Intraoperative Neuromonitoring in Pediatric and Adult Spine Deformity Surgery

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Study Design: Review of techniques and description of institutional clinical experience.

Objective: To provide a historical review and description of key neuromonitoring concepts, focusing on neurogenic motor-evoked potentials and descending neurogenic evoked potentials, and to review the authors' experience with neuromonitoring techniques in children and adults undergoing spinal deformity surgery.

Summary of Background Data: The original form of neuromonitoring, the Stagnara wake-up test, remains the "gold standard" for detecting true neurological deficits. Multiple newer modalities involving cortical and muscular monitoring, such as somatosensory evoked potentials and motor evoked potentials, have been developed and are widely used. Descending and neurogenic evoked potentials are becoming more common for neuromonitoring in patients undergoing spinal deformity surgery.

Methods: A PubMed search for literature related to "neuromonitoring" was performed, and recent, as well as historical, articles were reviewed. Clinical experience regarding the use of neuromonitoring in adult and pediatric spinal deformity surgery was obtained from institutional experts.

Results: Although not regularly used, the Stagnara wake-up test remains the gold standard for detecting neurological injury. Somatosensory evoked potentials measure signals transmitted from the periphery to the cortex and have historically been widely used but are limited by delay, poor localization, and the inability to detect damage to motor tracts. Motor evoked potentials continue to be used widely and measure muscular activity after cortical stimulation, but they are difficult to interpret in patients with underlying motor disorders and cannot be continuously monitored. Newer techniques such as descending neurogenic evoked potentials and neurogenic motor evoked potentials monitoring are used at some high-volume centers.

Conclusions: Familiarity with the history of neuromonitoring in spinal deformity surgery and an understanding of the physiological systems used for neuromonitoring provide a framework from which spine surgeons can select appropriate monitoring for their patients.

Key Words: intraoperative neuromonitoring, spine deformity, pediatric, adult, neurological injury

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Neurological monitoring, or neuromonitoring, provides critical information to the spine surgeon regarding the status of neural elements intraoperatively. Possible deficits can be identified in a timely manner, allowing the surgeon to adjust techniques in real time to achieve a better patient outcome. Our purposes were to provide a brief historical review and description of key neuromonitoring concepts and techniques, focusing on the more recent introduction of neurogenic motor evoked potentials (NMEPs) and descending neurogenic evoked potentials (DNEPs), and to review our experience with neuromonitoring techniques in children and adults undergoing spinal deformity surgery.

BRIEF HISTORY OF NEUROMONITORING

The Stagnara wake-up test,[1] previously the only form of neuromonitoring, has been replaced by multiple, less invasive methods, but it still serves as a tool for detecting or confirming neurological deficits. Somatosensory evoked potentials (SSEPs) were developed in the late 1970s[1] as an indirect method of monitoring the ventral corticospinal tracts through dorsal column integrity; however, their limitations became clear when multiple studies reported postoperative paraplegia in patients with maintained SSEPs.[2–5] Motor evoked potentials (MEPs) were developed to better characterize the integrity of the corticospinal tracts, and the importance of D-waves as sensitive indicators of the fast neurons of the corticospinal tract and H-reflexes for real-time monitoring of nerve root function has been considerably investigated.[2,6] In our experience, SSEPs continue to be used as a complement to MEPs intraoperatively despite the development of advanced MEP

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stimulation and recording techniques. Electromyography (EMG) augments these techniques as a method for real-time monitoring of nerve root function, particularly during times of surgical manipulation and tenuous placement of instrumentation. As detailed below, a combination of neuromonitoring techniques is used on the basis of patient characteristics (adult vs. child, type of deformity) and surgical site (cervical, thoracic, or lumbar spine).

INDICATIONS TO USE INTRAOPERATIVE NEUROMONITORING (IONM)

Data supporting the use of IONM in spinal surgery, specifically aimed at preventing neural injury from improperly placed implants, have led to routine use of these techniques in anterior cervical discectomy and fusion (ACDF), surgical management of myelopathy, and spinal trauma.[2,3] Here, we review indications for use of IONM in adult spinal surgery in the cervical, thoracic, and lumbar spine, with a brief summary of the literature.

Cervical Spine

Use of IONM in cervical spine surgery differs on the basis of the approach and extent of surgical intervention. In practice, anterior cervical procedures require varying levels of IONM depending on the underlying pathology. For example, IONM in an ACDF for cervical radiculopathy at 1 or 2 levels often consists of SSEPs alone with the addition of MEPs for multiple levels or when planning to remove the posterior longitudinal ligament. For cervical myelopathy, multimodal IONM consisting of SSEPs, MEPs, and EMG is used with prepositioning and postpositioning monitoring in severe cases. Laminoplasty may require EMG monitoring specifically of the C5 nerve root given the decreased length, and thus increased tension, after surgical intervention. All posterior cervical procedures require SSEPs, MEPs, and EMG.

There is little and often controversial evidence regarding use of IONM in the cervical spine. Multimodal use of IONM in ACDF is theoretically beneficial because SSEPs monitor dorsal ascending spinal column tracts, whereas MEPs allow monitoring of ventral tracts, and EMG allows monitoring of individual nerve roots. On the basis of their results in a case series of 1055 patients who underwent cervical spine surgery, 3.2% of whom were found to have new postoperative neurological deficits, Kelleher et al[7] recommend use of multimodal IONM. Use of SSEPs for detecting neurological injury in this series had a sensitivity of 52%, a specificity and positive predictive value of 100%, and a negative predictive value of 97%. For MEP, sensitivity was 100%, specificity was 96%, positive predictive value was 96%, and negative predictive value was 100%. For EMG, sensitivity was 46%, specificity was 73%, positive predictive value was 3%, and negative predictive value was 97%.[7] Alternatively, Taunt et al[8] argued against the use of SSEPs in ACDF, citing the low rate of neurological complications and lack of useful positive SSEP alerts in their series of 163 patients who underwent ACDF.

Thoracic Spine

The proximity of the thoracic spinal cord to the pedicles of the thoracic vertebrae and the small width of the spinal canal necessitate use of SSEPs and MEPs in all cases of thoracic spine surgery, including procedures for deformity, myelopathy, and trauma. Conversely, EMG is uncommonly used in the thoracic spine given the low morbidity of individual nerve root damage.

Lumbar Spine

The lumbar spine must be considered as 2 distinct regions: (1) the level of the conus and above and (2) the level below the conus. In the area of the conus and above, where the spinal cord is present within the canal, fully multimodal IONM is used, including MEPS, SSEPs, and EMG. Below the level of the cord, the extent of IONM depends on the use of instrumentation and/or osteotomies. Without instrumentation, no IONM is necessary. Instrumentation without an osteotomy requires use of EMG, whereas instrumentation with an osteotomy requires spontaneous EMG, particularly before and after reduction.

IONM in correction of spinal deformity has been well described and served as the initial basis for use of monitoring in other forms of spinal surgery. In a series of 102 adults who underwent surgery for spinal deformity with multimodal IONM (SSEPs, MEPs, and EMG), Quraishi et al[9] reported an overall sensitivity of multimodal IONM of 100% and specificity of 84%, whereas the sensitivity of SSEPs alone was 33%.

TECHNIQUES

The following monitoring techniques, each with advantages and drawbacks, are reviewed: the Stagnara wake-up test, SSEP, MEP, NMEP, DNEP, and EMG. In all techniques, the patients serve as their own controls. Baseline data were obtained intraoperatively after surgical exposure, and changes were recorded and interpreted by a trained neurophysiologist throughout the operation.

Stagnara Wake-up Test

The Stagnara wake-up test, which requires partially wakening the patient intraoperatively to test motor function, was the original form of intraoperative monitoring. Today, this test still has value to confirm a signal change identified with modern forms of intraoperative monitoring. As such, surgical teams and patients should be trained in performing this test because it serves as the ultimate measure of motor tract injury. To have a reliable Stagnara wake-up test, the patient's baseline motor function must be determined before surgery. The test is performed by asking the patient to voluntarily move the relevant extremities; it should be noted that, in our experience, patients tend to be able to move their upper extremities sooner after awakening than their lower extremities. The presence of clonus, representing return of lower motor neuron function before inhibitory upper motor neuron function (as is normal in a person awaking from anesthesia), is an indicator of recovery,[2,10] although

it is sensitive to the depth of anesthesia applied.[3] Notably, the Stagnara wake-up test does not provide any information on sensory pathways or individual nerve roots and represents only gross motor function.[10] Furthermore, a deficit noted with this technique is detected later than in real-time monitoring and may take longer to reverse if a cause can be identified. This test is also cumbersome to perform multiple times in a complex surgery and difficult to use in infants, patients with cognitive deficits, and patients with preexisting weakness of the lower extremities or absence of ankle function. Finally, the difference in timing between the regaining of motor function in the upper extremities versus the lower extremities makes it difficult to know when a patient is adequately awake for a valid test.[3]

SSEP

Sensory information from the periphery is transmitted to the somatosensory cortex through the ascending tracts of the posterior columns of the spinal cord, the medial lemniscus pathway at the level of the brainstem, and the thalamus, which serves as the final nucleus of information processing en route to the sensory cortex. These signals are measured objectively as evoked potentials—electrical activity generated as a response to stimulus—through peripheral nerve stimulation. Repetitive stimulation evokes a cortical or subcortical response that can be recorded continuously during the procedure. Of note, SSEPs measure proprioception and vibration signals transmitted through the dorsal column pathways but do not involve pathways sensing pain and temperature. Physiologically, dysfunction of the anterior cord, such as occurs in anterior spinal artery syndrome, may occur despite preserved SSEPs.[2,3] Data are recorded as amplitude (voltage of recorded response) and latency (time between stimulus and response) and compared with baseline and recently recorded values. Amplitude changes are a more specific indicator of damage than latency. Sustaining damage without having amplitude changes is uncommon, whereas isolated latency changes occur frequently in the absence of damage.[3] Concerning changes include a $>50\%$ decrease in amplitude or a $>10\%$ increase in latency.[11,12] Typical sites of peripheral stimulation include the median and ulnar nerves in the upper extremity and the posterior tibial and peroneal nerves in the lower extremity.[3,13] SSEPs can be recorded at cortical, subcortical, or brainstem sites. Peripheral recordings are also obtained to verify adequacy of peripheral stimulation. Cortical site recordings are sensitive to changes in cerebral blood flow that may occur secondary to anesthesia. Because subcortical and peripheral recording sites are less sensitive to anesthesia, a concerning change in a cortically measured value can be compared with changes at subcortical and peripheral sites to ascertain whether the change is a result of anesthesia or a true indicator of damage. Subcortical recording sites are also valuable in patients with cortical abnormalities. Halogenated agents should be used at 0.5 of minimum alveolar concentration or less, nitrous oxide at 50% or less, and intravenous anesthetics as an infusion rather than a bolus to limit interference with SSEP recording[14] (Table 1). Limitations to SSEPs include a delay in data availability secondary to signal averaging over time, inability to localize damage because signals represent the entire sensory pathway, sensitivity of signals to systemic influences such as general anesthesia and body temperature, and inability to detect damage to motor tracts because they are only indirectly represented by SSEPs.[2,3]

MEPs

MEPs are signals measured in the periphery after stimulation of the motor cortex. Transcranial (Tc) stimulation is a surrogate for technically difficult direct motor cortex stimulation.[2] Electrical (TcMEP) or magnetic excitation is used to elicit impulses from descending motor pathways. Magnetic excitation is rarely used because of the difficulty of the technique.[3] Electrical stimulation in the form of a high-voltage, short-duration stimulus through scalp electrodes activates the corticospinal tract through the underlying motor cortex and descends through the spinal cord to activate skeletal muscles. Typically, MEPs are measured directly from skeletal muscle as compound muscle action potentials (CMAPs). CMAPs are recorded through subdermal needle electrodes placed in specific upper and lower extremity muscles[3] (Table 2). MEP signals may be interpreted as indicative of signal change on the basis of an all-or-nothing criterion

TABLE 1. Brief Anesthetic Reference for Neuromonitoring

Anesthetic	Transcranial Electric Motor Evoked Potential	Somatosensory Evoked Potential	Electromyography
Dexmedetomidine[15]	No limitations	No limitations	No limitations
Halogenated volatile agent	0.3 MAC	0.5–1.0 MAC	No limitations
Ketamine	No limitations	No limitations	No limitations
N_2O	< 70%, or avoid	< 50%, or avoid if baseline somatosensory evoked potentials is poor	< 70%
Propofol[16]	50–300 μg/kg/min	Increases latency in a dose-dependent fashion	No limitations
Narcotics	No limitations	No limitations	No limitations
Neuromuscular blockade	Limited use	No limitations	Limited use
Remifentanil[17]	No limitations	No limitations	No limitations

*MAC indicates minimum alveolar concentration.

TABLE 2. Upper and Lower Extremity Skeletal Muscles and Corresponding Spinal Level

Spinal Level	Muscle
C5	Deltoid
C6	Biceps
C7	Triceps, wrist extensors/flexors
C8/T1	Hand intrinsics, abductor pollicis brevis
L2	Adductor longus
L3	Adductors, vastus medialis
L4	Vastus medialis, vastus lateralis
L5	Anterior tibialis, extensor hallucis longus
S1	Medial gastrocnemius, abductor hallucis
S2-S5	Perianal musculature (anal sphincter)

that requires a complete signal loss from baseline, a more sensitive requirement of an 80% change in signal in at least 1 of 6 recording sites, a requirement of an increase in the threshold necessary to elicit a CMAP, or a requirement of a change in pattern or duration of waveforms (eg, polyphasic to biphasic). Key anesthetic considerations include using a short-acting muscle relaxant for intubation allowing muscle tone during MEP monitoring, using a bite block to prevent the common complication of tongue laceration secondary to jaw clenching when using TcMEP, disabling pacemakers before surgery, and avoiding the use of TcMEP in patients with seizure disorders or skull-based metal implants. Ideally, an infusion of intravenous anesthetics is used intraoperatively because inhalational anesthetics depress MEP signal amplitudes in a dose-dependent manner; however, risks of delayed recovery and prolonged intubation should be considered in pediatric patients.[14] Total intravenous anesthesia may be used to prevent the interference of inhalational options. Unlike SSEPs, MEPs cannot be monitored continuously and can be more challenging to obtain, particularly when a patient has a preoperative motor deficit.

D-waves result from a single pulse stimulation of the motor cortex as 1 component of the descending signal. They are measured at the epidural or subdural space and represent fast tract neurons. D-wave monitoring is particularly relevant in patients undergoing spinal cord surgery, whereas MEP monitoring without D-waves is often sufficient in spine surgery that does not involve the spinal cord.[2]

H-reflexes represent motor pathways within the spinal cord and are sensitive indicators of spinal nerve root injury.[2] H-reflex monitoring provides immediate and real-time feedback of nerve root injury.[6] The reflex pathway starts with an afferent signal caused by peripheral muscle stimulation, most commonly the gastrocnemius. A CMAP is recorded after the afferent signal passes through a monosynaptic reflex arc. Anesthetic considerations include ensuring a functioning neuromuscular junction for recording H-reflexes and allowing concomitant SSEP, MEP, and EMG recording. H-reflexes have not been studied extensively as a neuromonitoring technique and are not currently used at our institution, but further research seems warranted given the advantageous real-time feedback of these signals.[6]

EMG

SSEP and MEP monitoring techniques do not allow for specific nerve root monitoring. EMG of individual myotomes permits more specific monitoring without the sensitivity to anesthetics that is associated with dermatomal monitoring through SSEPs. EMG recordings may be spontaneous, as when continuous monitoring is necessary such as in decompression or instrumentation placement, or triggered, as when time-specific neuromonitoring is necessary such as in pedicle screw placement.[3] A progressively increasing stimulus is applied until a threshold necessary to cause nerve root CMAPs is reached. Breaching of the cortex during pedicle screw placement removes the natural barrier to nerve root irritation and thus decreases the threshold necessary to cause a CMAP.[3] As with MEPs, signals are recorded through subdermal needles placed in corresponding muscle groups (Table 2). EMG recordings may show burst activity, resulting from any mechanical contact with the nerve root, which may be of surgical value. However, train activity results when persistent nerve root stimulation occurs.[3] Although peripheral muscles, particularly in the lower extremity, serve as sites for EMG recording when operating on the lumbar spine, the increased use of pedicle screws in the thoracic spine has mandated methods for using EMG to detect screw penetration in this region. Particularly helpful in thoracic pedicle screw placement, intercostal EMG has been studied as a tool[18] for detecting cortical breakthrough. Stimulation thresholds necessary to elicit CMAPs in intercostal muscles are measured through ascending stimulation as with other forms of EMG.[19] Shi et al[20] used intercostal EMG in 87 patients with pedicle screws placed in the range of T1-T12 and found a 97.5% negative predictive value for stimulation thresholds >11 mA with computed tomography as the gold standard for detecting cortical penetration by a pedicle screw. Rodriguez-Olaverri et al[19] placed 311 pedicle screws in the T6–T12 range in 50 patients and reported 11 screws with medial cortical penetration with intercostal EMG detecting a 60%–65% decrease in mean threshold value for all breached screws and a 98% negative predictive value of cortical breakthrough for all intact screws with a stimulation threshold between 6 and 20 mA. Thoracic monitoring is not widely used. There are fewer anesthetic considerations with EMG monitoring because signals are less sensitive to inhaled agents. The only notable consideration is avoidance of muscle relaxants because tone is necessary for EMG monitoring.

DNEPs

DNEPs measure peripheral nerve antidromic sensory signals resulting from spinal cord level stimulation. Needle electrodes may be placed in adjacent spinous processes, percutaneously into consecutive cervical laminae, or after laminotomy through an epidural catheter into operative spinal levels.[13] Signals are recorded from the sciatic nerve at the popliteal fossa.[13,21] Similar to SSEPs, noteworthy signal changes include an 80% decrease in amplitude and/or a 10% or greater increase in

latency.[13] DNEP monitoring is highly sensitive to spinal cord deficits, and studies[13,22] have shown reliable and repeatable results. In a review of a 23-year study of 3436 children undergoing spinal surgery, Emerson[21] noted only 1 instance (of 74 deficits) in which DNEPs did not successfully predict a postoperative deficit. Although DNEPs have greater sensitivity than SSEPs, their major drawback is that they do not represent motor pathways[5]; however, Emerson[21] has argued that the combined use of DNEPs and SSEPs as measures of sensory tract function may be adequate for using the sensory pathways as a surrogate for motor pathways, similar to pre-MEP neuromonitoring. Unlike MEPs, DNEPs are not sensitive to patient movement, but rather require complete muscle relaxation.

NMEPs

Similar to DNEPs, NMEPs require direct spinal cord stimulation through spinous processes or percutaneously into the lamina of the posterior cervical spine (PERC-NMEPs) and measuring conduction of signals at the sciatic nerve or popliteal fossa.[23] NMEPs, however, directly monitor motor tracts. Disadvantages of the spinous process NMEP technique include greater dissection and pooling fluids within the wound that can interrupt signal detection. PERC-NMEPs eliminate many of these obstacles because they are not placed in the wound; however, large body habitus and head/neck positioning may affect PERC-NMEP monitoring. The percutaneous method allows for preoperative baseline monitoring. An 80% reduction in amplitude or 10% increase in latency is, again, considered a loss of signal.[23] In a study of 147 and 122 cases in which spinous process NMEPs or PERC-NMEPs, respectively, were used, there was no significant difference in reliability between the 2 methods.[23]

ANESTHESIA AND NEUROMONITORING

A necessary component of any spinal surgery, anesthesia presents a challenge to neuromonitoring in that almost all forms affect the cortical, subcortical, and spinal signals being measured (Table 1). Inhaled agents, and less markedly intravenous agents, decrease SSEP and MEP signal amplitude and increase latency.[3,14] MEPs are usually more sensitive to anesthesia than SSEPs, given the greater length of the motor tracts compared with sensory pathways.[14] Muscle relaxation, although not affecting SSEP recording, will prevent accurate monitoring of MEPs and EMG.[3] Conversely, muscle relaxation is necessary for DNEP recording. Intravenous anesthetics are ideally infused at a steady rate, avoiding boluses that may lead to a sudden signal loss.[14] Total intravenous anesthesia is advocated by some for its lack of signal depression compared with volatile agents and nitrous oxide.[24] However, in children, extubation and recovery from anesthesia may be prolonged.

Neuromonitoring in Our Practice

Pediatric Patients

IONM is used in all of our pediatric patients with adolescent idiopathic scoliosis or kyphosis, those with neuromuscular disorders that have residual motor function, or those undergoing growing rod or vertical expandable prosthetic titanium rib placement and/or distraction. At our institution, we use primarily SSEPs and TcMEPs for standard neuromonitoring (Table 3) (see below for our response to signal irregularity) (Figs. 1A–D). Patients with neuromuscular disorders represent a continued challenge because useful monitoring is impossible in at least 10% of patients,[25,26] especially those with cerebral palsy or severe motor atrophy (Figs. 2A–D). Spondylolisthesis is also challenging to monitor because it is a single-level abnormality with a very distal location.

Adult Patients

IONM is used in all adult deformity patients at our institution. In patients with severe myelopathy or instability, neurological status is obtained before any patient movement and again before surgical manipulation to identify the influence of intubation and patient positioning on neurological signaling in patients with a vulnerable neurological baseline. Three-column osteotomies of the lumbar spine require use of MEPs; however, EMG alone is used when no 3-column osteotomies are performed (Table 3).

Practical Steps After Signal Change

Understanding methods of neuromonitoring is critical to applying these techniques in practice, and, for

TABLE 3. Recommended Neuromonitoring by Level of Spine Surgery*

Spinal Level	Neuromonitoring	
	Adult	Pediatric
Cervical	Upper and lower extremity somatosensory evoked potentials Motor evoked potential Spontaneous cervical electromyography	Upper and lower extremity somatosensory evoked potentials Motor evoked potential Spontaneous cervical electromyography
Thoracic	Upper and lower extremity somatosensory evoked potentials Motor evoked potential	Upper and lower extremity somatosensory evoked potentials Motor evoked potential
Lumbar	Upper and lower extremity somatosensory evoked potentials Spontaneous lumbar electromyography Triggered electromyography Motor evoked potentials (3-column osteotomies only)	Upper and lower extremity somatosensory evoked potentials Spontaneous cervical electromyography

*In cervical cases, upper extremity somatosensory evoked potentials are recorded after median and ulnar nerve stimulation. In thoracic and lumbar cases, upper extremity somatosensory evoked potentials are usually performed only from median or ulnar nerve stimulation.

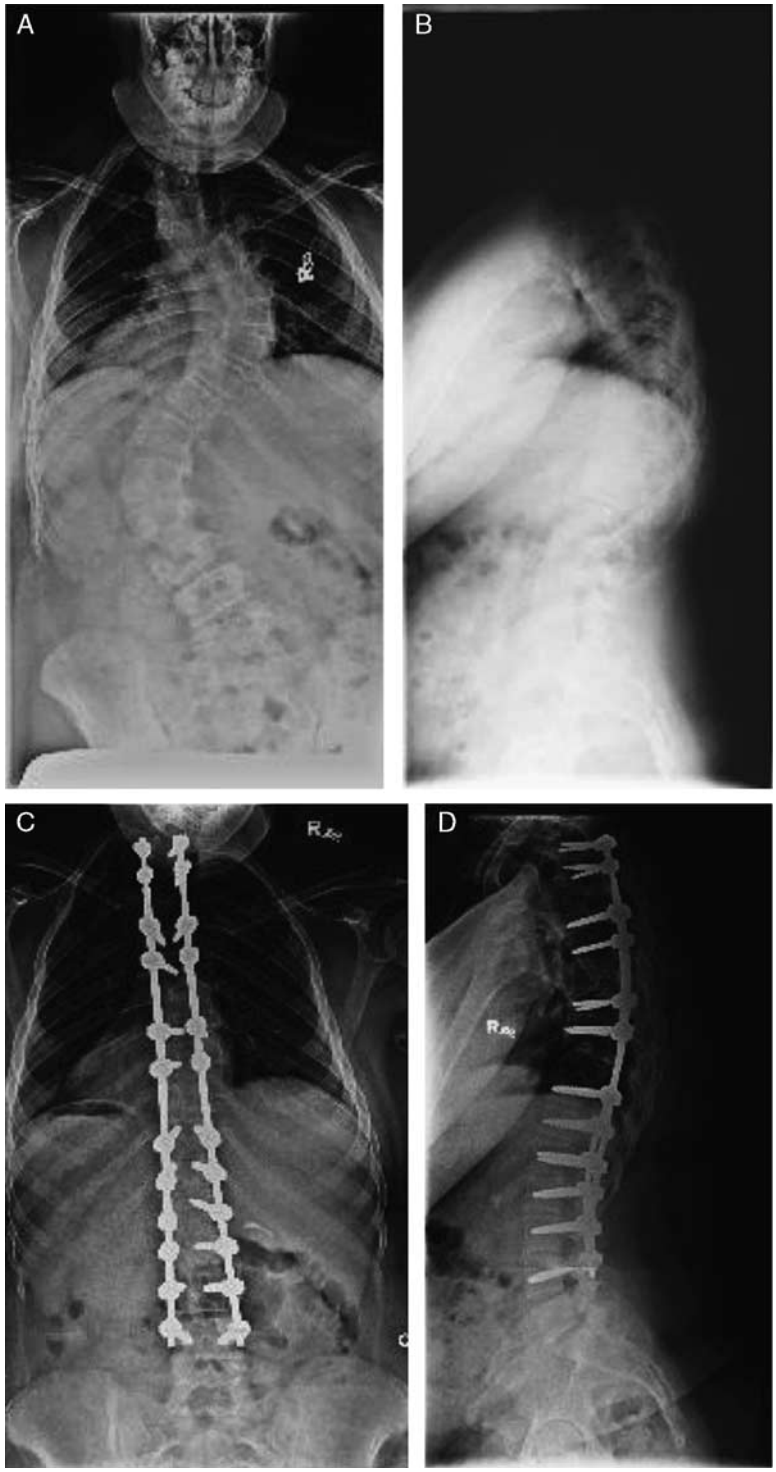

FIGURE 1. This 13-year-old girl with adolescent idiopathic scoliosis and a 75-degree right thoracic curve, as well as a 72-degree left lumbar curve, underwent posterior spinal fusion and had loss and return of motor evoked potentials twice intraoperatively. Somatosensory evoked potentials were unable to be monitored at baseline. Despite return of motor evoked potentials, the patient was found to have weakness and sensory changes on the evening of postoperative day 0, which resolved with dopamine-induced pressure elevation in the pediatric intensive care unit for 2 days after surgery and therefore were thought to be secondary to cord ischemia. A, Preoperative anteroposterior radiograph. B, Preoperative lateral radiograph. C, Postoperative anteroposterior radiograph. D, Postoperative lateral radiograph.

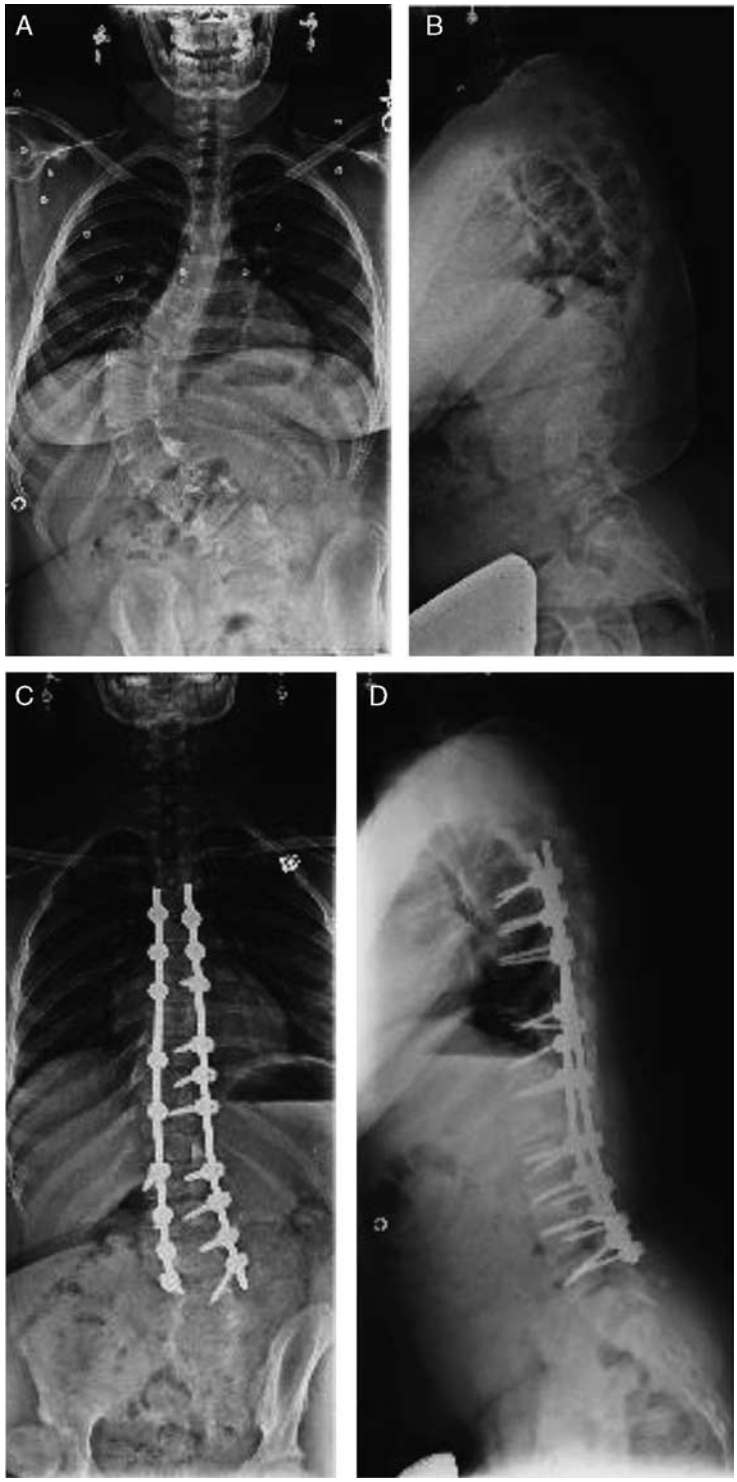

FIGURE 2. This 13-year-old girl with myelodysplasia and a 75-degree curve was ambulatory at baseline. She underwent posterior spinal fusion with an asymmetrical pedicle subtraction osteotomy at the apex of her curve and spinal cord untethering. Motor evoked potentials were lost at the time of rod insertion and returned with removal of the rod. To remedy concerns for canal translation and screw placement on the concave side of the curve, we repositioned 1 screw and removed 1 screw with motor evoked potentials intact at closure. Although motor evoked potentials are difficult to monitor in patients with myelodysplasia at baseline, a switch from anesthetic gas to total intravenous anesthesia (remifentanil and propofol) improved intraoperative signals and she was successfully monitored through motor evoked potentials. A, Preoperative anteroposterior radiograph. B, Preoperative lateral radiograph. C, Postoperative anteroposterior radiograph. D, Postoperative lateral radiograph.

patient safety, understanding the practical steps to take in the presence of a signal change is equally important. Key steps include ruling out technical causes; the clinician should ensure electrodes are in place, monitoring equipment is in working order (stimulators may break, recording boxes may flood with blood or irrigation, wires may accidentally be unplugged), and no new electrical equipment has been introduced to the field that can cause electrical interference (such as microscopes, warmers, lamps, or Bovie knives). At the same time, one needs to evaluate for recent anesthetic changes, including changes in gases, switching of anesthetics, or bolus administration of neuromuscular junction blocking agents. After ruling out these causes, the next steps include stopping inhaled anesthetics; assessing arterial blood gas for an unrecognized metabolic abnormality; optimizing the spinal cord environment by elevating mean arterial pressure to 90 mm Hg; increasing the concentration of inspired oxygen; reversing severe anemia; lessening distraction forces; checking for anchor malposition, localized translation, or stenosis of the spinal canal; and irrigating the wound with warm saline. At this point, a Stagnara wake-up test should be performed to confirm signal changes; if the latter are concerning for a neurological deficit, further modification or removal of instrumentation and administration of steroids should be considered.

REFERENCES

1. Vauzelle C, Stagnara P, Jouvinroux P. Functional monitoring of spinal cord activity during spinal surgery. *Clin Orthop Relat Res*. 1973;93:173–178.
2. Deletis V, Sala F. Intraoperative neurophysiological monitoring of the spinal cord during spinal cord and spine surgery: a review focus on the corticospinal tracts. *Clin Neurophysiol*. 2008;119:248–264.
3. Devlin VJ, Schwartz DM. Intraoperative neurophysiologic monitoring during spinal surgery. *J Am Acad Orthop Surg*. 2007;15:549–560.
4. Lesser RP, Raudzens P, Luders H, et al. Postoperative neurological deficits may occur despite unchanged intraoperative somatosensory evoked potentials. *Ann Neurol*. 1986;19:22–25.
5. Toleikis JR, Skelly JP, Carlvin AO, et al. Spinally elicited peripheral nerve responses are sensory rather than motor. *Clin Neurophysiol*. 2000;111:736–742.
6. Leppanen RE. Monitoring spinal nerve function with H-reflexes. *J Clin Neurophysiol*. 2012;29:126–139.
7. Kelleher MO, Tan G, Sarjeant R, et al. Predictive value of intraoperative neurophysiological monitoring during cervical spine surgery: a prospective analysis of 1055 consecutive patients. *J Neurosurg Spine*. 2008;8:215–221.
8. Taunt CJ Jr, Sidhu KS, Andrew SA. Somatosensory evoked potential monitoring during anterior cervical discectomy and fusion. *Spine (Phila Pa 1976)*. 2005;30:1970–1972.
9. Quraishi NA, Lewis SJ, Kelleher MO, et al. Intraoperative multimodality monitoring in adult spinal deformity: analysis of a prospective series of one hundred two cases with independent evaluation. *Spine (Phila Pa 1976)*. 2009;34:1504–1512.
10. Hoppenfeld S, Gross A, Andrews C, et al. The ankle clonus test for assessment of the integrity of the spinal cord during operations for scoliosis. *J Bone Joint Surg Am*. 1997;79:208–212.
11. Brown RH, Nash CL Jr, Berilla JA, et al. Cortical evoked potential monitoring. A system for intraoperative monitoring of spinal cord function. *Spine (Phila Pa 1976)*. 1984;9:256–261.
12. York DH, Chabot RJ, Gaines RW. Response variability of somatosensory evoked potentials during scoliosis surgery. *Spine (Phila Pa 1976)*. 1987;12:864–876.
13. Thuet ED, Winscher JC, Padberg AM, et al. Validity and reliability of intraoperative monitoring in pediatric spinal deformity surgery: a 23-year experience of 3436 surgical cases. *Spine (Phila Pa 1976)*. 2010;35:1880–1886.
14. Deiner S. Highlights of anesthetic considerations for intraoperative neuromonitoring. *Semin Cardiothorac Vasc Anesth*. 2010;14:51–53.
15. Tobias JD, Goble TJ, Bates G, et al. Effects of dexmedetomidine on intraoperative motor and somatosensory evoked potential monitoring during spinal surgery in adolescents. *Paediatr Anaesth*. 2008;18:1082–1088.
16. Liu EHC, Wong HK, Chia CP, et al. Effects of isoflurane and propofol on cortical somatosensory evoked potentials during comparable depth of anaesthesia as guided by bispectral index. *Br J Anaesth*. 2005;94:193–197.
17. Palmer GM, Pirakalathanan P, Skinner AV. A multi-centre multinational survey of anaesthetists regarding the range of anaesthetic and surgical practices for paediatric scoliosis surgery. *Anaesth Intensive Care*. 2010;38:1077–1084.
18. Reidy DP, Houlden D, Nolan PC, et al. Evaluation of electromyographic monitoring during insertion of thoracic pedicle screws. *J Bone Joint Surg Br*. 2001;83:1009–1014.
19. Rodriguez-Olaverri JC, Zimick NC, Merola A, et al. Using triggered electromyographic threshold in the intercostal muscles to evaluate the accuracy of upper thoracic pedicle screw placement (T3-T6). *Spine (Phila Pa 1976)*. 2008;33:E194–E197.
20. Shi YB, Binette M, Martin WH, et al. Electrical stimulation for intraoperative evaluation of thoracic pedicle screw placement. *Spine (Phila Pa 1976)*. 2003;28:595–601.
21. Emerson RG. NIOM for spinal deformity surgery: there's more than one way to skin a cat. *J Clin Neurophysiol*. 2012;29:149–150.
22. Raynor BL, Bright JD, Lenke LG, et al. Significant change or loss of intraoperative monitoring data: a 25-year experience in 12,375 spinal surgeries. *Spine (Phila Pa 1976)*. 2013;38:E101–E108.
23. Komanetsky RM, Padberg AM, Lenke LG, et al. Neurogenic motor evoked potentials: a prospective comparison of stimulation methods in spinal deformity surgery. *J Spinal Disord*. 1998;11:21–28.
24. Scheufler KM, Zentner J. Total intravenous anesthesia for intraoperative monitoring of the motor pathways: an integral view combining clinical and experimental data. *J Neurosurg*. 2002;96:571–579.
25. DiCindio S, Theroux M, Shah S, et al. Multimodality monitoring of transcranial electric motor and somatosensory-evoked potentials during surgical correction of spinal deformity in patients with cerebral palsy and other neuromuscular disorders. *Spine (Phila Pa 1976)*. 2003;28:1851–1855. discussion 1855-1856.
26. Noonan KJ, Walker T, Feinberg JR, et al. Factors related to false-versus true-positive neuromonitoring changes in adolescent idiopathic scoliosis surgery. *Spine (Phila Pa 1976)*. 2002;27:825–830.