Neuromonitoring changes in pediatric spinal deformity surgery: a single-institution experience

Clinical article

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Object. Intraoperative monitoring of the spinal cord has become the standard of care during surgery for pediatric spinal deformity correction. The use of both somatosensory and motor evoked potentials has dramatically increased the sensitivity and specificity of detecting intraoperative neurophysiological changes to the spinal cord, which assists in the intraoperative decision-making process. The authors report on a large, single-center experience with neuromonitoring changes and outline the surgical management of patients who experience significant neuromonitoring changes during spinal deformity correction surgery.

Methods. The authors conducted a retrospective review of all cases involving pediatric patients who underwent spinal deformity correction surgery at Shriners Hospital for Children, Philadelphia, between January 2007 and March 2010. Five hundred nineteen consecutive cases were reviewed in which neuromonitoring was used, with 47 cases being identified as having significant changes in somatosensory evoked potentials, motor evoked potentials, or both. These cases were reviewed for patient demographic data and surgical characteristics.

Results. The incidence of significant neuromonitoring changes was 9.1% (47 of 519 cases), including 6 cases of abnormal Stagnara wake-up tests, of which 4 had corroborated postoperative neurological deficits (8.5% of 47 cases, 0.8% of 519). In response to neuromonitoring changes, wake-up tests were performed in 37 (79%) of 47 cases, hardware was adjusted in 15 (32%), anesthesiology interventions were reported in 5 (11%), hardware was removed in 5 (11%), the patient was successfully repositioned in 3 (6%), and the procedure was aborted in 13 (28%). In 1 of the 4 patients with new postoperative deficits, the deficit had fully resolved by the last follow-up; the other 3 patients had persistent neurological impairment as of the most recent follow-up examination. The authors observed a sensitivity of 100% for intraoperative neuromonitoring.

Conclusions. Due to the profound risks associated with spinal deformity surgery, intraoperative neurophysiological monitoring is an integral tool to warn of impending spinal cord injury. Intraoperative neuromonitoring appears to provide a safe and useful warning mechanism to minimize spinal cord injury that may arise during scoliosis correction surgery in pediatric patients.

Key Words • intraoperative monitoring • neuromonitoring • SSEP • MEP • scoliosis • pediatric spine

Given the delicate nature of spinal surgery and the inherent risks associated with it, development of surgical tools to reliably augment safety is critical. Since its inception in the mid-1970s, intraoperative spinal cord monitoring, also known as intraoperative neurophysiological monitoring or intraoperative neuromonitoring (IONM), has become increasingly popular in spinal surgery. Prior to the development of this tool, spinal surgeons relied primarily on the Stagnara wake-up test to diagnose iatrogenic spinal cord injury during surgical procedures. With the use of IONM, the surgeon is notified of potential injury to the spinal cord earlier, thus allowing for more effective management and avoidance of potential permanent neurological insults. IONM is now commonplace in the management of deformity correction surgery.

Intraoperative neuromonitoring consists of several modalities that provide information regarding the physiological function of the spinal cord while the patient un-
dergoes surgical deformity corrective procedures, and it has been validated as a monitoring system to minimize iatrogenic spinal cord injury during surgery. Somatosensory evoked potentials (SSEPs) were the first modality to be widely adopted, and have been routinely employed for over 20 years. SSEPs inform the surgeon about the integrity of afferent information in the dorsal columns of the spinal cord. Some limitations of SSEPs include the delay associated with the signal averaging requirements related to data collection and the fact that the anterior spinal artery does not directly supply the dorsal columns. This is important to note, as it means that spinal cord ischemia may not be identified using SSEPs alone.

For these reasons, transcranial motor evoked potentials (tcMEPs) have gained favor in recent years, and they provide a more sensitive measure of the function of the spinal cord. This modality allows for direct monitoring of descending pathways in the anterior portion of the cord, which is crucial to prevention of surgery-related spinal cord injury. The higher incidence of false positives with tcMEPs may be attributed to their higher sensitivity, as well as to the effects of anesthesia. Taken together, SSEP and tcMEP monitoring provide exceptionally high sensitivity and specificity for communicating intraoperative changes in the spinal cord.

Despite the increased use of IONM throughout the field of spinal surgery, there is a paucity of literature related to its use in pediatrics as compared with the spinal surgery in adults. We present the experience of a single institution with IONM and pediatric spinal deformity surgery and one of the largest reported series of IONM changes to date.

Methods

After obtaining IRB approval, a retrospective review was performed on consecutive cases in which spinal deformity correction was performed at Shriners Hospitals for Children, Philadelphia, from January 2007, when we initiated transcranial motor monitoring for all patients undergoing spinal deformity correction to March 2010. In total, 519 cases were reviewed and 47 were identified in which neuromonitoring changes. Demographic, clinical, operative, and radiographic fields were collected on the 47 patients with IONM changes. Due to the nature of the surgeries performed and sequelae of neuromonitoring changes, several patients underwent multiple procedures. All patients were < 18 years of age at the time of the index surgery.

Neuromonitoring was used in all cases and included SSEPs, tcMEPs, and EMG testing. Though EMG data were collected during these cases, it is not included in this study due to the low sensitivity and positive predictive value reported in the literature.

Of the 519 cases, 47 operative cases (involving 39 patients) were identified as having significant neuromonitoring changes during the procedure. A “significant change” in IONM, as reported at this institution, indicates a reduction in SSEP amplitude of more than 50% or an increase in latency of more than 10% or a reduction of transcranial motor-evoked potentials (tcMEPs) by more than 75%. Although there is variability in the literature, this is consistent with an accepted threshold.

Monitoring of SSEPs and tcMEPs was performed as described by Schwartz et al. and is briefly reviewed here. SSEP monitoring is performed by electrically or mechanically stimulating a peripheral nerve and recording the average electrical response rostral to the area of surgical intervention, primarily over the somatosensory cortex. The most common nerves used for SSEP monitoring are the posterior tibial or peroneal for the lower extremities and the ulnar nerve for the upper extremities.

Transcranial MEP monitoring, in contrast, requires stimulation of the scalp over the primary motor cortex. A signal, an anodal pulse train of 2–7 pulses, is generated (interstimulus interval of 1–5 ms) on the scalp over the motor cortex. The brief (50 μsec) and high-voltage (250–500 V) stimulus is used to test the physiological integrity of the efferent pathways, and therefore the impulse is detected by monitoring the electrical response of the peripheral musculature bilaterally. The muscle most commonly tested is the tibialis anterior muscle, though others are used as well, including the iliopsoas, quadriceps, abductor hallucis, and foot flexors. The first dorsal interosseous muscle of the hand is also tested to determine whether there is a true distinction between the signals of the upper extremities and lower extremities. Since the hands are innervated by the cervical levels of the spinal cord, they are typically rostral to the surgical operative site in the majority of pediatric deformity surgeries and therefore can serve as a control.

Results

Patient Details

Of 519 operative cases, 47 were identified in which there were notable changes in neuromonitoring during surgery. These cases involved a total of 39 patients, with 7 of these patients undergoing multiple operations. This group included 11 male patients (13 surgical cases) and 28 female patients (34 surgical cases). Analyzed by case, the mean patient age at surgery was 14.0 ± 3.3 years (range 4–19 years). The 47 surgical procedures were performed for the treatment of congenital scoliosis (15 cases); idiopathic scoliosis (14 cases); neuromuscular scoliosis, including syndromic (12 cases); kyphosis—Scheuermann’s and kyphoscoliosis (5 cases); and spondyloptosis (1 case).

After IONM changes occurred and interventions were performed to address underlying issues, the surgical fusion was completed without further complication in 35 (75%) of 47 cases. In the remaining instances, the procedure was completed at a future time in 3 (6%) of 47 cases, and in 9 (19%) of 47 the originally planned procedure was either never completed or the patient was lost to follow-up. Therefore, in 81% of patients with IONM changes the surgical fusion procedure was completed.

Radiographic Details

The average pre- and postoperative coronal Cobb angles were 70° ± 35° (range 0°–139°) and 42° ± 29° (range 0°–128°), respectively, indicating an average correction
of 40%. The average pre- and postoperative degrees of kyphosis were $63^\circ \pm 25^\circ$ (range $15^\circ$–$120^\circ$) and $58^\circ \pm 26^\circ$ (range $17^\circ$–$102^\circ$), with an average of 8% correction (Figs. 1 and 2). Excluding the 9 procedures in which the posterior spinal fusion was not completed, the mean preoperative Cobb angle was $70^\circ \pm 36^\circ$ (range $0^\circ$–$139^\circ$), which corrected to $34^\circ \pm 23^\circ$ (range $0^\circ$–$108^\circ$), translating into a 45% correction on average. The sagittal plane went from a preoperative angle of $53^\circ \pm 24^\circ$ (range $15^\circ$–$120^\circ$) to a postoperative measurement of $51^\circ \pm 23^\circ$ (range $17^\circ$–$152^\circ$), correlating to a 2.3% change. For the 5 cases in which the diagnosis was kyphosis only, the average correction was 27%.

Neuromonitoring Changes

Out of 519 cases performed during the designated time period, 47 (9.1%) involved at least 1 significant IONM change during the procedure. In 5 of the 47 (11%) cases, the changes involved SSEPs only, in 22 (47%) they involved tcMEPs only, and in 20 (42%) abnormalities were observed in both SSEPs and tcMEPs (Table 1). These changes resulted in the following corrective actions by the surgical team: Stagnara wake-up tests in 37 cases, hardware adjustment in 15 cases, termination of the procedure in 13 cases, hardware removal in 5 cases, confirmed anesthesia interventions (for example, increase mean arterial pressure, temperature changes, anesthetic adjustments) in 5 cases, repositioning of the patient in 3 cases, and unknown actions taken with return of signals in 3 cases. Frequently, these corrective actions were performed concomitantly in an attempt to restore the signals as quickly as possible. Therefore several patients had multiple adjustments performed simultaneously. Typically, after confirmation that the IONM changes are not due to technical difficulties (lead displacement), we request that the anesthesiologist elevate the mean arterial pressure above 80 mm Hg and verify that the patient is normothermic. Similarly we request transfusion of packed red blood cells and discontinue any inhaled agents (total intravenous anesthesia). Simultaneously, we will reverse the last surgical procedure performed (remove the last screws and verify the tracts; remove the rod, verify that no hemostatic agent, bone, or hematoma is compressing the cord across osteotomy sites), and if necessary will remove all instrumentation for MRI. Although there are proposed algorithms for the decision-making process, the surgeon must determine the most effective sequence of events after signals are lost or diminished (Fig. 3).

In 10 cases, a Stagnara wake-up test was not performed either because of improvement in the IONM prior to the patient’s waking or due to the patient’s inability to follow commands at baseline. In 6 cases, the wake-up test showed abnormalities and surgery was aborted. In 2 of

Fig. 1. Preoperative posteroanterior (left) and lateral (right) radiographs obtained in an 11-year-old girl with adolescent idiopathic scoliosis.

Fig. 2. A: Intraoperative radiograph showing correction with 1 rod. The patient suddenly lost all IONM activity after deformity correction. Management involved removal of the rod and elevation of mean arterial pressure > 80 mm Hg with return of baseline IONM. This image reflects the final correction with 1 rod after IONM returned to baseline. B: Final postoperative posteroanterior radiograph with less correction of the curvature than initially obtained with loss of IONM. C: Postoperative lateral radiograph.
these cases, the patients did not move in response to command during the test but had normal examination findings at the end of surgery. In the other 4 cases, the patients had new postoperative neurological deficits: 1 patient developed bilateral lower-extremity paralysis after osteotomies were performed and during screw placement; 1 patient had loss of MEPs during the deformity correction using rod translation and was found to have no dorsiflexion of both feet; the remaining 2 patients both had left lower-extremity weakness. One of the patients with left lower-extremity weakness has since recovered completely, but the deficits have remained in the other 3 patients.

Perioperative Details

The average estimated total blood loss was 2319 ± 2350 ml (range 65–10,000 ml), and estimated blood loss at the time of neuromonitoring changes was 1388 ± 1465 ml (range 50–7200 ml). The mean arterial pressure at the time of neuromonitoring changes was 77 ± 10 mm Hg (range 62–100 mm Hg). The total operative time was 8 hours and 17 minutes (range 2 hours 48 minutes to 17 hours 9 minutes), with an average time from incision to neuromonitoring event of 4 hours and 4 minutes (range 2 hours 48 minutes to 17 hours 33 minutes). In 3 cases the length of time between the beginning of surgery and the IONM changes was not recorded, and these cases were therefore excluded from the analysis.

Sensitivity and Specificity

Of the 47 cases, there were 20 with both SSEP and tcMEP changes, 22 with only tcMEP changes, and 5 with SSEP changes. In 3 of the 5 cases with only SSEP changes, there was documented difficulty with the baseline signals for tcMEP, implying that tcMEP was not a reliable modality during the operation in these cases. In all of the remaining cases, there were reliable tcMEPs at baseline.

At the onset of IONM changes, adjustments were initiated to address and reverse any physiological impairment, therefore normal neurological examination during the wake-up test may have been due to anything from decreased anesthesia to true correction of hypoperfusion. Our inability to differentiate between a change in IONM that may not be correlated with a neurological deficit and changes in IONM associated with true neurological impairment is a source of variability in determining sensitivities or specificities of IONM. Currently IONM is used as an “early warning system” and may identify patients at risk for developing neurological deficits. To better understand the applicability of IONM, we have performed 2 analyses using differing definitions of a true positive finding: 1) accepting all IONM changes as true positives, or 2) only accepting cases in which patients had a positive Stagnara wake-up test or postoperative neurological deficit as true positives. True negatives were defined as those cases in which the patients did not have notable changes in IONM and recovered from their surgery without neurological impairment. There were no false negatives, defined as a new neurological deficit after surgery without significant IONM changes.

Based on the first assumption that all IONM changes were “real,” there were no false positives, defined as the presence of IONM changes without neurological impairment. We observed a sensitivity and specificity of 100% (both) and a positive predictive and negative predictive value of 100% as well. However, if we assume conversely that only cases with a positive Stagnara wake-up test or postoperative deficits were true positives, then we have 4 true positives and 43 false positives. The sensitivity and negative predictive values are similar at 100%, however the specificity becomes 92% with a positive predictive value of 8.5%.

Discussion

Intraoperative neuromonitoring has become routine in spinal deformity surgery, but a relative paucity of literature exists evaluating its role in the pediatric population. Vitale et al. identified risk factors related to spinal deformity surgery in 151 children who underwent spinal surgery with IONM. They reported that 11 (8%) of these 151 cases resulted in a true neurophysiological event, with 2 of those resulting in a new postoperative neurological deficit.15 Kamerlink et al. performed a joint adult and pediatric study investigating the preoperative risk for intraoperative neurological injury using IONM in spinal deformity surgery. In their series of 264 patients, 154 were pediatric cases, and the authors reported incidences of neuromonitoring changes and neurological deficit of 4.6% and 1.1%, respectively.4 Kundnani et al. evaluated 354 consecutive adolescent idiopathic scoliosis patients who underwent spinal deformity surgery with IONM.
They had 13 true neurophysiological alerts (3.7% of 354 cases), with 2 (0.6%) of those 13 demonstrating postoperative neurological deficits. In the largest series to date, Thuet et al. reported an incidence of 2.2% true positive IONM changes from a cohort of 3436 pediatric spinal deformity patients. We observed a slightly higher rate of 9.1%, with 0.8% of our patients having new postoperative neurological deficits. The differences noted between our series and other previously reported incidences may be partially explained by the variability of neuromonitoring techniques and thresholds considered significant in each series.

The true incidence of neural injury as well as the sensitivity and specificity of IONM may also be quite variable due to variations in the definition of true positive findings. The Stagnara wake-up test is often used as...
the “gold standard” to corroborate IONM changes, but it can contribute to ambiguity, as multiple modifications in management are typically initiated simultaneously at the onset of IONM changes. Also, as a patient progresses toward lighter sedation during a wake-up test, often improvement in the neuromonitoring can be observed. This raises questions as to whether the IONM changes were due to the anesthetic dosing or another variable being altered concurrently (for example, elevation of mean arterial pressure or reduction of correction). Thuet et al. reported that 79% of their patients with IONM changes woke up neurologically intact after the causes of the neurophysiological impairment were addressed, whereas 14% had transient postoperative neurological deficits and 7% suffered permanent neurological injury. Only 9% of our cohort had a postoperative neurological deficit, but we may have adopted a more conservative management approach. Our lower reported rate of postoperative neurological deficit may be a reflection of fewer completed spinal fusions.

The Stagnara wake-up test has been considered the gold standard for detection of intraoperative neurological changes since it was developed by Vauzelle and Stagnara in 1973. The test consists of decreasing anesthesia and asking the patient to move his upper and lower extremities. A test is considered positive if the patient is unable to demonstrate movement in all 4 extremities or shows loss of motion in limbs that previously had active movement in the case of a patient with preexisting loss of motion. The wake-up test has several clear limitations. It cannot be used accurately on patients who are very young or those with cognitive deficits that prevent them from following commands. The surgeon must also consider preoperative strength when performing the test. Finally, the test itself carries inherent risk related to the patient not being fully anesthetized, such as excessive movement, extrusion, and intravenous access loss. For these reasons, it is important for the surgical team to hold instrumentation in place for the duration of the wake-up test.

In our series, at least 1 wake-up test was performed in 37 of 47 cases due to IONM changes. In 31 of these cases, the test results were considered to be normal, and in 6 abnormal. There were 4 instances of new neurological deficit after a positive wake-up test, with 1 patient making a full recovery and 3 who did not regain full neuromuscular function as of the most recent follow-up. In the other 2 cases, the results of the Stagnara wake-up tests were abnormal and the procedure was terminated, but the patients had no neurological deficits postoperatively; it was assumed that with decreased sedation their examination findings improved. There were no instances in which the results of the wake-up test were normal and the patient had true neurological changes postoperatively, indicating a specificity and sensitivity of 100% for the Stagnara test. We typically rely more heavily on the sensitivity of MEPs; we are less concerned with other changes if MEPs are normal as they have lower specificity. However, concurrent changes in both SSEPs and MEPs are very alarming. The sensitivity of IONM in our series was 100%, but the specificity and positive predictive value vary based on the definition of a true positive finding. We found that use of the combination of SSEPs and tcMEPs was sufficient to provide excellent sensitivity and specificity.

Hamilton et al. reported outcomes from the Scoliosis Research Society Morbidity and Mortality database summarizing 108,419 adult and pediatric (< 21 years) patients with spine deformity. In the pediatric population, the incidence of neurological injury was 1.32%. IONM was used in 65% of all reported cases and 87% of pediatric cases, but IONM was only used in 238 of 293 patients who suffered spinal cord injuries. The sensitivity and specificity for concurrent use of SSEP and tcMEP in detecting spinal cord injury were 43% and 98%. Although multimodality monitoring is becoming the mainstay, significant variability in its use is still apparent.

Other series have similarly echoed the increasing use and validation of multimodality monitoring. Thuet et al. combined electromyography and monitoring of SSEPs, tcMEPs, neurogenic mixed evoked potentials (NMEPs), and dermatomal SSEPs in 3436 pediatric patients undergoing placement of spinal instrumentation and observed neurophysiological changes in 74 patients (2.2%). SSEPs were the only indicator in 35% of cases; NMEPs alone were abnormal in 33%; both were abnormal in 27%; SSEPs and tcMEPs were the indicators in 1.5%; and SSEPs with dermatomal SSEPs represented the only change in 1.5%. Seven patients still had false negative readings and awoke with new neurological deficits. The majority of these deficits were due to nerve root injuries, but 1 spinal cord injury was reported. Using the combination of modalities, Thuet et al. suggested that IONM was able to detect permanent neurological changes in 97.9% of patients. Although multimodality monitoring appears to dramatically improve our ability to detect and prevent neurological injury, sporadic false negatives can occur and warrant caution.

There are several proposed causes for IONM changes, including mechanical forces on the spinal cord as a result of corrective manipulation of the vertebral column, procedures to the vertebral column such as osteotomies and implantation of pedicle screws, decreased mean arterial pressure, use of inhalant anesthesia, and, rarely, direct trauma to the spinal cord. The altered anatomical structure of pediatric patients with severe spinal deformity must be taken into consideration when performing a correction, as overcorrection can cause abnormal forces on the cord and result in injury. Performing procedures on the individual segments of the vertebral column has the potential to breach the medial wall of the pedicle, possibly resulting in communication with the vertebral canal with risk for direct injury to the cord. These include placing pedicle screws, hooks, and wires, as well as performing osteotomies. With blood pressure, a certain amount of hypotension is desirable during spinal deformity surgeries to minimize blood loss. However, this carries with it a risk for ischemic injury to the spinal cord. For this reason, it has been recommended that the mean
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arterial pressure remain between 65–70 mm Hg during spinal deformity surgery and may be elevated higher during corrective maneuvers, thus allowing for adequate perfusion while limiting excessive bleeding.12

Once IONM changes are deemed real, several treatments can be employed concurrently to optimize recovery. As noted above, blood pressure and mean arterial pressure should be within acceptable limits (> 80 mm Hg) to ensure adequate perfusion. The hematocrit should be checked to ensure it is within the normal range and blood transfusions administered as necessary. If the blood pressure is already in the acceptable range, or adjusted into this range without return of signals, the next step should be to identify operative procedures surrounding the event that may have contributed to the loss of signals and simply reverse the most recent maneuver. If the signals were lost during the correction of the deformity, the surgeon should release or decrease the amount of correction and reassess for signal return. The signals may be lost due to aberrant placement of instrumentation, especially with respect to a medial wall breach. If the signals were lost in close proximity to placement of screws or hardware, these should be removed and the patient should be reassessed. If the spinal cord has been exposed through osteotomies, these sites should be checked to examine for compressive pathology from osseous fragments, hemostatic agents, instrumentation, or hematomas.

If any of these procedures are performed with successful return of signals, it is the decision of the surgeon to determine how to proceed. An isolated loss of signals with expedient return may allow the surgeon to proceed as planned, or to alter his correction or instrumentation to avoid another incident. If all of these procedures are performed without successful return of signals, however, the next step should be to perform a wake-up test as outlined above. Often the sedation wean is started at the onset of IONM changes since it takes a moderate amount of time to perform an examination. If the patient is able to adequately move all 4 extremities without issue, and the signals have not still returned, the surgeon may deduce that there is a technical issue with the IONM, and the surgery may proceed with caution. Further inconsistent IONM findings may also favor technical problems as a source of IONM changes such as involvement of the upper extremities when surgery only involves the thoracic or lumbar spine. It may be useful to use serial wake-up tests at certain critical points in the operation if this is the case. In the event of a positive wake-up test, we recommend removal of all hardware and exploration of all exposed areas to rule out any compression of neural structures. If no problems are identified, the patient should be fully awake for a more complete neurological examination and sent for emergent MRI and CT studies to further investigate the etiology of the possible injury.

In our series, the relative rate of surgical procedure completion after initial IONM changes was 75% (35 of 47 cases). In some instances, the surgeon opted for a reduced correction due to the IONM changes, indicating IONM played a significant role in the surgical decision-making process, in addition to serving its primary role as a form of alert.

Conclusions

Scoliosis deformity correction surgery carries significant inherent risk, with profound clinical and functional impact on children and young adults. For this reason, any adjuvant tool that can minimize risk of injury is of great clinical benefit. IONM appears to be a safe and useful warning mechanism for potential problems that may arise during surgery. It is not recommended to replace but rather to supplement the Stagnara wake-up test.

Disclosure

Dr. Samdani reports a consultant relationship with Depuy Synthes Spine, SpineGuard, Stryker, and Zimmer. Author contributions to the study and manuscript preparation include the following. Conception and design: Hwang, Samdani. Acquisition of data: Ferguson. Analysis and interpretation of data: Hwang. Drafting the article: Hwang, Ferguson, Tataryn. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Hwang. Statistical analysis: Hwang. Study supervision: Hwang, Samdani.

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