The Spine Journal 23 (2023) 1920−1927

Clinical Study

Utility of intraoperative neurophysiological monitoring in detecting motor and sensory nerve injuries in pediatric high-grade spondylolisthesis

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Received 8 March 2023; revised 30 July 2023; accepted 5 August 2023

Abstract

BACKGROUND CONTEXT: Intraoperative neuromonitoring (IONM) during surgical correction of spinal deformity has been shown to reduce iatrogenic injury in pediatric and adult populations. Although motor-evoked potentials (MEP), somatosensory-evoked potentials (SSEP), and electromyography (EMG) have been shown to be highly sensitive and specific in detecting spinal cord and nerve root injuries, their utility in detecting motor and sensory nerve root injury in pediatric high-grade spondylolisthesis (HGS) remains unknown.

PURPOSE: We aim to assess the diagnostic accuracy and therapeutic impact of unimodal and multimodal IONM in the surgical management of HGS.

STUDY DESIGN/SETTING: Retrospective cohort study.

PATIENT SAMPLE: Pediatric patients undergoing posterior spinal fusion (PSF) for treatment of HGS.

OUTCOME MEASURES: Data on patient demographics, spinopelvic and spondylolisthesis parameters, and the presence of pre-and postoperative neurological deficits were collected.

METHODS: Intraoperative MEP, SSEP, and EMG alerts were recorded. Alert criteria were defined as a change in amplitude of more than 50% for MEP and/or SSEP, with or without change in latency, and more than 10 seconds of sustained EMG activity. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy were calculated for each modality and the combination of MEP and SSEP. The 95% confidence intervals (CIs) were calculated using the exact (Clopper-Pearson) method.

RESULTS: Fifty-four pediatric patients with HGS undergoing PSF between 2003 and 2021 in a single tertiary center were included. Seventy-two percent (39/54) of patients were female; the average age of patients was 13.7±2.3 years. The sensitivity of MEP in detecting new postoperative neurologic deficit was 92.3% (95% CI [64.0−99.8]), SSEP 77.8% (95% CI [40.0−97.2]), EMG 69.2% (95% CI [38.6−90.9]), and combination MEP and SSEP 100% (95% CI [73.5−100]). The specificity of MEP was 80.0% (95% CI [64.4−91.0]), SSEP 95.1% (95% CI [83.5−99.4]), EMG 65.9% (95% CI [49.4−79.9]), and combination MEP and SSEP 82.9% (95% CI [67.9−92.9]). The accuracy of SSEP was 92.0% (95% CI [80.8%−97.8%]), and the combination of MEP and SSEP was 86.8% (95% CI [74.7%−94.5%]). Twelve (22.2%) patients had a new motor or sensory deficit

FDA device/drug status: Not applicable.

Author disclosures: ***CL***: Nothing to disclose. ***RK***: Nothing to disclose. ***SS***: Nothing to disclose. ***MV***: Nothing to disclose. ***SJL***: Nothing to disclose. ***RZ***: Nothing to disclose. ***MC***: Nothing to disclose. ***BR***: Nothing to disclose. ***DEL***: Nothing to disclose.

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https://doi.org/10.1016/j.spinee.2023.08.002

diagnosed immediately postoperatively. Nine patients made a full recovery, and 3 had some neurologic deficit on final follow-up.
CONCLUSION: Unimodal IONM using SSEP and MEP alone were accurate in diagnosing sensory and motor nerve root injuries, respectively. The diagnostic accuracy in predicting motor and sensory nerve injuries in pediatric HGS improved further with the use of multimodal IONM (combining MEP and SEP). We recommend the utilization of multimodal IONM in all HGS PSF surgeries.

Keywords: Electromyography; High-grade spondylolisthesis; Intraoperative neuromonitoring; Motor evoked potentials; Pediatric spondylolisthesis; Somatosensory evoked potentials; Spondylolisthesis

Introduction

The surgical management of high-grade spondylolisthesis (HGS) carries a risk for neurologic injury, most commonly L5 radiculopathy and sacral root dysfunction [1,2]. Overall rates of postoperative neurological injury in HGS patients undergoing in situ fusion or reduction followed by fusion are estimated to be 2.1% and 10.0%, respectively [3]. Causes for mechanical nerve root injuries include ischemia resulting from injury to the vascular supply, retraction of paravertebral muscles, direct injury after fenestration of the lamina, and retraction of the nerve root [4,5]. In HGS the most common cause of nerve root injury is from stretch during reduction and manipulation procedures [6,7]. Increased disc height and reduction have been shown to significantly increase the tension on the L5 nerve root [6].

Currently, multimodal intraoperative neuromonitoring (MIONM), using a combination of free-run electromyography (EMG), somatosensory-evoked potentials (SSEP), and transcranial motor-evoked potentials (MEP) are commonly used in spine surgery as they have been shown to be highly sensitive and specific in detecting and preventing iatrogenic neurological complications during adult spine surgery [8−10]. While several studies have investigated the effectiveness of MIONM in the cervical spine, spine deformity, and intramedullary lesion surgery [11−16], none have addressed the accuracy of IONM in predicting new-onset neurological deficits after pediatric HGS surgery.

In the present study, we aim to assess the diagnostic accuracy of IONM in the surgical management of pediatric HGS. We hypothesize that multimodal IONM is highly sensitive and specific in diagnosing nerve root injuries in pediatric patients with HGS undergoing posterior spinal fusion surgery (PSF).

Methods

After obtaining approval from our institution's research ethics board, we carried out a retrospective analysis of all pediatric patients surgically treated with posterior spinal fusion with or without instrumentation and with or without reduction (Figs. 1 and 2) for HGS (Meyerding grade 3 or more), between January 2003 and March 2021. A total of 5 different surgeons and 3 IONM neurophysiologists performed the cases included in the analysis. There were a total of 67 procedures involving 54 patients. Thirteen revision cases from 8 of these patients were excluded. Patient demographics, radiographic parameters, and the presence of new postoperative neurological deficits were collected. All patients underwent multimodal IONM which incorporated posterior tibial SSEPs, MEPs, and EMGs and alerts for each were extracted. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy were calculated for each modality. Accuracy

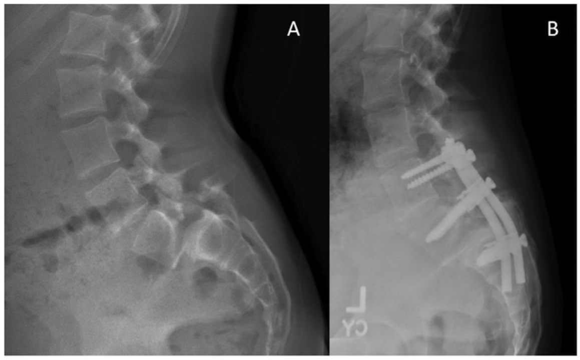

Fig. 1. Preoperative (A) and postoperative (B) X-Rays of a patient with HGS (high-grade spondylolisthesis) treated with posterior spinal instrumentation and fusion.

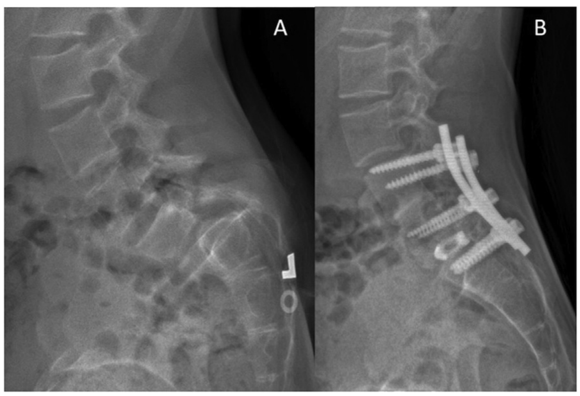

Fig. 2. Preoperative (A) and postoperative (B) X-Rays of a patient with HGS (high-grade spondylolisthesis) treated with posterior spinal instrumentation, reduction and fusion.

was defined as ratio of total correct predictions to the total number of patients examined. True-positive (TP) and true-negative (TN) cases were defined as, IONM correctly identified the presence or absence of a neurological complication, respectively. For false-positive (FP) cases, IONM incorrectly predicted the presence of a neurological complication, while for a false-negative (FN), IONM was unable to identify a neurological complication.

Anesthetic protocol

Over the course of the 19-year study period, a uniform anesthesia protocol was followed for all patients, facilitated by the consistent presence of one of our neurophysiologists performing IONM. A total intravenous anesthetic (TIVA) protocol was utilized to facilitate IONM. A bolus of Rocuronium (0.6 mg/kg) was used to facilitate tracheal intubation; no further neuromuscular blockade was given. Maintenance of anesthesia was a mixture of 30% oxygen in the air, continuous infusions of propofol at a rate of 90 to 150 μg/kg/min, and remifentanil at 0.1 to 0.3 μg/kg/min. Anesthesia was subsequently adjusted according to hemodynamic response and depth of anesthesia. Reversal of neuromuscular paralysis from the initial bolus was confirmed by recording a train-of-four muscle twitch prior to obtaining MEP, SEP, and EMG baselines. Infusions were discontinued after surgery.

All surgeries involving pedicle screw constructs included triggered EMG to test pedicle integrity. Any screw falling below the stimulation threshold was removed and reinserted along a safer trajectory. In addition, the screw position was further confirmed with an intraoperative X-ray.

Somatosensory evoked potentials

Bilateral L5 and S1 nerve roots were monitored by recording cortical and subcortical SSEPs after stimulation of the left and right posterior tibial (S1) and deep peroneal nerves (L5) using the Nicolet Endeavor CR platform (Natus Medical, Inc., Middleton, WI, USA) (Supplemental Fig. 2). The initial 32 procedures utilized only posterior tibial SEPs, and the remaining 35 procedures utilized both posterior tibial and peroneal SEPs. Stimulation was provided through surface gel electrodes (Rochester Electro-Medical, Tampa, FL, USA) placed over the posterior tibial nerve at the medial malleolus, and the deep peroneal nerve at the dorsum of the ankle, medial to the extensor hallucis longus tendon. A constant current 300-μs square-wave pulse was delivered at a rate of 4.7 per second, presented in turn to the posterior tibial and peroneal nerves. Stimulation intensity levels ranged from 30 to 40 mA based on maximal amplitude response of each individual patient. Signals were averaged until a clear, reproducible waveform could be identified. Cortical potentials were recorded from subdermal needle electrodes placed at Cpz, Cp3, Cp4, and Fpz according to the international 10 to 20 system using both a bipolar and transverse montage. Subcortical potentials were recorded similarly with an electrode placed over the region of the second cervical vertebra referenced to Fpz. Responses were recorded through a 30 to 500-Hz bandpass filter and displayed in a 100-ms window. Both the peroneal nerve and posterior tibial nerve SSEPs were examined at intervals of 5 minutes or less.

Motor evoked potentials

Transcranial electric motor evoked potentials were elicited using the Digitimer D185 (Digitimer, Hertfordshire, England) (Supplemental Fig. 1); delivering brief, 50 μs, high-voltage pulse trains. Stimulation was delivered between two subdermal needle electrodes inserted 2 cm anterior to C1 to C2 (international 10−20 system) overlying the motor cortex region. Stimulation parameters were optimized to achieve maximal amplitude response for the individual patient. Trains of five to nine pulses with an interstimulus interval ranging from 1.1 to 4.1 ms, were delivered with a constant voltage (200−500 V) at the anode. Resultant compound muscle action potentials (CMAPs) were recorded using subdermal needle electrodes, in a bipolar montage. The myogenic responses were recorded from bilateral adductors (L2−L4), rectus femoris (L2−L4), tibialis anterior (L4−L5), gastrocnemius (S1−S2), and anal sphincter muscles (S2−S4). In addition, recordings from first dorsal interosseous muscles were used as controls. The responses were recorded through a 30 to 1000-Hz bandpass filter and displayed in a 100-ms window. MEPs were intermittently tested between SSEP trials. During alerts or high-risk maneuvers such as spine reduction or cage insertion, both MEPs and SEPs were assessed more frequently.

Free running electromyography

Free running EMG was recorded across a 10 second sweep and 100 Uv display gain with same filter settings and muscle groups used to record MEPs. Furthermore, free-running EMG was continually monitored throughout the procedure. All procedures involving pedicle screw constructs included triggered EMG to test pedicle integrity. Any screw falling below the stimulation threshold, was removed and reinserted along a safer trajectory. In addition, screw position was further confirmed with intraoperative X-ray.

Alert criteria

Any decrease in SSEP or MEP amplitude was considered to be a deterioration of response and cause for examination. Significant SSEP or MEP alerts were classified as amplitude reductions greater than 50% of baseline with or without change in latency. Once technical issues were ruled out, significant changes occurring unilaterally or bilaterally warranted prompt action by the surgeon. All changes, including recovery after signal deterioration, were reported to the surgeon immediately. EMG was considered significant if there was ≥ 10 seconds of sustained neurogenic EMG activity.

Statistical analysis

Descriptive data was presented using means and standard deviations (SD). The Fischer's exact test was used to compare nominal variables. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy were calculated for each modality and for the combination of MEP and SSEP. The 95% confidence intervals (CIs) were calculated using the exact (Clopper-Pearson) method.

Results

Fifty-four patients with HGS undergoing PSF between 2003 and 2021 in a tertiary care center were reviewed and included in this analysis. The demographics of the cohort are shown in Table 1. Mean follow-up was 4.6 years (range 1.2−8.8 years). Thirty-nine patients (72.2%) were female and the average age was 13.7 (range 11.4−16.1) years. There were 27 patients (50%) with a preoperative Meyerding grade (MG) 3, 21 patients (38.9%) with MG 4 and 6 patients (11.1%) with MG 5. Patients were classified as Labelle 4 in 13 cases (24.1%), Labelle 5 in 27 cases (50%) and Labelle 6 in 14 cases (25.9%). Mean pelvic tilt (PT) was 35.2° (range 10°−87°). Pelvic incidence (PI) was 69.1° (range 27°−91°). Fifty patients (92.6%) had instrumentation. Table 2 demonstrates a summary of available information on perioperative factors and surgical procedures of the included patients.

Nineteen patients (35.2%) had intraoperative alerts that included changes in either SSEP or MEP alone or combined that were consistent with misplaced pedicle screws, decompression, and/or reduction of the spondylolisthesis. All SSEP alerts were identified after peroneal nerve stimulation. There were no changes to the posterior tibial nerve SSEPs. Surgical responses to these alerts included redirection of pedicle screws, further decompression of the nerve roots, and/or a decrease in the amount of spinal reduction.

Table 1
Baseline characteristics and spondylolisthesis parameters

Baseline demographics	
Sex	Female 39 (72%)
	Male 15 (28%)
Average Age	13.7 (Range: 11.4−16.1)
Meyerding Grade	Grade 3: 27 patients
	Grade 4: 21 patients
	Grade 5: 6 patients
Labelle Score	L4: 13 patients
	L5: 27 patients
	L6: 14 patients
Pelvic Tilt (PT)	35.2° (range 10°−87°)
Pelvic Incidence (PI)	69.1° (range 27°−91°)
Sacral Slope	37.0° (Range: 14−73)
Balanced Pelvis	Unbalanced: 41 patients
	Balanced: 13 patients
Balanced Spine	Unbalanced: 14 patients
	Balanced: 40 patients
Mean Follow Up	4.6 y (range 1.2−8.8)

Table 2
Surgical procedures and postoperative spinopelvic paraments

Perioperative factors	
Average number of levels fused	1.8 (SD: 0.4)
	28 L4−S1
	16 L4-Pelvis
	5 L5−S1
	2 L4−S2
	2 L5-Pelvis
	1 L3-Pelvis
Average reduction in Meyerding grade	1.6 (SD: 1.4)
Use of strut graft	2/54 cases (3.7%)
Use of interbody cages	12/54 cases (22.2%)
Average postoperative pelvic tilt (degrees)	33.4 (SD: 12.1)
Average postoperative pelvic incidence (degrees)	68.5 (SD: 16.0)
Average postoperative sacral slope (degrees)	40.9 (SD: 11.1)
Average postoperative C7-SVA (mm)	29.2 (SD: 26.4)

Twelve patients (22.2%) showed new postoperative weakness or dysesthesia in the L5 and S1 distribution. Three patients (5.6%) were symptomatic at last follow-up (Table 3). Alerts in all 12 patients were identified during the procedure, thus having no false negatives.

Seven patients (12.9%) had an intraoperative alert which resolved following a surgical response (Table 4). These patients were labeled as transient positives. All were asymptomatic postoperatively.

We created two models in order to classify these patients. The first model considered the transient positive patients as false positive since all awoke with no deficits. The second model considered these patients as true positives, as the signals recovered with surgical intervention (Table 5):

Model 1 - Transient positive considered as false positive

The sensitivity of combined MEP and SSEP was 100% (95% CI [73.5−100]), MEP 92.3% (95% CI [64.0−99.8]), SSEP 77.8% (95% CI [40.0−97.2]) and EMG 69.2 (95% CI [38.6−90.9]) (Table 5A). The specificity of combined MEP and SSEP was 80.5% (95% CI [65.1−91.2]), MEP 80.0% (95% CI [64.4−90.95]), SSEP 95.1% (95% CI [83.5 −99.4]) and EMG 65.9 (95% CI [49.4−79.9]).

Model 2- Transient positive considered as true positive

The sensitivity of combined MEP and SSEP was 100% (95% CI [82.4−100]), MEP 95.0% (95% CI [75.1−99.9]), SSEP 81.8% (95% CI [48.2−97.7]) and EMG 69.2 (95% CI [38.6−90.9]) (Table 5B). The specificity of combined MEP and SSEP was 97.1% (95% CI [84.7%−99.9%]), MEP 96.97% (95% CI [84.2%−99.9%]), SSEP 100% (95% CI [91−100]) and EMG 65.9 (95% CI [49.4−79.9]).

Table 3

Patients with new neurological postoperative deficit: IONM status at the end of procedure (% of baseline) and clinical postoperative evolution

Patient ID	Year of surgery	Year of last follow up	Meyerding	Labelle	MEPs						Peroneal SSEPs						Alert event	Response taken	Clinical examination (Motor, Sensory)	
					Alert		Postresponse		Close		Alert		Postresponse		Close				Inpatient stay	Last follow-up
					LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT				
1	2019	2022	5	5	L5 0%	L5 0%	L5 5%	L5 5%	L5 5%	L5 5%	0%	0%	10%	10%	10%	10%	after rod securing	decompress	Bilat L4−S1 3/5, 1/2	Resolved
10	2011	2015	3	5	100%	L5 10%	100%	L5 10%	100%	L5 100%−10%	100%	25%	100%	25%	50%−100%	75 %−25%	bony decomp, rod compression	decompress	Left L5−S1 5/5, 1/2	Resolved
18	2014	2015	3	5	L5 20%	100%	L5 20%	100%	L5 100%−20%	100%	0%	100%	0%	100%	100%−0%	100%	rod compression, reduction	decompress	Left L5 4/5, 2/2	Resolved
20	2011	2018	3	6	L5 5%	L5 25%	L5 20%	L5 50%	L5 25%	L5 75%	100% to N/A (peroneal SSEP not monitored)						reduction	decompress	Left L5 3/5, 2/2	Left L5 4/5
21	2007	2011	3	5	100%	L5-S1 50%	100%	L5-S1 70%	100%	L4-S1 75%	100%	100%	100%	100%	100%	100%	screw insertion	surgical pause	Right L4 2/5; L5 3/5, 2/2	Resolved
33	2017	2019	4	5	L4−5 50%	L4−5 50%	L4−5 50%	L4−5 50%	L4−5 50%	L4−5 50%	5%	5%	5%	5%	100%− 5%	100%− 5%	reduction	decompress x2	Bilat L4−L5 1/5, 2/2	Bilat L4-L5 4/5, neuropathic pain
36	2020	2021	4	4	L4−S1 10%	L4−S1 20%	L4−S1 10%	L4−S1 30%	L4−S1 10%	L4−S1 100%−40%	100%	100%	100%	100%	75%	100%	rod securing, reduction	pause, remove rod, decompress	Left L4−S1 4/5, 1/2	Resolved
40	2017	2019	4	6	L4/5 5%	L4−S1 0%	L4/5 5%	L4−S1 5%	L4/5 5%	L4−5 5%	0%	0%	0%	0%	0%	0%	reduction	decompress, release correction, remove screw	Left L4−5: 3/5, 1/2 Right L4−5: 0/5, 1/2	Left L4-5: 4/5, 1/2 Right L4-5: 2/5, 1/2
41	2008	2017	4	5	100%	S1 10%	100%	S1 40%	100%	S1 50%	100%	100%	100%	100%	100%	100%	retraction of nerve	release retraction, surgical pause	Bilat L4−S1 4/5, 1/2	Resolved
48	2008	2013	4	5	100%	100%	100%	100%	100%	100%	N/A (peroneal SSEP not monitored)						Unknown	[missed alert]	Bilat L4−5 5/5, 1/2	Resolved
53	2014	2018	3	5	L4/5 0%	L4/5 0%	L4/5 10%	L4/5 10%	L4/5 10%	L4/5 10%	0%	0%	10%	10%	10%	10%	cage insertion	smaller cage, decompress	Bilat L4−S1 4/5, 1/2	Resolved
54	2020	2022	3	6	L5−S1 25%	100%	L5 50%	100%	L5 50%	100%	100%	100%	100%	100%	100%	100%	screw insertion, reduction	reshape rod x2, decompress	Left L5 4/5, 2/2	Resolved

Table 4
Patients with transient positive IONM: alert, surgical response changes, IONM status at closure (% of Baseline), and response taken

Patient ID	MEPs						Peroneal SSEPs						Alert event	Response taken
	Alert		Postresponse		Close		Alert		Postresponse		Close			
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT		
5	L5−S1 50%	L5−S1 50%	L5−S1 70%	L5−S1 70%	L5: 100% S1: 80%	L5−S1 100%	100%	100%	100%	100%	100%	100%	mechanical hit of nerve	surgical pause
19	100%	S1 50%	100%	S1 70%	100%	S1 100%	100%	100%	100%	100%	100%	100%	discectomy	surgical pause
36	L5 25%	100%	L5 50%	100%	L5 100%	100%	0%	100%	25%	100%	50%	100%	reduction	decompress
44	L5−S1 40%	100%	L5−S1 50%	100%	L5−S1 75%	100%	100%	100%	100%	100%	100%	100%	reduction	decompress
60	L4−S1 0%	L4−S1 0%	L4−S1 100%	L4−S1 100%	L4−S1 100%	L4−S1 100%	0%	0%	80%	80%	100%	100%	reduction	rod release x5, decompress, decrease reduction
61	100%	L5−S1 5%	100%	L5−S1 75%	100%	L5−S1 75%	100%	100%	100%	100%	100%	100%	reduction	rod release, decrease reduction
62	L5 50%	100%	L5 100%	100%	L5 100%	100%	100%	100%	100%	100%	100%	100%	reduction	decrease reduction

Discussion

IONM has been shown to be an effective tool in reducing and preventing intraoperative neurologic injury in a variety of adult and pediatric spine surgeries [17]. However, the accuracy and efficacy of IONM in pediatric HGS is not well examined. In this study we sought to determine the diagnostic accuracy of various IONM modalities for pediatric HGS. Based on this cohort unimodal IONM using SSEP or MEP alone were accurate in diagnosing sensory and motor nerve root injuries, respectively. The diagnostic accuracy in predicting motor and sensory nerve injuries in pediatric HGS improved further when multimodal IONM was utilized. In over 54 studied patients, the negative predictive value reached 100%. On the contrary, EMG alone was not accurate in diagnosing injury, with a sensitivity and specificity of 69.2% and 65.9%, respectively.

In this cohort 22.2% of patients showed new postoperative weakness or dysesthesia in the L5 and S1 distribution, of whom 5.6% of cases had neurologic symptoms at last follow-up. Our findings are in line with previous studies; in the immediate postoperative period, the rate of new neurologic deficits is estimated to be between 20% and 50%, and permanent neurologic deficit is reported to between 2% and 10%, depending on surgical method (in situ fusion vs reduction followed by fusion) [3,18−20]. In this cohort all patients with new postoperative neurological deficits were identified using IONM, resulting in no false negatives and a sensitivity of 100% using a combined MEP and SSEP approach.

Furthermore, seven patients (12.9%) had an intraoperative alert which recovered following a surgical response and these patients were asymptomatic postoperatively (transient positive patients). We decided to create two

Table 5
Tables displaying sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy of various neuromonitoring modalities. A - Transient positive considered as false positive and B - Transient positive considered as true positive

Modality's effectiveness in predicting all (motor and sensory) outcomes

A- Model 1

	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Accuracy (%)
MEP & SSEP	100.0%	80.5%	60.0%	100.0%	84.9%
MEP	92.3%	80.0%	60.0%	97.0%	83.0%
SSEP	77.8%	95.1%	77.8%	95.1%	92.0%
EMG	69.2%	65.9%	39.1%	87.1%	66.7%

B- Model 2

	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Accuracy (%)
MEP & SSEP	100.0%	97.1%	95.0%	100.0%	98.1%
MEP	95.0%	97.0%	95.0%	97.0%	96.2%
SSEP	81.8%	100.0%	100.0%	95.1%	96.0%
EMG	69.2%	65.9%	95.1%	87.1%	66.7%

different models (Model 1 - transient positive considered as false positive and Model 2 - transient positive considered as true positive) since currently there is no agreement in the literature on how to classify them [8,10,15,21,22]. Neira et al. [22] considered cases in which an alert signal that recovered with no new neurologic deficits as true positives. Thuet et al. [21] had warning criteria events in 79% of their patients, which was followed by an intervention; patients subsequently awoke with unchanged neurologic status and these patients were classified as transient true positives as well. Conversely, Wilent et al. [8] classified their transient positive cases as false positive if patients awoke with unchanged neurologic status. Previously, Holdefer et al. [23] discussed the challenges associate with classification of reversible signal changes. They argue against use of 2 × 2 contingency analysis for reversible signals as there is no consensus on classification of such reversible signal changes.

In our study, there are two possible explanations for these seven patients. Either these alerts were impending deficits and improvement in all cases were due to surgical intervention, or these cases were false positives and the recovery in the IONM alert was not due to the interventions attempted. As such, in this study we constructed two models in which transient positive patients were considered as false positives or true positives. This led to two different models, both of which demonstrated 100% sensitivity with acceptable specificities of 80.5% and 97.1%, respectively, when combining MEP and SEP.

While based on this methodology, no robust causality can be made in attributing the resolution in alerts to intraoperative interventions applied, we hypothesize that these changes are due to intraoperative surgical interventions considering the rates of postoperative neurologic deficits in our cohort compared to the Scoliosis Research Society Morbidity and Mortality database on patients undergoing surgery for high-grade spondylolisthesis [24]. Therefore, it can be argued that not only is combined IONM a sensitive tool for detecting impending neurologic injury, but it can also lead to the prevention of poor neurological outcomes. Accordingly, the global adoption of multimodal IONM in HGS surgery could be highly beneficial.

Strengths and limitations

This is the first study to investigate IONM accuracy in pediatric HGS. High-grade pediatric spondylolisthesis is relatively rare; thus, a strength of this study is that it presents a large cohort of surgically treated pediatric patients with HGS. Furthermore, this study considers and offers two models for calculating the accuracy of IONM for HGS surgery. Limitations of this study include its retrospective nature, which inherently increases the likelihood of inaccurate or incomplete chart documentations. Furthermore, this study presents the results of a single tertiary center and may not be generalizable to other settings with different IONM setups.

Conclusion

The risk of new neurologic nerve root injury is high during reduction of high-grade L5/S1 spondylolisthesis. Unimodal IONM using SSEP and MEP alone were accurate in diagnosing sensory and motor nerve root injuries, respectively. The diagnostic accuracy in predicting motor and sensory nerve injuries in pediatric HGS improved further with the use of multimodal IONM (combining MEP and SEP). We recommend the utilization of multimodal IONM in all HGS PSF surgeries, as accurate diagnosis of nerve root injuries may allow for timely intraoperative interventions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

There was no funding or financial support utilized to carry out this research.

Supplementary materials

Supplementary material associated with this article can be found in the online version at https://doi.org/10.1016/j.spinee.2023.08.002.

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