Neuromonitoring Changes in Spinal Deformity Surgery

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KEYWORDS

- Neuromonitoring changes • Scoliosis • Cord injury • Motor evoked potential
- Somatosensory evoked potential

KEY POINTS

- Spinal cord injury is one of the most feared complications in spinal deformity surgery, with an incidence of major neurologic injury reported to range from 0.01% to 0.05%.
- By monitoring afferent and efferent pathways, spinal cord injury is detected early and potentially corrected before it becomes irreversible.
- Understanding the spinal cord anatomy, and the modes of monitoring for injury, helps the physician better understand the response to intraoperative signal changes.
- Having a well-defined, algorithmic protocol in place helps direct the response to intraoperative signal changes and avoid errors during these stressful moments.

INTRODUCTION

Injury to the spinal cord or exiting nerve roots is one of the most feared complications of spinal surgery.[1] The effects of intraoperative complications are devastating not only for the patient, but for the surgeon and all involved. The concept of the surgeon being the "second victim," and the hospital system being the "third victim" is well described in literature.[2,3] This refers to the psychological and financial impact these complications have on the surgeon and health care system and can have a ripple effect that goes well beyond those involved in the primary incident. Not all complications are created equally, and those in spine surgery have devastating, and potentially life-threatening repercussions. The presence of deformity, and associated variation in anatomic location of nerves and vessels augment the potential for these complications.[4] Patients and surgeons are aware of the potential complications of surgery, but little can prepare them for the psychological, mental, and emotional toll that one of these complications has. Fortunately, with improvements in neuromonitoring, the incidence of cord injury has significantly decreased.[5]

The cord depends on adequate perfusion to function, and is sensitive to mechanical changes. Thus injury to the cord can come either from direct trauma through errant screw placement, indirect trauma via hypoxic insult, or neuropraxic insult via stretch during correction.[6] The spinal cord consists of ascending sensory nerve fibers, and descending motor nerve fibers. During surgery, one or both are monitored to provide warning signs when there is injury to the cord, or an excessive amount of stress. Simultaneous multimodal monitoring provides nearly 100% sensitivity and specificity for injury,[7,8] so monitoring both is ideal. It is also best to have an experienced neuromonitoring technician in the room evaluating the feedback, because multiple studies have shown a direct relationship between experience and reliability in monitoring interpretations.[9,10] These same studies also show that there is an increased rate of postoperative neurologic deficit with less experience.

Even with an exceptional understanding of anatomy, and appropriate neuromonitoring, all surgeons experience intraoperative neuromonitoring changes in their career. The incidence of major neurologic injury is reported to range

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from 0.01% to 0.05%, with some centers reporting a monitoring change leading to an alert 13% of the time.[11,12] This is a stressful moment where all sources of injury must be considered to potentially reverse the cause and prevent long-term deficit. A surgeon's performance suffers under stress and time pressure,[6] and cortisol released during these moments can significantly impair memory retrieval.[13] It is best to avoid poor technique and acute memory loss during time critical moments in surgery, so having an established protocol printed and in the room as a visual aid for all to reference improves the efficiency of the team. Use of a checklist in crisis situations in the operating room resulted in a six-fold reduction in failure of adherence to critical steps in management.[6]

RELEVANT ANATOMY

The anatomy of the vertebral column is a complex circuit. The vertebral column is made up of osseous and neurovascular structures. Specifically of interest to this article, are anatomic structures that are at risk during deformity correction. The cervical, thoracic, and lumbar spine have variable pedicle morphology, which can pose a challenge during surgery. Specific to adolescent idiopathic scoliosis (AIS), Kuraishi and colleagues[14] found that pedicle morphology differs in patients with AIS, specifically in regards to the diameters. They noted the concave side of the deformity in patients with AIS was significantly narrower than the contralateral side, further suggesting that pedicle screw insertion for patients with AIS in the apex of the curve on the concave side should be avoided.

Kothe and colleagues[15] found that in the thoracic spine, the lateral cortex of the pedicle is significantly thinner than the medial cortex. Having a thicker medial cortex is protective when placing pedicle screws, because just medial to it lies the dura mater, and traversing nerve roots. In addition to the dangers medially to the pedicle, inferior to the pedicle also poses danger. The inferior wall of the pedicle is the roof of the neural foramen, with the exiting nerve root often abutting against it. Penetration through the medial or inferior wall of the pedicle has the potential for nerve injury and radicular pain from root irritation.[16]

One must also understand the crucial role of the spinal cord vascularity and associated structures in regard to cord perfusion. The spinal cord is sensitive to decreased perfusion, making monitoring blood pressure and limiting blood loss an important aspect of the procedure. The anterior two-thirds of the spinal cord receives its blood supply from one large anterior spinal artery, and the posterior one-third from paired posterior spinal arteries. These vessels anastomose via the arterial vasocorona, which wrap around the cord, supplying blood to the periphery and lateral aspects. There are large venous and arterial plexus surrounding the facet joints, that are prone to bleeding during facetectomies. Of note in the thoracic region, there is an area of decreased vascularity between T4 and T9, because it is the narrowest aspect of the spinal canal.[17] With most apical deformity in AIS located in these segments, perfusion is tenuous, and potential for injury increased.

There are ascending sensory and descending motor tracts that are important when specifically looking at neuromonitoring in deformity surgeries. More specifically, there are nine specific pathways that have distinct functions including movement, pain and temperature, position/fine touch, light touch, and short spinal connections (**Fig. 1**). A vascular insult or trauma may well affect these individual tracts in a unique way. For example, the dorsal columns that relay proprioception are dorsal-based tracts, and therefore more sensitive to blunt trauma. Most motor tracts are anterior, and are more sensitive to hypoperfusion from the blood supply.[17] Finally, the dysplastic nature of spinal deformity creates unique anatomy that is difficult to anticipate without appropriate preoperative imaging. Therefore, it is important to understand the relationships between anatomic structures and how to interpret changes in neuromonitoring while in the operating room.

TYPES OF NEUROMONITORING

There are many different ways of monitoring the spinal cord, each with their own nuances to consider. As noted earlier, the combined use of all types provides the best intraoperative prediction for postoperative neurodeficit.[7,8] The general concept is that an action potential is induced at one end of a nerve, and its latency and amplitude are evaluated at the other end after it has traveled the course of the nerve. The latency is a measure of time and distance, and the amplitude is a measure of power. When there is an increase in latency, or a decrease in amplitude higher than a certain threshold, this is a warning that the nerve is considered at risk for irreversible injury.

In somatosensory evoked potential (SSEP) monitoring, the action potential is propagated through the dorsal columns and dorsomedial tracts to the contralateral cerebral cortex. To

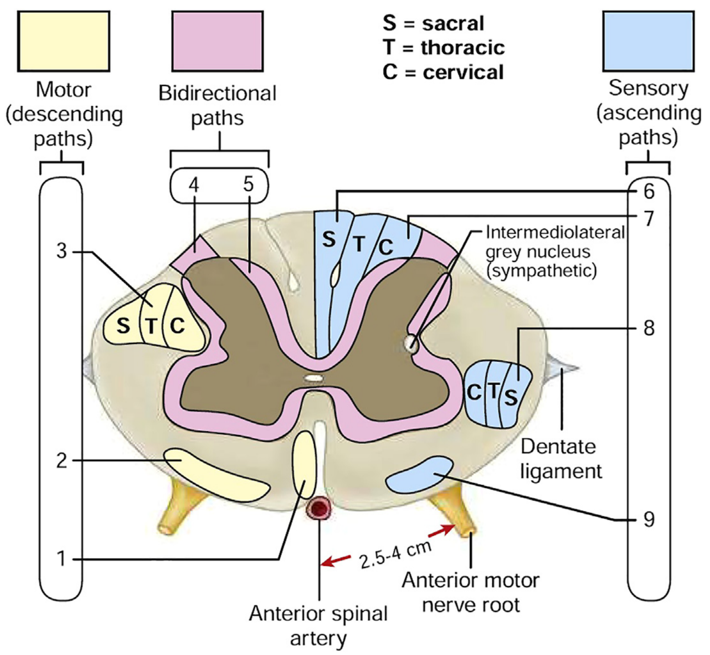

Fig. 1. Cross-sectional anatomy of the spinal cord, showing the motor and sensory paths. These include the anterior corticospinal tract (1), vestibulospinal tract (2), lateral corticospinal (pyramidal) tract (3), dorsolateral fasciculus (4), fasciculus proprius (5), fasciculus gracilis (6), fasciculus cuneatus (7), lateral spinothalamic tract (8), and anterior spinothalamic tract (9). (With permission from "Frederick Azar, S. Terry Canale, James Beaty, Campbell's Operative Orthopaedics, 14th edition, v4. Philadelphia, PA, Elsevier Inc. 2021, chapter 37, pg 1643".)

do this, repetitive electrical stimulation of the peripheral nerves is instigated through epidural electrodes on the patient's skin at certain locations, and measured via subdermal electrodes on the scalp (**Fig. 2**). Different institutions have different thresholds, but generally an increase in latency by more than 10%, or a decrease in amplitude more than 50% initiates a warning to the surgeon of injury to these nerves.[18] SSEPs provide a good basic indicator of spinal cord function because they are continuously being evaluated; however, results need to be averaged over time to exclude background noise (**Fig. 3**). Because of this, they do not provide real-time feedback, and can take even up to 5 to 10 minutes to detect acute changes.[19] One study of 176 patients undergoing spinal surgery for deformity correction showed that SSEPs lagged MEPs by an average of 15 minutes when both were found to be positive.[20]

Motor evoked potentials (MEPs) allow selective and specific assessment of the functional integrity of descending motor pathways, from the motor cortex to the peripheral muscles.[18] These potentials are elicited by neurogenic stimulation at the spinal cord with epidural electrodes, or via myogenic stimulation through transcranial electrodes placed over the motor cortex on the scalp. Transcranial motor evoked potentials (TcMEPs) do not need to be averaged, and thus provide immediate response. Typically a reduction in amplitude greater than 50% is a warning of injury. TcMEPs, however, are more sensitive to the effects of general anesthetics, which need to be considered before the start of surgery.

Another way of monitoring is via electromyography (EMG), which provides real-time recording from peripheral musculature.[19] Because EMG does not require stimulation, it can be continuously recording, and is most helpful with monitoring for injury to peripheral nerves, most often during pedicle screw placement. When a peripheral nerve is irritated, the associated innervated muscle shows spikes or bursts of activity on the EMG. One can also test each exiting nerve root selectively by electrically stimulating the pedicle screw at the associated level with increasing intensity. Because a well-placed screw is surrounded by cortical bone that insulates it, no activity should be seen at lower intensities. If neurotonic discharges are seen at less than 10 mA, one should suspect cortical breach of the screw, and should warrant further investigation.

The gold standard for ultimate assessment is the wake-up test, first described by Vauzelle and coworkers[21] in 1973, because all methods of cord monitoring have their inherent weaknesses. The surgeon should develop a routine that considers each individually, and uses multiple methods to avoid unnecessary surgical delay

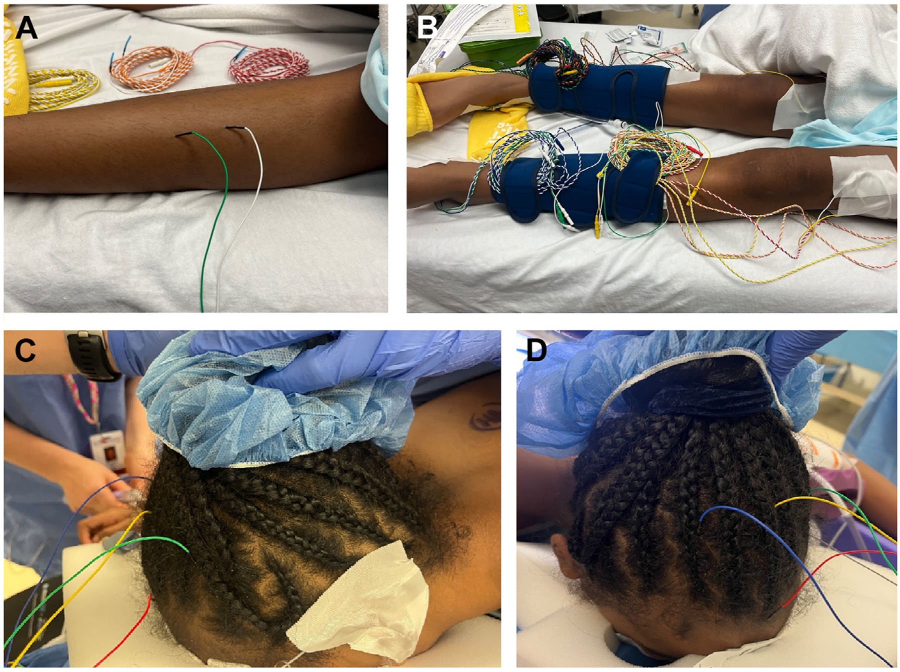

Fig. 2. Subdermal electrodes are placed in the upper and lower extremities (*A, B*), and in the head (*C, D*) for inducing and measuring action potentials in the motor and sensory tracts.

and risk by waking the patient to evaluate their neurologic status. SSEPs are easy to record, less affected by pharmacologic agents, and continuously record, but have delayed responses and may not provide warning until the injury is irreversible. There are reports of paralysis despite normal results of SSEPs.[22] TcMEPs provide instantaneous feedback, but

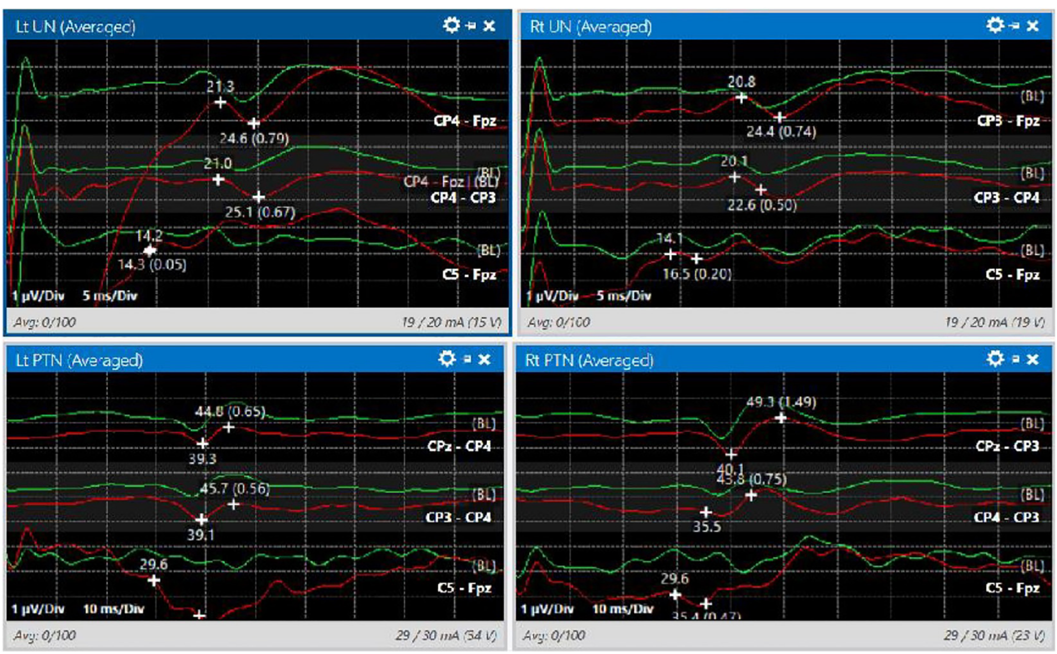

Fig. 3. Screen image of averaged SSEPs of bilateral upper and lower extremities. The *green lines* represent the baseline, and the *red lines* represent the current potentials.

are more sensitive to pharmacologic agents, cannot be constantly monitored, and are less accurate in kyphosis surgery.[12] Most institutions use a standard of continuous SSEPs and EMG, with TcMEPs performed at various checkpoints during the procedure, or when injury is suspected. Some routinely test pedicle screws with EMG after all are placed, removing the screw and palpating all cortices if the activity is seen lower than a certain threshold to confirm appropriate position of the screw. By combining all methods, one ensures the least likelihood of unexpected postoperative nerve deficit.

PERIOPERATIVE PATIENT SELECTION/RISK FACTORS FOR INTRAOPERATIVE NEURAL MONITORING LOSS AND INCREASE IN ELECTROPHYSIOLOGIC EVENTS

A successful surgery begins long before the patient enters the operating room. Appropriate patient selection and preoperative optimization is essential to minimize intraoperative risk. Although highly sensitive monitoring modalities can detect potentially reversible neurologic injury, there are medical comorbidities that can affect the reliability of one or both of these monitoring modalities, resulting in a statistically significant decrease in the likelihood of successful neurologic monitoring.

Vitale and coworkers reviewed 162 cases that demonstrated successful combined monitoring in 83% of spinal deformity surgeries.[12] Pelosi and colleagues[8] demonstrated similar results of 82%, success being defined by obtaining technically reproducible signals in sensory or motor stimulation under surgical conditions. Of the total patients unable to be monitored, risk factors included neuromuscular scoliosis, kyphosis, cerebral palsy, neuromuscular comorbidities, and anatomic comorbidities. Neuromuscular scoliosis, kyphosis, and cerebral palsy resulted in a statistically significant decrease in the ability of MEP monitoring to be obtained compared with idiopathic scoliosis. Cerebral palsy was also statistically less likely to have successful SSEP monitoring compared with idiopathic scoliosis. SSEP monitoring was trending to be less successful in neuromuscular scoliosis and kyphosis; however, statistical significance was not obtained. Neuromuscular comorbidities were less likely to be successfully monitored by MEP when compared with those patients without comorbidities. Even though these comorbidities decreased the likelihood to obtain one method of intraoperative neural monitoring (IONM), there was no difference found in the overall success of combined IONM. More recent literature has corroborated these findings. Pastorelli and coworkers[23] demonstrated that IONM was reliable in patients with neuromuscular disease. However, the interpretation of IONM may be more challenging because the rate of false-positive results may be higher.[23] Hammett and colleagues[24] also stated that IONM is possible in neuromuscular patients but cautioned surgeons to take careful considerations when using IONM in this population.

In contrast, anatomic comorbidities, such as congenital anomalies, neoplasia, spondylolisthesis, and overgrowth, resulted in a decrease in the ability to monitor MEPs and SSEPs, and the overall success of the IONM.[6] Despite identifiable differences in success based on medical comorbidities, there is also a clear relationship with electrophysiologic changes and neurologic events.[12] Vitale and colleagues identified that surgeries involving spondylolisthesis, kyphosis, and cardiopulmonary comorbidities showed high rates of electrophysiologic events. Similarly, Feng and coworkers[20] identified kyphosis, procedures requiring osteotomies, and cobb angle corrections greater than 90° increased the likelihood of electrophysiologic events.

Besse and coworkers[25] investigated neuromonitoring in minimally invasive fusionless procedures for nonidiopathic scoliosis. They demonstrated an increase in loss of neurogenic mixed evoked potential monitoring (NMEP) in nonidiopathic patients undergoing surgery with large preoperative Cobb angles. Patients with central nervous system disease with elevated body mass index also demonstrated a statistically significant risk of NMEP signal loss.[25] They found no significant relationship between SSEP and NMEP loss with age, number of rods, upper instrumented vertebra, or lower instrumented vertebrae. However, the use of a traction table during surgery increased the risk of IONM loss.

Careful preoperative planning should take place in patients with medical comorbidities. MEP monitoring is less likely to be successfully obtained in neuromuscular scoliosis, kyphosis, cerebral palsy, and neuromuscular disease. SSEPs are difficult to obtain in cerebral palsy. During certain operations NMEP monitoring is affected by body mass index. Procedures involving corrections of large Cobb angles, kyphosis, spondylolisthesis, anatomic comorbidities, corrective osteotomies, and traction tables should be undertaken with increased caution because of the increase in risk of electrophysiologic events. The possibility of failure to obtain baseline neuromonitoring, increased risk of IONM loss, and decreases in the overall success of IONM in patients with comorbidities should be carefully considered by the operative surgeon.

SOURCES OF INJURY TO SPINAL CORD

Injury to the cord can come from several sources, but can ultimately be divided into direct trauma or secondary ischemia. Direct trauma is avoided by having a good knowledge of anatomy, appropriate operative technique, and sufficient intraoperative neuromonitoring. Secondary ischemia is avoided by preoperative patient optimization; intraoperative hemostasis; and maintaining vigilant watch over the patient's blood pressure, heart rate, and temperature. Although there is no definitive way of preventing all injuries, understanding the potential sources helps the surgeon have safe technique, and decrease the risk of complications.

Direct injury to the cord or exiting nerve root comes from errant screw placement, inadequate osteotomies, or traction during deformity correction. The anatomy of the thoracic pedicles in AIS is well described.[26,27] The pedicles of the apical and adjacent vertebrae are significantly shorter and narrower on the concave side, with an isthmus less than 4 mm in diameter in 62% of patients.[14] Furthermore, there are significant consequences of screw pullout, so choosing an appropriately sized screw is vital to construct stability. This anatomy, and the desire to place larger diameter pedicle screws make these pedicles more prone to screw breachment (**Fig. 4**), and potential nerve injury. Many surgeons rely on the concept of pedicle expansion; however, this decreases the overall pullout strength, and there is less expansion of the outer cortical diameter than the inner diameter.[28] Surgeon experience, and appropriate neuromonitoring help guide the choice of screw size and trajectory.

An extensive review of the Scoliosis Research Society morbidity and mortality database shows a 50% increase in complications, and more than double the amount of new neurologic deficit when osteotomies are performed.[1] Inadequate decompression can lead to ligament flavum involution and pressure on the cord, particularly on the convex side. Osteotomies also result in increased surgical time and blood loss, placing increased ischemic risk to the cord. A review of risks and costs associated with Ponte osteotomies from a different national database also showed no increased odds of neurologic complications, but did show 17.4% higher costs, 50% increase in readmissions, and 100% increase in reoperations within 90 days.[29]

Correction of the scoliosis also has a lengthening effect on the spine, with one study showing an average increase by 32.4 mm $\pm$ 10.8 mm.[30] The resulting lengthening of the spine can cause a traction neuropraxia resulting in postoperative neurodeficit (**Fig. 5**). This is also true with reduction of a spondylolisthesis. These patients are at a higher risk for cord injury,[12] with patients undergoing a reduction having a six-fold increased risk in new neurologic deficits.[1]

Secondary ischemia results from any factor that decreases the oxygenation of the cord. This is caused by hypotension, decreased hemoglobin, hypothermia, blood clots, intraoperative blood loss, or hematoma from vessel injury. Preoperative optimization is important because the rate of true electrophysical events is significantly higher in patients with cardiopulmonary comorbidities because of decreased oxygenation and perfusion.[12] During surgery, it is ideal to have background noises at an appropriate level, and the patient's vital signs displayed for all to see, so the whole team can be aware of any drastic changes. Hypotensive anesthesia during the surgical dissection can minimize blood loss, whereas maintaining Mean Arterial Pressures (MAPs) at 80 mm Hg ensures adequate cord perfusion during hardware placement and correction there is the highest risk of nerve injury.[19] One study showed that 20% of intraoperative signal changes improved by simply increasing the MAP to greater than 85 mm Hg.[30] Also, having an established standardized protocol in response to ischemic injury helps find the source, minimize the time to correction, and decrease the risk of irreversible injury.

USE OF A STANDARDIZED PROTOCOL

As mentioned previously, spinal surgery in scoliosis is stressful at baseline, with distorted anatomy and medically complicated patients. Hearing the neuromonitoring technician say that signals are diminished, or gone altogether increases the stress in the room and can easily result in poor surgeon performance, and difficulty with memory recall.[6,13] This is why the use of a standardized checklist is vital for management of these situations, because it puts everyone on the same page, gives everyone a role in finding and correcting the problem, and decreases time to correction by increasing efficiency. Although there are some published products that can be used,[6,31] there is not one that is better than another, and it is ideal that whichever you use is standardized to your institution. This limits variability for the supportive

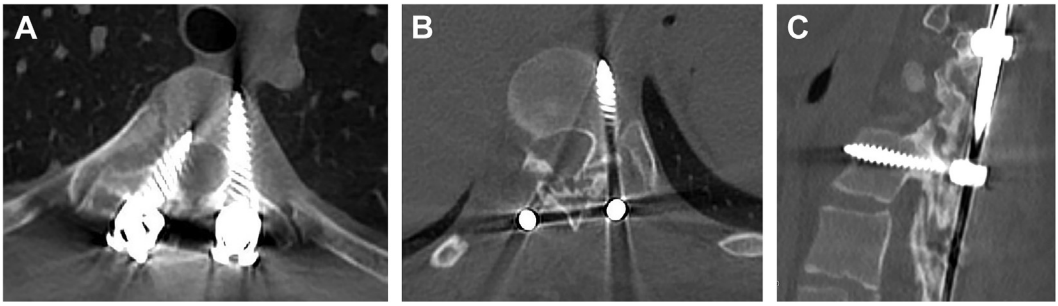

Fig. 4. Axial computed tomography showing a thoracic pedicle screw breaching the medial cortical wall (*A*) and lateral wall (*B*), and sagittal computed tomography of a thoracic pedicle screw breaching the anterior vertebral wall (*C*).

staff and improves the overall proficiency in the room. It should also be printed and visible in a known location. At our institution, the protocol is printed on a large poster board right next to the large monitor that displays the patient's vital signs (Fig. 6). It may even be beneficial to add its location, and assignments to the preoperative time out.

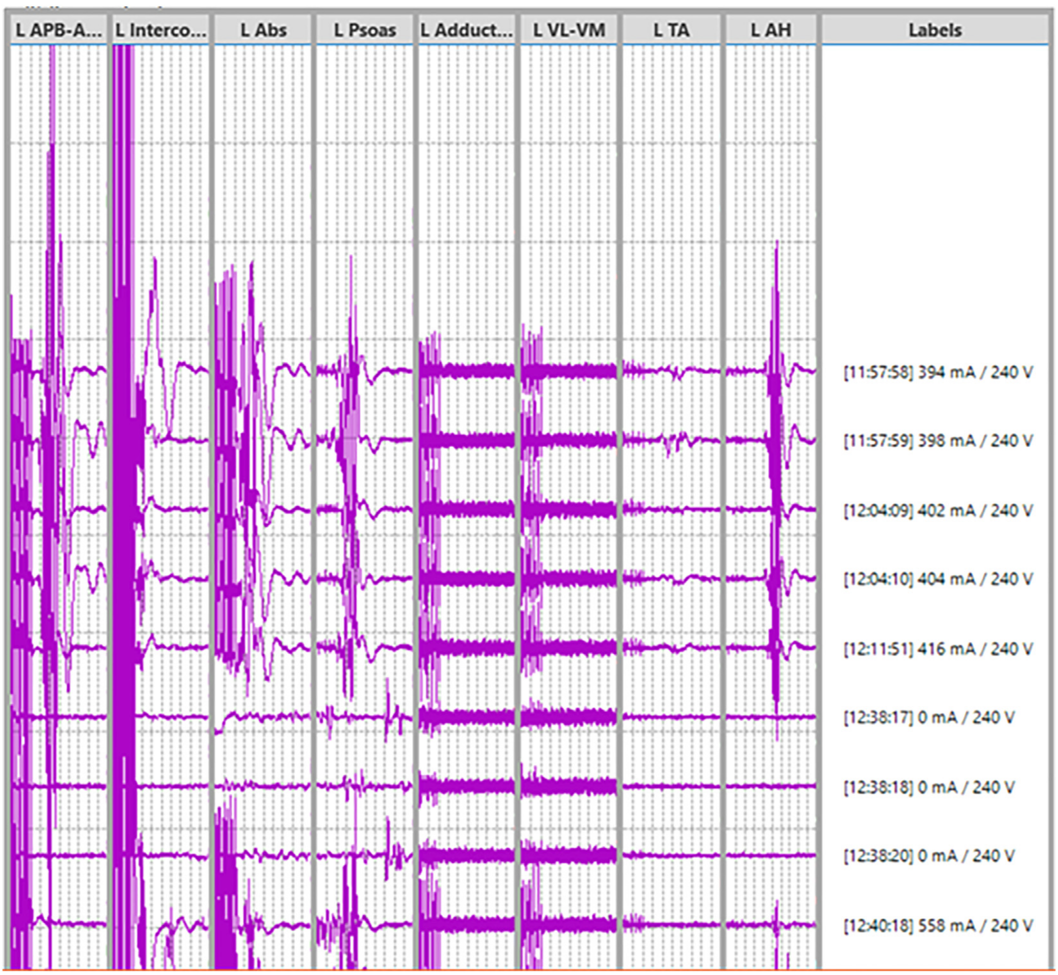

Fig. 5. Screenshot showing MEPs measured during the spinal correction in an AIS posterior spinal fusion. After final screw placement, all potentials were present and appropriate at 12:11. After correction of the spine to the rod, motors were lost in the left lower extremity at 12:38. Vitals and temperature were appropriate, so the correction was reversed, and the motors returned at 12:40.

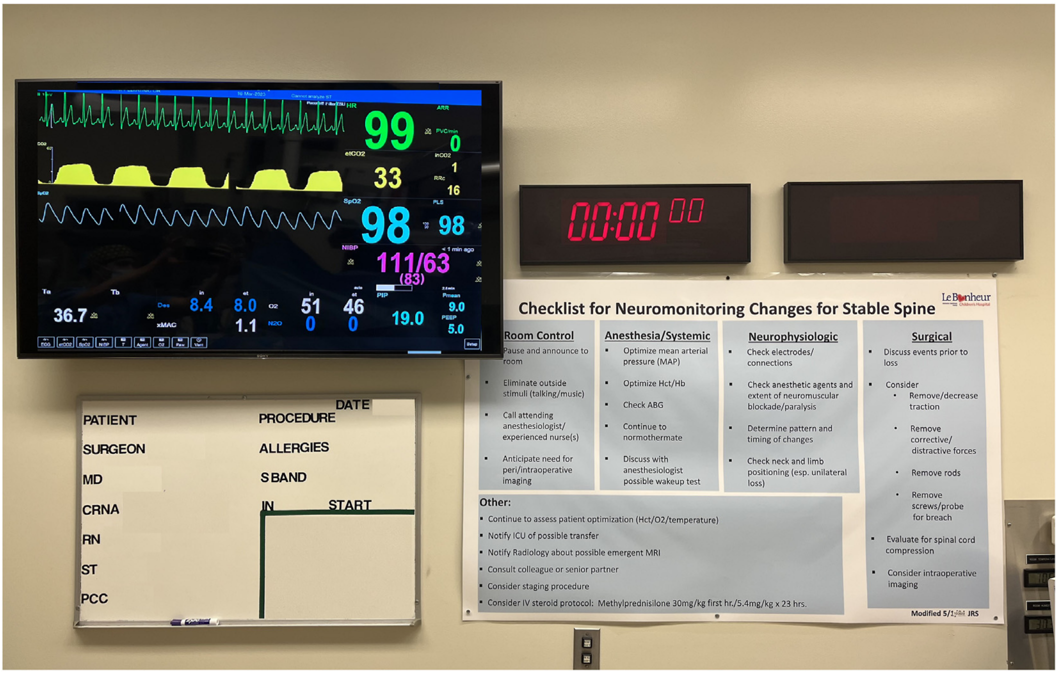

Fig. 6. This is an image of the wall in the operating rooms at our institution where spinal surgery is performed. It is always in view of the lead surgeon, and conveniently places the checklist next to the patient's vital signs, and the names of everyone in the room.

Whatever mode you use to organize the staff in the room, it should be simple and clear, and take into consideration the roles of the surgeon, anesthesiologist, and nursing staff. It should include the potential need for calling the assistance of senior staff, and the potential for advanced imaging with the patient anesthetized. The surgeon should also consider the timing in surgery where there were signal changes, because it is a clue to the cause. Next are general considerations that should be addressed.

General Considerations at all Times

Regardless of time at which there are signal changes, the surgeon should take control of the room by stopping; announcing the situation; and eliminating extraneous stimuli, such as music or side conversations.[6] The surgeon should verbally discuss any recent actions taken before the signal loss, and consider reversing them. Anesthesia should comment on any recent changes in use of pharmacologic agents, or changes in vital signs that would affect cord perfusion, and how it can be optimized. The neuromonitoring technician should specify which signals are affected (MEPs, SSEP, or EMG), and should consider any external causes, such as circuit discontinuity, electrode dislodgement, or electrical interference from external sources, such as cautery tools, magnetic devices, or warming blankets.

Signal Changes at Induction or Positioning

When there are signal changes before incision, the physician should check the leads, and consider transitioning to total intravenous anesthesia. The neuromonitoring technician should consider increasing baseline stimulation for SSEPs and anesthesia should consider decreasing propofol, which has a dose-dependent effect on MEP signals. Patient can be warmed, because hypothermia decreases signals, and as always, check patient positioning and vital signs. If signals do not return, consider aborting the case for a more extensive preoperative neurologic work-up.[19]

Signal Changes During or After Surgical Dissection

When signals change after exposure, it is likely caused by blood loss, anesthetics, or vital signs. Increase blood pressure to a MAP greater than 85 mm Hg[32] and warm the patient. Check an arterial blood gas and consider giving blood to maintain a hemoglobin greater than 7 mg/dL. Avoid boluses of propofol, considering a maximum dose of 150 µg/kg/min, because it is lipid-soluble and can accumulate with higher doses in heavier patients[33] and affect MEPs. If there is no improvement, consider a wakeup test, or aborting the case for further work-up.

Signal Changes During Screw Placement

When signals are lost during screw placement, the surgeon should still consider all things discussed previously; however, they must also consider the position of the screw and the concern that it is the offending agent. Simply evaluating the screw harmony, and its relationship to the other screws already placed can provide insight if it is malpositioned. A change in SSEPs could indicate a previously placed screw because of the delay from signal averaging, but spikes in EMG indicate acute irritation/injury to a nerve. The surgeon should promptly remove the screw and palpate the cortices of the pedicle, and consider individually testing the previous screws with EMG. The screw should be appropriately repositioned, or place hooks or sublaminar bands if an appropriate trajectory cannot be found.

Signal Changes with Osteotomies or Rod Placement/Correction

When there are signal changes during osteotomies, consider the degree of change and which pathway is affected. Motor pathways that are anterior may be more prone to perfusion, whereas sensory pathways that are posterior are more prone to direct insult. Evaluate the extent of the osteotomy to ensure there are no sharp edges that can impinge or irritate the cord, and ensure adequate hemostasis. If there are signal changes during rod placement and correction, immediately reverse the most recent action. If osteotomies were performed, make sure excess soft tissue and bone was removed. Once again, consider previously stated causes after the reversal to rule out any other potential cause. Consider a wake up test, and in situ fixation to allow further work-up if necessary.

Signal Changes During Closure or Postoperative

When there are signal changes during closure, particularly changes in SSEPs, consider it a delay in response and reverse the correction to see if it returns to baseline. Ensure the fluid you wash the wound out with is warm because the cord is sensitive to temperature change. If there were intraoperative changes at any point in time, consider admission to pediatric intensive care unit for a higher level of blood pressure monitoring and neuromuscular evaluation. If there are postoperative deficits with no intraoperative signal changes, consider drain output, intraoperative blood loss, and the need for advanced imaging.

SUMMARY

Although cord/nerve injury is a feared complication in scoliosis spine surgery, the overall complication rate is low, with incidence of major neurologic injury reported to range from 0.01% to 0.05%.[1,11,12] This is primarily because of better preoperative planning, and improvements in the ability to monitor the cord. Simultaneous monitoring of multiple pathways improves the detection of injury to nearly 100%.[7,8] Having an understanding of the different types of nerve monitoring and their individual strengths and weaknesses helps surgeons decide what is being injured and how to correct it. Also, having an established protocol in these situations maintains surgeon and staff composure, improves proficiency, and decreases the chances of the patient waking up with a nerve deficit.

CLINICS CARE POINTS

- Monitoring afferent and efferent pathways provides early detection of spinal cord injury, significantly decreasing incidence of irreversible cord damage.
- Use of an experienced neuromonitoring technician increases accuracy of monitoring, and decreases false-positive warnings.
- Having a well-defined, algorithmic protocol in place helps direct the response to intraoperative signal changes and avoid errors during these stressful moments.
- SSEPs lag behind because of averaging values, therefore monitoring sensory pathways alone can provide delayed warnings, theoretically increasing risk of irreversible injury.
- Decreasing thresholds for neuromonitoring alerts increases the sensitivity of cord injury, but decreases the specificity for true cord injury, resulting in false-positive alerts.

DISCLOSURES

None.

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