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Intraoperative Neurophysiological Monitoring in Spine Deformity Surgery

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Abstract

Although the incidence of neurologic injury in deformity surgery is low, the repercussions are devastating; therefore, every measure available should be adopted to minimize that risk. Advances in instrumentation have been paralleled by the development and improved understanding of intraoperative neurophysiological monitoring which enables lower morbidity in increasingly complex surgeries. Currently, multimodality intraoperative neurophysiological monitoring includes somatosensory-evoked potentials, transcranial motor–evoked potentials, triggered electromyographic stimulation, and mixed neurogenic evoked potentials. The combination of these monitoring modalities provides the greatest sensitivity in detecting impending neurologic compromise during deformity surgery.

Keywords: Intraoperative neurophysiologic monitoring; Somatosensory evoked potentials; Transcranial motor evoked potentials; Triggered electromyographic stimulation; Spine deformity

Introduction

Technological advances have allowed surgeons to perform more complex spinal procedures with lower morbidity. However, spinal cord injury continues to have a reported incidence of 0.3% to 1.4% [1,2]. The use of intraoperative neuromonitoring (IONM) has increased the safety of surgical deformity correction by providing a warning system designed to minimize the risk of neurologic injury.

Intraoperative clinical assessments, such as the wake-up and ankle clonus tests, however, are limited by their lack of a real-time and continuous assessment of spinal cord integrity [3,4]. These tests reflect global spinal function and are unable to provide an immediate assessment of specific dorsal sensory or ventral motor cord tracts. Furthermore, the time interval between injury onset and injury detection may jeopardize a window of opportunity for intervention, which may result in a transient neurologic deficit becoming permanent. Such limitations have served as the impetus for the development of IONM, which offers a real-time indicator of spinal cord integrity in patients undergoing corrective scoliosis surgery.

Somatosensory-Evoked Potential Monitoring

Somatosensory-evoked potential (SSEP) monitoring was first popularized by Nash et al. in 1977 for use in detecting impending neurologic injury during scoliosis surgery [5]. Since that time, SSEP has been described as the gold standard against which all other IONM techniques continue to be compared. SSEP monitoring represents the averaging of electrical responses to repetitive electrical or mechanical stimulation of a peripheral nerve, reflecting physiological recording of the primary sensory pathways. Parameters of abnormal change in SSEP monitoring are variable and

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range from decreases in amplitude of 50% to 60% to increased latency of 10% or 2 milliseconds [6-8]. Although specific parameters have not been standardized, multiple series have reported SSEP monitoring as highly effective at reducing the rate of neurologic injuries when compared with matched, unmonitored procedures [9,10].

Additionally, SSEP monitoring is able to detect injuries at the time of insult and obtain continuous recordings, and it can be performed on patients who are neurologically compromised [9,10]. SSEP monitoring can avoid the well-known complications of the wake-up test. Furthermore, ulnar nerve SSEP monitoring has demonstrated effectiveness in the detection of impending positional injury.

Numerous studies have demonstrated the efficacy of SSEP in reducing the rate of new neurologic deficits in patients with scoliosis [11]. Compared with the results from MacEwen et al. in 1975, in which no intraoperative monitoring was used [12], Nuwer et al. found that SSEP was effective at reducing the rate of major new-onset neurologic deficits by approximately 60% [10]. In their survey of 51,263 scoliosis procedures, the authors reported an overall sensitivity of SSEP of 92%, with a tendency toward a relatively high rate of false positives. Other series have reported SSEP sensitivity ranging from 27% to 100% with specificity ranging from 92% to 98% [6,10,11,13].

Despite its improvement over clinical evaluation, SSEP has limitations that have become a topic of growing concern among spinal deformity surgeons. Because SSEP primarily assesses the integrity of the dorsal sensory columns, primary motor injuries may go undetected. Pelosi et al. reported a 2.4% false-negative rate using SSEP, compared with no false negatives using transcranial motor−evoked potential (tcMEP)[14]. Others have similarly reported a failure of SSEP to detect new-onset neurologic deficits that were identified by tcMEP [6,15,16]. In contradiction, Thuet et al. reported SSEP changes as the only warning in 26 of 74 patients with neurologic changes from a series of 3,436 pediatric patients undergoing spinal instrumentation [7].

In addition to reduced sensitivity in the detection of impending neurologic injury, there is a well-documented delay in the detection of ischemic injury when using SSEP compared with tcMEP. Schwartz et al. showed that the average time to SSEP detection of an intraoperative alert lagged behind that of tcMEP by an average of 5 minutes [6]. Although SSEP monitoring may not be as sensitive to impending spinal motor injury as other neuromonitoring modalities, its use provides additional benefits that increase the safety of deformity surgery in the appropriate setting.

Transcranial Motor−Evoked Potential Monitoring

Motor pathway monitoring with tcMEPs with spinal cord signal (D wave) and muscle compound motor action potential (CMAP), electrical potential that results from stimulation of the motor nerve innervating a specific group of muscles, was introduced in 1986 [17,18]. Merton's initial single stimulus work was instrumental to the development of tcMEPs [18], but widespread use was significantly hampered because of the effects of volatile anesthetics. Introduction of high-frequency multi-pulse stimulation technique permitted tcMEP recording under some forms of anesthesia [19]. Advances in anesthesia, specifically total intravenous anesthesia, have made tcMEPs easier to obtain.

Transcranial motor−evoked potential monitors corticospinal tract activity via stimulation at the level of the motor cortex or spinal cord and is selective for motor pathways, albeit only monitoring 4% to 5% of the motor neuron pool. TcMEP monitoring relies upon intervening thalamic synapses to prevent antidromic firing of spinal sensory tracts. The stimulation site for tcMEP is the cerebral cortex. TcMEP endpoint data are ascertained from the spinal cord (D wave) or from the end muscle (CMAP) and, although not mutually exclusive, have strengths and weaknesses attributable to each (Table).

Stimuli are presented as single high-voltage or multiple small stimuli. Train stimulus is preferable because it permits reduced voltage application and thus diminished muscle reactivity. There is no clear consensus on the optimal parameters of the short-train stimuli. Sources of stimulation include magnetic and electrical. Types of electrodes include cup, needle, and corkscrew. Although occasionally associated with scalp edema and unreliable recordings, corkscrew electrodes are preferable given their low impedance and secure positioning in the scalp.

Peripheral data are commonly electromyographic (EMG) via CMAP. The CMAP is best monitored at sites rich in corticospinal tract innervation, such as the distal limb muscles. Common recording sites are abductor pollicis brevis or adductor hallucis brevis, with viable alternatives of long forearm flexors and extensors in the upper extremity [19] and tibialis anterior in the lower extremity. Although there does not appear to be any monitoring advantage to increasing the number of monitored muscles, increased muscle group testing might provide a benefit in identifying positioning-related injury.

An alternative to CMAP monitoring is recording at the spinal cord itself (D wave). The D wave is the initial wave associated with direct conduction of corticospinal neurons. The advantages and disadvantages of CMAP versus D-wave recordings have been described (Table). CMAPs are a reflection of the entire motor system [20] and may be more sensitive to ischemic changes [21]. Because patient movement during CMAP recording can affect a surgeon's desire to perform testing, frequency of testing is reduced, which reduces sensitivity of testing. As opposed to myogenic recordings, D-wave recordings benefit from complete muscle relaxation with the advantage of elimination of patient movement.

Transcranial motor−evoked potential monitoring reliability diminishes in the isolated population of patients with antecedent neurologic deficit. Further, although tcMEP monitoring is considered to be safe, relative contraindications include epilepsy, cortical lesion, skull defect (eg,

Table
Comparison of CMAP versus D wave utility when used as part of transcranial motor–evoked potential monitoring.

Intraoperative Monitoring Function	CMAP	D Wave
Reflection of entire motor system	X [20]	
Delineates laterality	X	
Lower false-positive rate in scoliosis surgery	X	27% false pos [43]
Can monitor lowest sacral roots including sphincter	X	D wave difficult to acquire below midthoracic levels [22]
Less sensitive to halogenated anesthetics		X
Can be recorded with neuromuscular blockade		X
Causes little or no movement during application and can be performed continuously		X
Valuable for IMSCT resection	X	X
Absent in 20% of patients with IMSCT or postradiative myelopathy		X [44]
Provides earliest warning of vascular cord compromise	X [45,46]	
May be effective for spinal cord embolism procedures	X	
Requires epidural catheter placement		X
Data acquisition potentially inhibited by dural adhesions and scar		X
Sensitive to muscle ischemia	X [21]	
May be more predictive of motor outcome with resection of IMSCT		X

Abbreviations: CMAP, compound motor action potential; IMSCT, intramedullary spinal cord tumor.

fontanelle or previous craniectomy), proconvulsant medication, cardiac pacing, and implantable device [22].

Anesthesia can have a significant impact on synaptic junctions necessitating careful attention to pharmacology during surgery. Although inhalation anesthetics and muscle relaxants can be used for induction, their use must be curtailed immediately thereafter. Inhalational anesthetics reduce the effectiveness of cranial stimulation, and muscle relaxants inhibit data acquisition at the muscle endpoint. Initially, a balanced regimen of nitrous oxide, narcotic, and propofol was recommended, but there has been a shift towards the use of total intravenous anesthesia inclusive of propofol, ketamine, and, more recently, dexmedetomidine. Even when total intravenous anesthesia is applied appropriately, tcMEPs may not be successfully generated in all patients [23].

In 1,121 patients with idiopathic scoliosis, a 65% decrease in tcMEP amplitude always predicted postoperative motor deficit, whereas SSEPs picked up a change 43% of the time [6]. TcMEPs have also been demonstrated to be more sensitive in detecting spinal cord ischemia when not diminished by hypothermia and hypoperfusion [24]. Motor signals tend to deteriorate progressively, providing a time window for response and perhaps reversal, with the exception of anterior spinal artery syndrome [25].

Transcranial motor–evoked potential monitoring during resection of intramedullary spinal cord tumor correlates well with motor outcomes [26]. A 20% change in D wave can be considered a warning, whereas a 50% decrement should be regarded with urgency [26,27]. Because of significant overlap of myotomal innervation, it is unlikely that muscle tcMEPs can provide enough information about nerve roots to demonstrate intraoperative root lesion.

Transcranial motor–evoked potential monitoring provides a repeatable snapshot that permits immediate assessment of spinal cord function after high-risk maneuvers such as correction. This is contrary and superior to SSEPs, which require a 3 to 5 minute summation before warning of potentially irreversible changes.

An alternative or adjunct to tcMEPs showing some promise is the H-reflex. Loss of H-reflex, or significant amplitude reduction, correlates with neurologic motor outcome. The H-reflex is affected less by anesthesia than tcMEPs [28] and can be recorded in some patients in whom SSEPs and tcMEPs cannot [25]. Although false positives are known to occur, H-reflex monitoring provides information about the integrity of both afferent and efferent connections, and it alerts the surgeon to disruption of this pathway. It is assumed that when the motor pathways are injured, the subsequent hyperpolarization of the alpha-motoneurons will result in a significant decrease in the amplitude of the H-reflex.

Although TcMEP monitoring is linked to few untoward effects [22] and has clear advantages, it still requires that other monitoring modalities, such as SSEPs or electromyography, are used to provide the most complete picture of neurologic function.

Neurogenic Mixed–Evoked Potential Monitoring

Neurogenic mixed–evoked potentials (NMEP) were first described in 1991 by Owen et al. [29]. They were initially termed *neurogenic motor evoked potentials* and were thought to represent the motor and sensory pathways. More recent studies have suggested that NMEP appear to represent antidromic stimulation of sensory pathways or possibly a combination of both motor and sensory signals [30]. The term *descending neurogenic evoked potentials* has also been used to describe this modality of neuromonitoring.

The initial technique involved placement of an electrode at the base of the spinous process or in cancellous bone at the rostral surgical exposure with impulses recorded at distal peripheral nerves, such as the sciatic notch or popliteal fossa. However, variations have subsequently been described with comparable reliability and include rostral electrode placement through percutaneous techniques into 2 adjacent cervical interspinous spaces or percutaneously into the spinous processes [7,31,32]. As is the case with other neurologic monitoring modalities, significant variability exists in defining an abnormal change in neurophysiologic function; thresholds reported have ranged from 60% to 80% change in amplitude, 10% increase in latency, or nonspecific sudden changes in morphology or amplitude [7,8,32].

Several series have reported the benefit of concomitant use of NMEP along with other modalities in deformity surgery. Although Owen et al. initially reported no false positives from a series of 300 patients after technical errors were corrected [29], Schwartz et al. reported false-positive findings in 3 patients who underwent NMEP [33]. Several series have reported improved sensitivities with adjuvant use of NMEP and SSEP together [7,8]. Accadbled et al. reported a sensitivity of 100% using both SSEP and NMEP with epidural leads and a specificity of 52.7% [34]. In a larger series of 74 patients with potential neurologic deficits, Thuet et al. observed that NMEP was the only abnormal recording in 25/74 (33.5%) of abnormal cases, whereas 20/74 (27%) had both abnormal SSEP and NMEP values [7]. SSEP monitoring was the only abnormal recording in 26/74 (35%) of these cases, and 7 patients (0.2%) had neurologic deficits that were not identified by any neurophysiological monitoring [7]. As with other modalities, a range of sensitivities and specificities are associated with NMEP monitoring.

Although the exact physiological pathways stimulated and recorded through NMEP remain unclear, NMEP appears to provide the surgeon with additional information that can be used to minimize risk.

Electromyography

Electromyographic (EMG) monitoring is used to assess the integrity of the spinal nerve roots. EMG monitoring is performed by placing subdermal needle electrodes into the muscle groups innervated by the spinal nerves relevant to the surgery. For upper thoracic (T2–T6) pedicle screw placement, electrodes are placed at the corresponding intercostal space at the nipple line and CMAP activity from intercostal musculature is assessed. For lower thoracic (T7–T12) screws, according to the method described by Shi et al., paired electrodes are placed along the nipple line at evenly separated distances between the lower margin of the tenth rib and the iliac ridge [35]. In most instances of lower thoracic screw monitoring, CMAP activity from the rectus abdominus musculature is assessed [36].

The monitoring regimen consists of 2 components: 1) spontaneous EMG (spEMG) and 2) stimulated EMG (stEMG). Spontaneous EMG is continuously acquired data from spontaneous muscle activity at rest. With chronic nerve root compression, train activity in spEMG recordings is the most common pattern seen. More acute changes in spEMG activity may manifest as burst or train activity as a result of mechanical stretching, retraction, or sudden compression on a nerve root. The major contribution of spEMG monitoring is its ability to instantly notify the surgical team that a nerve root insult is present. It does not, however, provide information on the status of the conduction of the nerve root subsequent to intraoperative injury. The rate of postoperative neurologic injury after spEMG activity is low, indicating a low specificity. Stimulated EMG, however, involves the electrical stimulation of a pedicle channel or screw and the recording of the stimulation threshold that is required to achieve a CMAP. The EMG stimulating probe is placed into the pedicle channel and/or on the surface of the pedicle screw and a stimulation threshold is recorded.

Studies have confirmed a significant correlation between low screw stimulation thresholds and misdirected lumbar pedicle screws [35–37]. Overall, the negative predictive value of lumbar pedicle screw stEMG monitoring is 98% when the impedance values were $\geqslant$11 mA [35]. If the threshold is low ($<$6-7 mA), a pedicle breach is more likely. Raynor et al. reported that all screws with stimulating thresholds $>$6 mA were safe and without medial wall breach and that only thresholds less than 60% to 65% of the average of all other thresholds should be considered abnormal [36]. These criteria have been validated in a series [38]; however, when the senior author compared stEMG to postoperative computed tomography imaging in 937 thoracic pedicle screws, he observed that 17% of 47 medial breaches were associated with stimulation thresholds of $\leqslant$6 mA, whereas 49% stimulated between 6 and 10 mA, and 34% stimulated at $\geqslant$10 mA. Only 21.3% fulfilled criteria of a decrease in threshold value greater than 65%, and thresholds were not as reliable in predicting lateral breaches [39].

EMG monitoring of pedicle screws is more reliable in the thoracolumbar junction and the lumbar spine but does provide additional tools to minimize catastrophic injury in deformity surgery. Although insufficient when used alone as a safety measure, it provides additional information that can aid the surgeon and reduce risk to the patient.

Multimodality Intraoperative Monitoring

Somatosensory-evoked potential monitoring is the most common modality employed but is not always a sufficient proxy for all cord function. Failing to recognize the limitations of SSEPs can have dire consequences [40]. It has been shown that no single modality sufficiently monitors all spinal cord pathways. If the goal of IONM is to detect the onset of deficit for both sensory and motor pathways, then no single IONM approach meets the goal; however, a combination of testing methods might.

Multimodality intraoperative monitoring uses all electrophysiological techniques that can provide intraoperative information about the neural structures at risk. It permits assessment of both ascending and descending pathways concurrently, providing a certain degree of redundancy as many types of intraoperative injuries will compromise both motor and sensory pathways [41]. Redundancy is of great value when technical factors such as electrical interference or anesthetic limitations reduce effectiveness of one monitoring modality.

In scoliosis surgery, there is a higher risk of misdirection of instrumentation because of abnormal spine curvature and rotation, and also a higher risk of neural injury because of increased proximity of the spinal cord to the concave wall of the scoliotic spine. Furthermore, scoliosis surgery often requires significant correction that can place the cord at risk from mechanical and vascular injury.

Hamilton et al. reported outcomes from the Scoliosis Research Society Morbidity and Mortality database summarizing 108,419 spine patients [42]. The overall incidence of new neurologic injury was 0.95%, with 0.27% representing spinal cord injuries. In the pediatric population (younger than 21 years), the incidence of neurologic injury was 1.32%. IONM was used in 65% of all reported cases and 87% of pediatric cases; however, IONM was used in only 238 of 293 patients who suffered spinal cord injuries. Monitoring modalities varied from SSEP alone (41 patients), tcMEP alone (13), and both (61). The sensitivity and specificity for concurrent use of SSEP and tcMEP in detecting spinal cord injury was 0.43 and 0.98. In patients who developed new nerve root injury, SSEP and EMG used concurrently had a sensitivity and specificity of 0.13 and 0.99. Although multimodality monitoring is becoming the mainstay, significant variability in its use is still apparent [42].

Other series have similarly echoed the increasing use and validation of multimodality monitoring [6–8,14,16,32]. Thuet et al. combined SSEP, tcMEP, NMEP, EMG and dermatomal SSEP in 3,436 pediatric patients undergoing spinal instrumentation and observed neurophysiological changes in 74 patients (2.2%) [7]. SSEP was the only indicator in 35% of cases, NMEP alone was abnormal in 33%, both were abnormal in 27%, SSEP and tcMEP were the indicators in 1.5%, and SSEP with dermatomal SSEP was the only change in 1.5%. Still, 7 patients had false-negative readings and awoke with new neurologic deficits. The majority were nerve root injuries, but one spinal cord injury was reported. Using the combination of modalities, Thuet et al. suggested that IONM was able to detect permanent neurologic changes in 97.9% of patients [7].

What to Do When the Signals Change

The occurrence of a neuromonitoring alert necessitates a surgical pause with consideration of reversing the last corrective maneuver. This may include releasing distraction or removing a pedicle screw, hook, cable, or corrective rod if the timing of neuromonitoring alert corresponded with a specific event (Figs. 1 and 2). In addition, other potential systemic causes including technical issues (ie, unintentional lead removal), body temperature (>35.0°C), hemoglobin (>10), and anesthesia should be immediately evaluated. Simultaneously, the mean arterial blood pressure is increased to at least 80 mm Hg. For patients who are hypertensive at baseline, it is important to titrate the mean arterial blood pressure so it exceeds baseline values. The surgeon should ensure that there has been no inadvertent mass effect on the spinal cord, such as from gel foam, hematoma, or bone fragment. For cases where a 3-column osteotomy procedure has been performed, evaluation for excessive shortening, dural buckling, and spinal translation should be performed. After these are optimized, the signals should be rechecked, and if they remain reduced, a Stagnara wake-up test is performed. If there is no movement in the

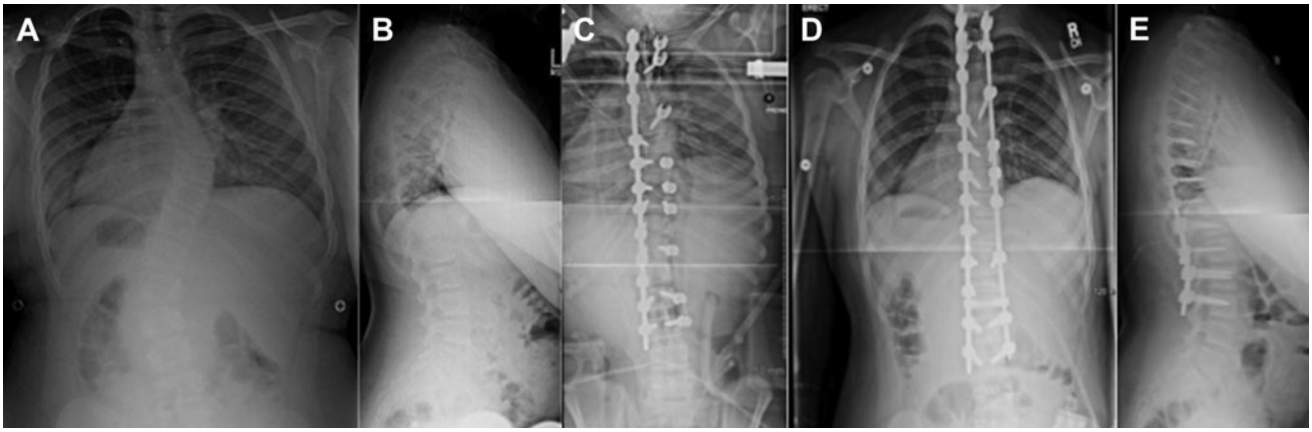

Fig. 1. (A and B) PA and lateral radiograph of a 12-year-old girl with a main thoracic curve measuring 54 degrees. Her proximal thoracic curve measured 26 degrees and her lumbar curve measured 47 degrees. She underwent a T2 to L3 posterior spinal fusion using pedicle screw fixation and Ponte osteotomies from T6 to L1. (C) During the rod translation, tcMEPs were lost in the lower extremities with stable SSEPs. Her mean arterial pressures (MAPs) had been maintained > 80 mm Hg at the time and her hematocrit was stable. No obvious etiology was identified and the rod was removed. Sedation was lightened as she was prepared for a Stagnara wake-up test. As she was starting to lighten, her tcMEPs returned to baseline. At this point the MAPs were increased to > 90 mm H and a decision was made to proceed with the surgery. Both rods were placed with slightly less correction. (D and E) Postoperative PA and lateral. radiographs.

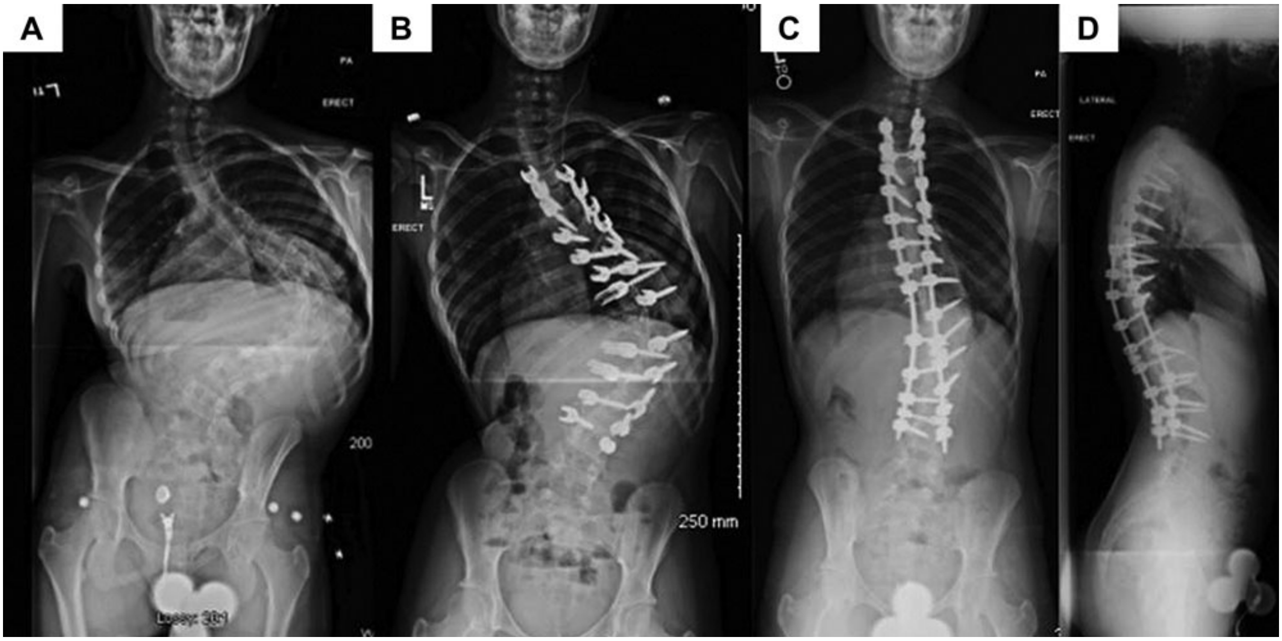

Fig. 2. (A) PA radiograph of a 16-year-old boy with neurofibromatosis I and a 140 degree curve. (B) He underwent a planned 2 stage procedure, where the first stage was composed of Ponte osteotomies from T2 to L4 and placement of the pedicle screws. (C and D) He was then placed in halo gravity traction and then later returned for apical wedge resection of T9 with completion of the correction. SSEP and TcMEP monitoring were used collaboratively in both stages without any significant changes. However, after completion of his correction, he was unable to dorsiflex his right foot. His remaining neurological exam was unremarkable with normal sensation and normal strength in remaining muscle groups, including foot inversion. CT imaging corroborated appropriate placement of screws without any breaches. He was thought to have had a peroneal nerve palsy that resolved over 2 weeks.

extremities with the Stagnara wake-up test, or if a Stagnara wake-up test is not possible, removal of any implants that have the potential for entering the spinal canal should be considered. Any neurologic deficit upon awakening from the surgical procedure requires advanced radiographic imaging that might include a computed tomography, magnetic resonance imaging, or computed tomography myelogram, depending on the status of the patient and whether implants are retained. Any persistent monitoring alert or deficit detected on Stagnara wake-up test usually results in halting the surgical procedure and returning to the operating room for completion at a later time. Typically, one should consider removing all the implants to ensure optimal postoperative imaging, except when the spine will be rendered grossly unstable, as with a vertebral column resection.

Summary

Progressive advances in IONM technology and new modalities have permitted increasing safety and lower morbidity in increasingly complicated surgeries. The incidence of neurologic injury is low but has devastating consequences for patients; therefore, every beneficial tool should be adopted by the surgeon to minimize the risk. Current optimal therapy includes multimodality intraoperative neurophysiological monitoring, but significant practice variability still exists. Even with multimodality monitoring, occasional cases of false negatives or delayed neurologic decline have been reported.

Intraoperative neuromonitoring is useful in minimizing complications; however, it is not perfect. Continued studies to standardize optimal parameters and improve upon current modalities are required. Future research efforts should be directed toward improved detection of nerve root injuries, as seen in spondylolisthesis reduction, and monitoring of the compromised spinal cord.

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