specificity of multimodality IONM for new immediate-onset lower extremity motor deficits were 100.0% (95% confidence interval: [64.6, 100.0]) and 92.2% (91.1, 93.1), respectively. Looking at the modalities in isolation, the sensitivity of MEPs was considerably better than either lower extremity sEMG or posterior tibial nerve SSEPs: 100.0% (78.5, 100.0) versus just 14.3% (4.0, 39.9) and 28.6% (8.2, 64.1), respectively. Surprisingly, the specificity of lower extremity MEPs was better than sEMG, 97.9% (97.5, 98.3) versus 95.4% (94.7, 96.0) ($\chi^2$=43.0, p<.001). The specificity of lower extremity SSEPs was 99.0% (98.5, 99.3). Only 4.4% of all procedures had a lower extremity MEP alert. There were 14 significant new nerve root injuries and all 14 had unresolved MEPs at closure. Total 85.7% of those nerve root injuries were dorsiflexion foot drop injuries and all had unresolved tibialis anterior MEP alerts. Although the overall rate of nerve root injuries was 0.32% (14/4,386), the rate for procedures with unresolved isolated tibialis anterior MEP alerts was 44.4% (12/27). The therapeutic impact is evident in the 2.0% of cases (87/4,386) with lower extremity MEP alerts that were able to be fully resolved by closure and for which the rate of injury was zero.

**CONCLUSIONS:** The diagnostic accuracy of MEPs for anterior tibialis-related nerve root dysfunction supports the inclusion of this modality during routine posterior extradural lumbosacral procedures, especially when the L4 or L5 nerve roots are at risk. Moreover, therapeutic interventions that lead to the resolution of MEP alerts avert postoperative neurologic injuries. 

*Keywords:* Foot drop; Intraoperative neuromonitoring; L5 nerve root; Lumbosacral; Motor evoked potentials

## Introduction

Surgery of the lumbar spine carries known risk of neurologic sequelae secondary to spinal nerve root injury. The incidence of new onset postoperative neurologic deficit following higher risk instrumented lumbar fusion procedures has been reported to exceed 25% [1,2]. The extent of mechanically induced nerve root injury likely depends on both the magnitude and duration of force applied to the roots and/or their vascular supply [3−6]. For posterior surgeries spanning the lumbosacral region, injuries to any lumbosacral nerve roots may occur, but the nerve roots (L4 or L5) innervating the tibialis anterior and/or extensor hallucis longus muscles are the most commonly injured nerve roots and result in foot drop deficit [7−9]. This weakness in foot and toe dorsiflexion affects the normal gait of the patient and can impact their quality of life. A primary muscle contributing to dorsiflexion function is the tibialis anterior muscle. Although this is putatively an L5 nerve root injury, foot drop often involves multiple nerve roots, consistent with the fact that the tibialis anterior is innervated almost equally from L4 and L5 nerve roots with a minor contribution from S1 [10]. Analyses of patients with foot drop also show that this deficit can result from L4 to L5 level posterolateral herniations, L5−S1 lateral disc herniations, or from a combination of multiple levels [11].

For nerve root monitoring during extradural spine procedures, the primary modality most often utilized is EMG; however, EMG has limitations in monitoring spinal nerve root function [12]. EMG is functionally separated into triggered EMG (tEMG) and spontaneous EMG (sEMG). Triggered EMG is typically used briefly, and at very specific times, for nerve proximity localization (eg, during pedicle screw stimulation). Because it is not used continuously during posterior lumbosacral procedures, it does not provide ongoing functional assessment. In contrast, motor evoked potentials (MEPs) can be systematically obtained during the surgery and do provide and an ongoing functional assessment throughout a procedure.

The major factor that may limit the sensitivity of MEPs in detecting nerve root dysfunction is the alert criterion employed. MEPs are historically used for spinal cord monitoring and the alert criterion employed is typically an 80% amplitude reduction or a complete loss of response [13]. However, studies in which MEPs had high sensitivity for detecting nerve root dysfunction used an alert criterion ranging from a 50% to 65% amplitude attenuation [7,9,12,14]. Thus, the challenge in spinal procedures is to differentially diagnose spinal cord versus nerve root or peripheral nerve injuries using different alert criteria [13].

The first goal of this study was to evaluate the diagnostic accuracy of MEPs during lumbar spine surgery in which MEP alert criteria were tailored to identify evolving spinal nerve root injury. The second goal was to assess the potential therapeutic impact of MEP alert information in prompting surgical and anesthetic teams to rapidly intervene when alerted to neurologic dysfunction.

## Methods

We retrospectively reviewed a multi-institutional database of adult (18 years and older) extradural lumbar and lumbosacral spine surgery with intraoperative neuromonitoring performed between October 2015 and October 2017. Procedures that did not include lower extremity sEMG and MEP monitoring were excluded, as were procedures that involved any thoracic spine level, tumor presence, or tethered cord. Any procedures that did not include either the L4−L5 or the

L5−S1 disc level were also excluded. This yielded 4,386 posterior lumbar procedures.

For sEMG and MEP monitoring, bipolar differential recordings were obtained from each muscle using subdermal uninsulated electrodes inserted approximately 2 cm apart in the same muscle. The muscles monitored varied somewhat based on the levels of the procedure, but, in general, iliopsoas muscles were used for L1 nerve root monitoring, adductor and quadriceps muscles were used for L2−L4 nerve root and lumbar plexus monitoring, tibialis anterior muscles were used for L4−L5 nerve root monitoring, gastrocnemius and abductor hallucis muscles were used for L5−S1 monitoring, and all were collectively used for general cauda equina monitoring. In addition, hand muscles (eg, abductor pollicis brevis, first dorsal interosseous) were used as a control for MEPs and potentially for detecting changes related to positioning of the upper extremities. All muscles were recorded bilaterally.

The published internal practice guidelines for alerts used by the IONM teams in this study stated, “Alarm criteria for transcranial electric MEPs can vary, depending on size and variability of responses, abruptness of change as well as other factors [14]. In practice, 75-80% attenuation of MEP amplitude during spine surgery warrants an alert, although changes that are smaller than this may also be significant.” No established criterion for spinal nerve root monitoring has been established [14]. This IONM group has historically employed a 50% amplitude reduction as a part of the criterion for C5 nerve root dysfunction [12]. Thus, the change in amplitude that prompted an MEP alert for putative nerve root injuries in this dataset was at the clinical discretion of the IONM team, after weighing multiple variables, but it was often a 50% attenuation that prompted an alert.

Posterior tibial nerve SSEPs were used to supplement sEMG and MEP monitoring in 2,585 procedures. Ulnar nerve SSEPs were recorded in all procedures to monitor upper extremity positioning. For SSEPs, a guideline of a 50% reduction in amplitude or 10% increase in latency was used as an alert criterion. For the analysis of multimodality IONM, the 2,585 procedures with sEMG, MEPs, and both ulnar and posterior tibial nerve SSEPs were used.

The surgical and anesthetic teams were immediately alerted to any significant neurophysiologic change, and the acknowledgment of the information and intervention were noted in the record. The surgeon was updated regarding the status of the signals and the closing status of the signal was noted as (A) no alert, (B) alert and fully resolved, or (C) alert and unresolved. For the purposes of measuring diagnostic accuracy, unresolved lower extremity MEPs or SSEPs at closing were considered a positive diagnostic result, and fully resolved MEPs or SSEPs at closing and procedures with no alerts were considered a negative diagnostic result. Spontaneous EMG was often reported to the surgeon, but only activity reported as an alert, or putative neurotonic activity was considered an alert. Since the alert is essentially the diagnosis and most all sEMG inevitably resolves, if sEMG activity was conveyed and denoted as an alert then this was considered a positive diagnostic test. For multimodality IOMN, if any test was positive, the collective IONM result was positive. Upper extremity SSEP and MEP alerts were also documented and analyzed separately.

For all procedures, the IONM team noted when a new neurological deficit was present, whether immediate onset or delayed onset, and the nature of the deficit. From an outcomes standpoint, procedures with an immediate onset new lower extremity motor deficit were considered positive for neurologic sequelae, that is, presence of deficit. Thus, if a positive diagnostic result (eg, unresolved MEP alert at closure) occurred and the patient was positive for new motor deficit, this was a true positive (TP); if the patient had no new deficit, then this was classified as a false positive (FP). Conversely, for negative diagnostic results (no alerts or fully resolved alerts), if the patient had no new deficit, this was considered a true negative (TN), and if they were positive for a new deficit this was considered a false negative (FN).

The sensitivity, specificity, and positive and negative likelihood ratios were calculated for each modality in isolation (lower extremity sEMG, lower extremity SSEPs, and lower extremity MEPs) and also for the collective multimodality IONM (Table 1). Confidence intervals, shown in brackets, were calculated using the Wilson method for sensitivity and specificity, and the Wald method for positive and negative likelihood ratio. Descriptive comparisons among groups were assessed with the chi-squared statistic.

## Results

The sensitivity of multimodality IONM for nerve root injuries was 100% (95% confidence interval [64.6, 100.0]). The 100% sensitivity was a function of the sensitivity of

Table 1
Sensitivity, specificity, positive likelihood ratio (PLR) and negative likelihood ratio (NLR) for each lower extremity monitoring modality individually and the combined multimodality IONM

| Modality | Sensitivity (95% CI) | Specificity (95% CI) | PLR (95% CI) | NLR (95% CI) |
|---|---|---|---|---|
| MEPs | 100% (78.5%, 100%) | 97.9% (97.5%, 98.3%) | 48.6 (39.6, 59.6) | 0 (N/A) |
| sEMG | 14.3% (4.0%, 39.9%) | 95.4% (94.7%, 96.0%) | 3.1 (0.9, 11.3) | 0.9 (0.7, 1.1) |
| SSEPs | 28.6% (8.2%, 64.1%) | 99.0% (98.5%, 99.3%) | 29.5 (8.6, 101.3) | 0.7 (0.5, 1.2) |
| Multimodality | 100% (64.6%, 100%) | 92.2% (91.1%, 93.1%) | 12.8 (11.2, 14.6) | 0 (N/A) |

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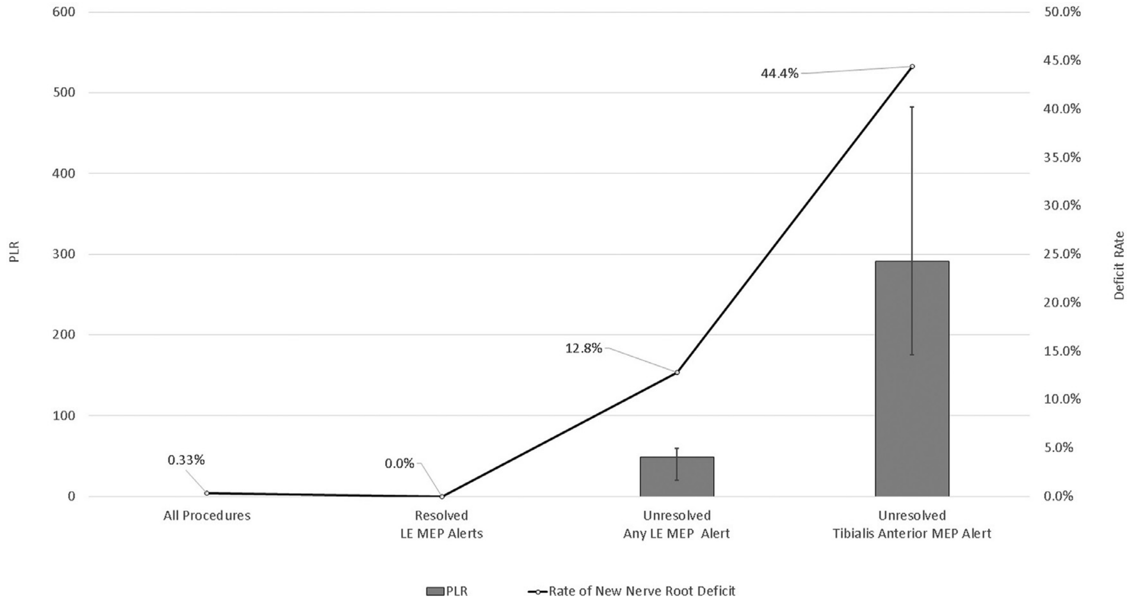


Fig. 1. Motor deficit rates for all patients compared to patients grouped by MEP alert type and status. Positive likelihood ratios (PLR) for new deficit are shown for patients with unresolved MEP alerts involving any muscle and for patients with unresolved tibialis anterior MEP alerts.

lower extremity MEPs, which was 100% (78.5, 100.0). The sensitivities of sEMG and lower extremity SSEPs were just 14.3% (4.0, 39.9) and 28.6% (8.2, 64.1), respectively. Surprisingly, the specificity of lower extremity MEPs was also better than sEMG, 97.9% (97.5, 98.3) versus 95.4% (94.7, 96.0; $\chi^2$=43.01, p<.001). Although SSEPs were less sensitive than MEPs, their specificity was 99% (98.5%, 99.3). The rate of lower extremity SSEP alerts was only 1.6%, and unresolved SSEPs were highly predictive of nerve root injuries; the positive likelihood ratio of a nerve root injury was 29.5 (8.6, 101.3; Table 1).

There were 14 new onset lower extremity motor deficits noted in the immediate postoperative period. The majority were functionally significant nerve root foot drop injuries (12/14) in which there was severe loss of dorsiflexion function; all 12 patients had unresolved tibialis anterior MEP alerts intraoperatively. The remaining nerve root injuries (2/14) were related to S1 gastrocnemius and/or adductor hallucis function and those 2 patients had unresolved gastrocnemius and/or adductor hallucis MEP alerts during surgery.

Overall, the immediate motor deficit rate was 0.32%. However, the rate of immediate new motor deficit was 13.5% for procedures with any unresolved MEP alert, and 44.4% for procedures with unresolved MEP alerts isolated to the tibialis anterior muscle (Fig. 1). The positive likelihood ratio for a new motor deficit given any unresolved MEP alert was 48.6 (39.6, 59.6; p<.001). The positive likelihood ratio for a new foot drop deficit given an unresolved tibialis anterior MEP alert was 291.5 (175.9, 483.1; p<.001). There were no deficits in cases with MEP alerts that were fully resolved by closure.

There were 191 procedures with a lower extremity MEP alert and 104 remained unresolved at closure. Of these, 90 were false positives in that the MEP alert remained unresolved at closure but the patient did not have any new clinically obvious postoperative motor deficits by gross physical exam in the immediate recovery period (Table 2). Unresolved MEP alerts were noted for 14 patients who awoke with new deficits and thus were true positives. There were 4,195 procedures with no MEP alerts and there were 87 procedures with fully resolved MEP alerts; there were no new lower extremity motor deficits in those 4,282 procedures and thus all 4,282 were true negatives (Table 2). There were no false negatives for new immediate onset lower extremity motor deficits in the immediate recovery period.

The 87 procedures with resolved MEP alerts were analyzed according to the muscle or muscle group alerted and the primary intervention that preceded the resolution of that alert. Of these, 29 were quadriceps alerts (33.3%), 17 were gastrocnemius and/or abductor hallucis alerts (19.5%), 15 were tibialis anterior alerts (17.2%), and 26 were alerts from multiple lower extremity muscle groups (29.9%). The majority, 60%, of quadriceps alerts resolved following repositioning of the leg or repositioning of the padding under the thigh. The putative insult was thus direct compression of the femoral nerve from patient positioning. There were no instances in which a major surgical action was taken in response to a quadriceps MEP alert (Fig. 2). There was one procedure with significant blood loss where an increase in blood pressure and a blood transfusion were given, resolving the alert (Fig. 2). In contrast, for isolated tibialis anterior muscle alerts, 80.0% of alerts prompted a surgical exploration and/or action, 13.3% involved a pharmacologic or physiological intervention, and just 6.7% involved repositioning of the limb (Fig. 2). A similar pattern was seen for isolated gastrocnemius/abductor hallucis muscle alerts

Table 2
Number of cases with lower extremity (LE) alerts and total true positives (TP), false negatives (FN), false positives (FP), and true negatives (TN) for multimodality LE IONM and for each modality in isolation

| Modality | Total cases | Cases with LE alerts | TP | FN | FP | TN |
|---|---|---|---|---|---|---|
| LE MEPs | 4,386 | 191 | 14 | 0 | 90 | 4,282 |
| LE sEMG | 4,386 | 203 | 2 | 12 | 201 | 4,171 |
| LE SSEPs | 2,585 | 42 | 2 | 5 | 25 | 2,553 |
| Multimodality LE | 2,585 | 243 | 7 | 0 | 202 | 2,376 |

and for multiple lower extremity muscle alerts where the intervention also typically involved surgical action and/or a pharmacologic or physiological intervention (Fig. 2). The surgical interventions included repositioning of screws, osteotomies, dura repairs, further decompression of a nerve root, increase or decrease of distraction, repositioning of an interbody graft, and/or removal of instrumentation.

A case example of MEP recordings during an L4−L5 transforaminal lumbar interbody fusion (TLIF) is shown to illustrate the therapeutic impact of a surgical action to mitigate permanent neurologic injury (Fig. 3). The surgeon was alerted to an attenuation of greater than 50% of the right tibialis anterior MEP amplitude at 13:08 hours, after pedicle screw placement and distraction. The surgeon was again alerted when the attenuation of right tibialis anterior MEP amplitude was greater than 70% at 13:14 hours, and the surgeon elected to redirect the right L4 pedicle screw. Resolution of the alert occurred at 13:22 hours, following release of distraction. There was no postoperative motor deficit.

It should be noted that upper extremity SSEPs and upper extremity MEPs from the hands were also recorded in this series. There were 103 upper extremity MEP alerts. The resolution of those alerts was invariably related to repositioning of the arm and/or adjustment of compressing forces on the arm.

## Discussion

Nerve root injury is a known complication during posterior lumbosacral spine procedures, but as recent meta-analysis has shown, the rate of injury reported in the literature varies greatly [15]. In reports with relatively higher rates of injury (>4%), the majority of procedures included in those studies involved the L5 nerve root [7,11,16]. We sought to evaluate the diagnostic accuracy and potential therapeutic impact of MEPs for putative L5 nerve root motor injuries when the L5 nerve root was directly or indirectly (L4−L5 disc level) involved. We did not delineate other factors related to diagnosis, for example, spondylolisthesis, or the nature of procedure, fusion or no fusion, or any other patient factors such as obesity or type II diabetes. The only procedural variable required for inclusion in the study was involvement of the nerve root (s) contributing to dorsiflexion function.

A recently published case report illustrates how tibialis anterior MEPs detected foot drop when there were no

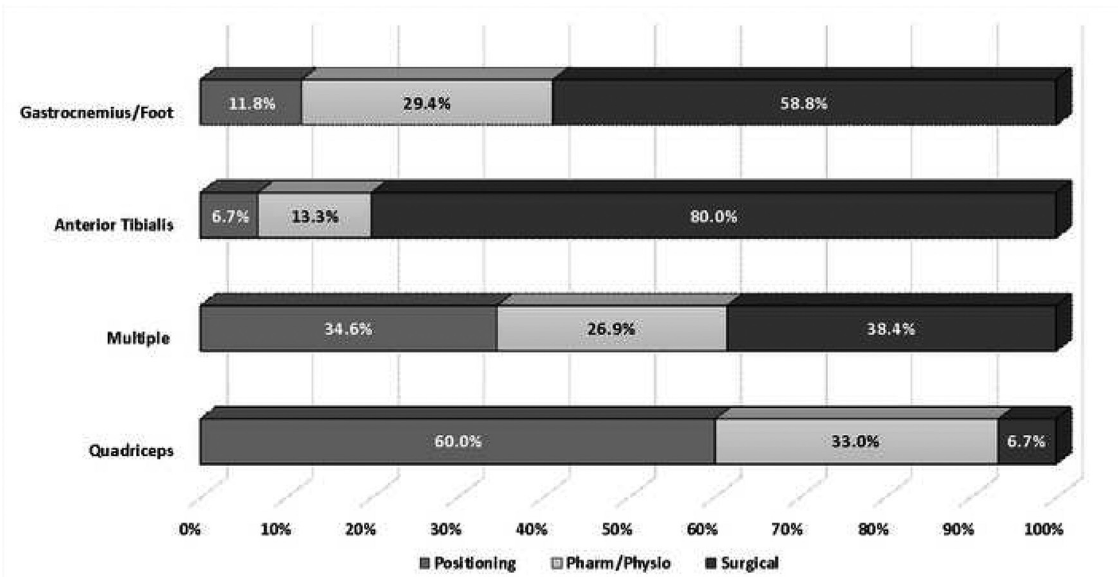


Figure 2. Intervention type, by percentage, preceding the resolution of the MEP alert by muscle or muscle group.

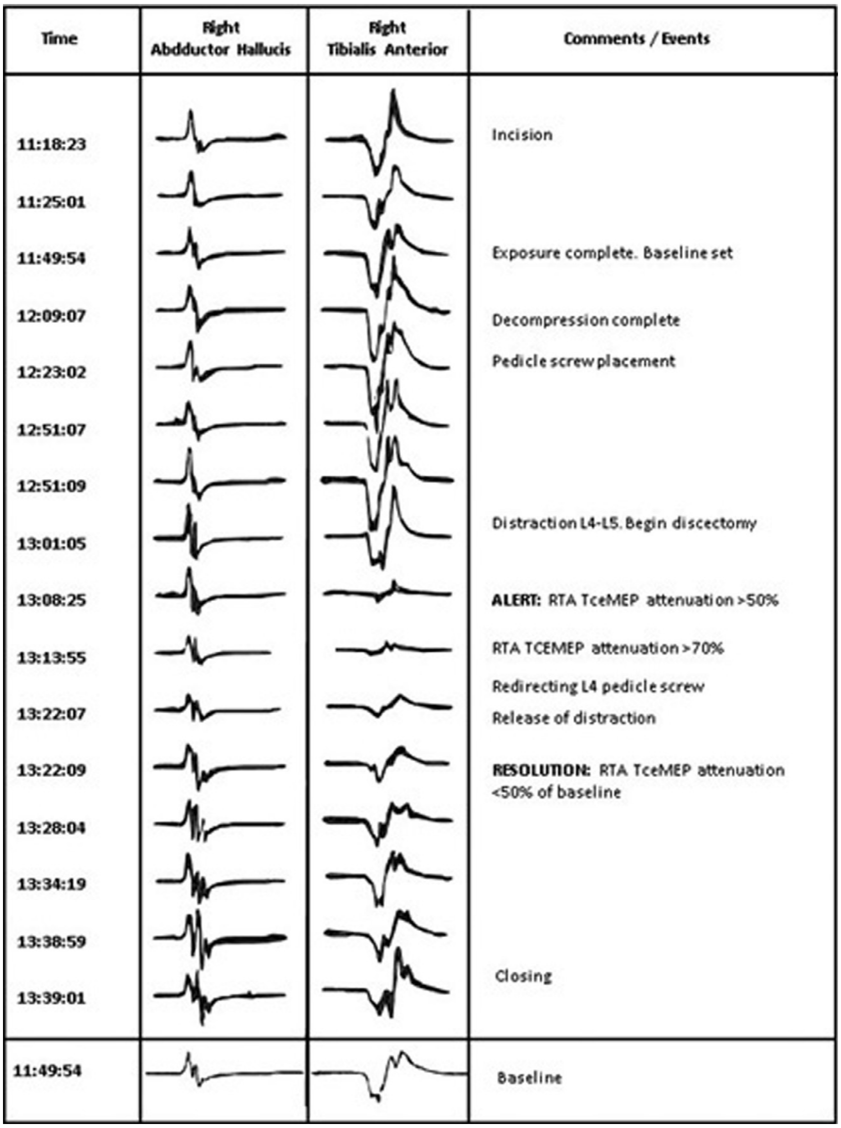


Figure 3. Case example.

Focal MEP changes in tibialis anterior muscle during a posterior L4−L5 transforaminal lumbar interbody fusion (TLIF) with pedicle screw fixation under propofol and remifentanil anesthesia. MEP trials shown from the first dorsal interosseous and tibialis anterior muscles. Attenuation of right tibialis anterior MEP amplitude greater than 50% was noted at 13:08, following pedicle screw placement and distraction. Attenuation of right tibialis anterior MEP amplitude was greater than 70% at 13:14, and the surgeon elected to redirect the right L4 pedicle screw. Resolution of alert occurred at 13:22, following release of distraction. There was no postoperative motor deficit.

changes in SSEPs or spontaneous EMG [17]. In another recent study of 130 lumbosacral procedures with MEP monitoring, 3 patients (2.3%) developed a severe foot drop and all 3 had >50% reduction in tibialis anterior MEPs [9]. An older larger study of 409 patients with multimodality IONM and an MEP alert criterion of 50% had a sensitivity of 90% for new neurologic deficits and also followed patients out long term [7]. There were 18 deficits, 5 of which persisted at 1-year follow-up; 4 were specifically L5 nerve root deficits and 1 was a lumbosacral plexus deficit.

Use of intraoperative neurophysiological monitoring in the present series was effective in detecting onset of significant neurologic change during surgery. Persistent attenuation of transcranial electric MEP amplitude was both highly sensitive and highly specific in predicting postoperative neurologic sequelae. Moreover, MEP monitoring may have played a role in reducing overall morbidity by prompting intraoperative modifications to the procedure.

The results of this study showing the value of combined MEP and sEMG monitoring of nerve root function in the lumbar spine are consistent with those reported for the cervical spine [2,6]. Although MEPs appear to be more sensitive than sEMG in predicting new onset postoperative neurologic deficits, their combined use sharpens the interpretation of neurophysiological changes. Ideally, presence of spontaneous neurotonic electromyographic activity during surgery should prompt a functional assessment of nerve root conduction with MEPs. The results of the present study suggest that nerve roots are at elevated risk of injury when MEP attenuation is prolonged. In the latter situation, prompt redirection of the surgeon's attention to possible underlying causes of MEP attenuation is warranted to avoid exacerbation of injury.

Spontaneous EMG in the procedure has some utility in providing an ongoing recording of activity from the muscles and provides information regarding nerve root proximity, but it is very poor at definitively diagnosing dysfunction and is prone to false negative findings. The recording electrode most often used for muscle recordings in IONM is not ideal for reliably resolving the high frequency spikes that are indicative of injury, that is, neurotonic activity [18]. Even when using an optimal recording technique for detecting neurotonic discharges, activity may not be produced when the putative insult is an ischemic, compression, or slow stretch injury [12,19,20]. For MEPs, the electrode choice is optimized to record the low frequency compound muscle action potential (CMAP) that is evoked by transcranial stimulation, and MEPs can diagnose the impairment in conduction caused by ischemia, stretch, or compression [9,12,21].

SSEPs can detect nerve root injuries, and a loss of SSEPs that remains unresolved is associated with a significant increase in morbidity; however, the overall sensitivity of SSEPs during posterior lumbosacral surgery is reportedly low, which is consistent with the finding here [22]. There are a few limitations in the ability of SSEPs to detect nerve root dysfunction. First, typically only one nerve (the posterior tibial nerve) is stimulated bilaterally, and thus SSEPs can only detect injuries to nerve roots contributing to that one nerve being stimulated. Second, the SSEP is a sensory response and does not directly monitor motor function. Third, the posterior tibial nerve derives from multiple nerve roots and it is possible that an injury to one contributing nerve root may not reduce the amplitude of the response to a level that warrants an alert.

The decision to utilize MEPs during posterior lumbosacral procedures, in addition to SSEPs and EMG, is based on the potential benefit to the patient from an outcomes perspective. There are, however, potential issues associated with adding this modality, particularly as they relate to false positive MEP alerts that may occur. There were 90 false positive lower extremity MEP alerts in this series. None of the 90 procedures with false positive MEPs were aborted because of the alerts. It is important to distinguish between different types of lower extremity MEP alerts to understand the practical impact of false positives during lumbosacral spine surgery. In this study, the lower extremity muscle most commonly affected was the quadriceps. Quadriceps MEPs are often low in amplitude at baseline, and the majority of the quadriceps MEP alerts occurred after positioning but before completion of exposure. Repositioning of the legs or the padding underneath the legs often resolved the MEPs, but not always. These alerts were typically attributed to quadriceps compression and not a putative nerve injury, and thus surgeries proceeded with minimal disruption. There were 15 false positive tibialis anterior (TA) MEP alerts and thus only 1 in 292 procedures was associated with possibly unnecessary surgical action. However, given the rate of foot drop injury in patients with unresolved TA MEP alerts, the potential benefit of a reasonable attempt to assess and/or alleviate possible stretch or compression of the nerve root was thought to be justified. There are several factors that can act to limit the sensitivity and specificity of MEPs during spinal nerve root monitoring [18]. These include overlapping innervation of muscles from more than one nerve root, highly selective activation of the lower motor neuron pool via transcranial electrical stimulation of the corticospinal tract, inherent variability in the amplitude, threshold and morphology of MEPs, as well as effects of anesthesia and systemic factors on MEP response parameters. Each of these may be exacerbated by interindividual variability. The effects of these limiting factors can be mitigated to some extent but not eliminated completely by sampling responses from multiple muscles with overlapping innervation patterns and by careful management of the anesthetic regimen to reduce response variability and improve accuracy of interpretation.

The sensitivity of MEPs during these procedures is also dependent on reliable baseline MEPs from the tibialis anterior muscle. In this study, a reliable tibialis anterior MEP could not be obtained for 3.4% of patients. This was typically due to one of two reasons. The primary reason was the presence of preexisting lower extremity weakness and foot drop. A secondary reason was the impact of anesthetic regimen. The majority (72.6%) of procedures in the present series utilized a total intravenous regimen, but a significant minority (28.4%) employed a mixed regimen with inhalational anesthetics, which are known to decrease the probability of obtaining baseline MEPs [14]. Fortunately, there were no new deficits in the patients who were neurologically intact before surgery but for whom responses could not be obtained at baseline because of the anesthetic regimen.

Given the aforementioned factors, it is also important to appreciate that the value and justification of MEPs is dependent on diagnostic skill of the IONM team and the planning and communication among all teams: surgical, anesthesia, and IONM. MEPs were originally introduced to monitor spinal cord function during spine surgery. Loss of response, or a greater than 80% attenuation in response amplitude, is very sensitive to spinal cord dysfunction, but there is no consensus as to the best alert criterion for diagnosing nerve root injury. However, there is agreement that different criteria are needed to diagnose evolving spinal nerve root versus evolving spinal cord dysfunction. Published reports demonstrating a high level of sensitivity to nerve root injury have employed a 50% to 65% amplitude attenuation criterion [9,12,14]. For those who have traditionally used MEPs for spinal cord monitoring, it may be a practice adjustment to employ a 50% to 65% criterion for nerve root specific monitoring, but this flexibility is needed to achieve the sensitivity seen in the present study. Communication and planning among the surgical, anesthesia, and IONM teams are needed to limit the frequency and potential impact of false positives. Other steps that may reduce the frequency of false positives include concurrent recording of MEPs from additional muscles involved in ankle dorsiflexion, such as the extensor hallucis longus, to confirm L5 nerve root alerts.

These skill requirements notwithstanding, the results of this study suggest that the combined use of MEPs and sEMG facilitates early detection of evolving nerve root dysfunction in the lumbar spine, prompting timely investigation of likely proximate causes and initiation of interventional measures by the surgical and anesthesia teams to reverse or mitigate the severity of emerging deficit. It should be noted that while sEMG has limited sensitivity in delineating activity that is related to mechanical injury or innocuous manipulation, there is still clinical value in reporting sEMG to increase the surgeon's awareness of relative proximity to neural tissue.

Visual inspection and diagnostic imaging can also be used to assess if there is anatomical evidence of nerve root injury. However, these modalities do not provide information about possible nerve root dysfunction in the presence of grossly normal anatomy. MEPs are sensitive to impaired conduction caused by excessive nerve root stretch or microvascular compromise, which may otherwise go undetected during surgery. This functional information, interpreted in surgical context, may help in determining effective intervention. Given that the duration of mechanical or vascular stress placed on a nervous system structure correlates with the severity of dysfunction and prognosis for recovery, timely and accurate diagnosis of evolving injury using MEPs can prompt appropriate intervention to avoid or mitigate postoperative deficits

Last, as evidenced in the case example, the impact of neuromonitoring and effectiveness of an intervention requires both an accurate and timely diagnosis. Frequent MEP testing allows for a timely diagnosis that also has context in the sequence of surgical events, thus facilitating the interpretation and intervention determination.

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