International Journal of Multiphysics
Volume 18, No. 3, 2024
ISSN: 1750-9548

Intraoperative Neurophysiological Monitoring in Spine Surgery in Pediatric Population

Randa Abdeldayem Abdeldayem Said, Tarek Hassan Abdelbarey, Magdy Elsayed Hassan Rashed, Radwa Mahmoud Azmy Mohamed and Ahmed Ali Morsy

Neurosurgery Department, Faculty of Medicine, Zagazig University, Egypt

***Corresponding author:** Randa Abdeldayem Abdeldayem Said

Abstract:

Intraoperative neurophysiological monitoring (IONM) has become an essential adjunct in pediatric spine surgery for prevention of iatrogenic neurological injury during correction of spinal deformities, congenital anomalies, and complex spinal procedures. Pediatric patients represent a unique challenge because of immature neural pathways, variable anesthetic responses, and complex deformity patterns, which may affect monitoring reliability. Multimodal IONM, including somatosensory evoked potentials, motor evoked potentials, and electromyography, provides real-time assessment of sensory and motor pathway integrity and improves intraoperative detection of impending neurological compromise. Recent advances have expanded its indications, refined alert-response algorithms, and strengthened multidisciplinary strategies for signal interpretation and intervention. This review highlights the current role of IONM in pediatric spine surgery, focusing on monitoring modalities, indications, intraoperative alert management, technical challenges, and contemporary evidence regarding its effectiveness in improving surgical safety and neurological outcomes.

Keywords: Intraoperative neurophysiological monitoring; Pediatric spine surgery; Somatosensory evoked potentials; Motor evoked potentials; Electromyography; Multimodal monitoring; Spinal deformity; Neurological injury prevention.

Introduction:

Primary spinal developmental anomalies, also known as congenital spine anomalies, are birth defects affecting the spine, including neural tube defects like spina bifida and myelomeningocele, spinal deformities such as scoliosis, kyphosis, and lordosis, and malformations like tethered spinal cord. These conditions can range from minor to severe and may result in significant functional impairments if not managed (**1).**

Spina bifida literally means “spine in two parts” or “open spine”. Spinal dysraphism involves a spectrum of congenital anomalies resulting in a defective neural arch through which meninges or neural elements are herniated, leading to a variety of clinical manifestations. They are divided into aperta (visible lesion) and occulta (with no external lesion) (**2).**

Pediatric orthopedics has become one of the main indications for IONM or neurophysiological monitoring. Children are affected by progressive spinal deformity the most. While neurological complications during this surgery are extremely rare, the consequences could be disastrous. IONM has been used daily in operating rooms (OR) for 20 years (**3).**

The technological features of neuromonitoring in children

Electrophysiological methods

Common IONM modalities used in paediatric spine surgery include somatosensory-evoked potentials (SEPs), motor-evoked potentials (MEPs) and EMG. The neural pathways monitored by these modalities are summarised in Table 1 **(4).**

Table 1. Intraoperative neuromonitoring modalities **(4).**

	SEP	**MEP**	**EMG**
Stimulation site	Peripheral sensory nerves	Transcranial motor cortex	Triggered (or none)
Recording site	Cortical	Extremity muscle	Muscle
Advantages	Sensory specificity; continuous signal capture	Motor specificity; large-amplitude signal	Continuous monitor; allows for surgical correlation with pedicle screw stimulation
Limitations	Low amplitude; requires averaging (possible introduction of delays)	TIVA preferable; intermittent signal; variable stimulation thresholds with age	No neuromuscular block; difficulty distinguishing innocuous from serious injury; insensitive to complete nerve injury

SSEP monitoring is among the most frequently used intraoperative spinal monitoring modality in the contemporary era. It consists of cortical responses generated by peripheral stimulating electrodes, which allows for monitoring of sensory pathways and detection of perioperative neurologic changes with excellent reliability. Although SSEPs are monitored continuously throughout the surgery, its interpretation requires temporal summation, which can delay the detection of a signal change by up to 16 minutes. Moreover, there have been several reports of false-positives and false-negatives with this technique that have raised safety concerns as to whether SSEPs can be used as a standalone monitoring technique **(5).**

In contrast to SSEPs, MEPs involve generating a stimulus either at the level of the spinal cord (D-wave) or at the motor cortex, often referred to as transcranial MEPs (tcMEPs). Subsequently, the signal is measured peripherally at multiple predetermined upper and lower extremity muscle groups by recording electrodes. With this protocol, MEPs allow for monitoring and tracking of the corticospinal tract activity during the operative procedure (**6).**

Although MEPs have been shown to be reliable for detecting new postoperative deficits, the extreme sensitivity to inhaled volatile gases prevents the practice of routine anesthesia and necessitates the use of intravenous anesthetic agents.[21,22] Additionally, the requirement of a triggered stimulus to register the MEP prevents continuous ongoing monitoring (**7).**

EMG, which comes in the form of spontaneous (sEMG) or triggered (tEMG), is a valuable tool for neuromonitoring specific nerve roots at risk of injury during spinal instrumentation. Similar to SSEPs, sEMG is recorded continuously, thus giving the advantage of real-time feedback throughout the entire procedure. However, in order to have a proper sEMG response, neuromuscular blockade is prohibited (**8).**

On the other hand, tEMGs are obtained by stimulating the center of the tulip of the pedicle screw. The response is then recorded from the appropriate muscle group. Lower thresholds might be suggestive of cortical breach, putting the nerve root at risk. Since its introduction, this technique has also been shown to be an effective tool for detecting cortical bone breaches during pedicle screw insertion (**7).**

While each modality has its own intrinsic advantages and weaknesses, summarized in Table 2, together the strategies complement each other allowing for comprehensive monitoring of the anatomical areas of the spinal cord. Hence, the concept of multimodal intraoperative neurophysiological monitoring (MIONM) has gained in popularity and has become the standard practice for a variety of surgical procedures **(5).**

However, despite the advancements in these techniques, reports still exist of false-positive alerts that can lead to unnecessary precautionary actions taken by the surgical team. Therefore, the purpose of this review is to summarize relevant studies regarding the effectiveness of IONM in spine surgery published in recent years **(9).**

Table 2. Summary of Strengths and Weaknesses of IONM Modalities **(5).**

Type of Monitoring	**Strengths**	**Weaknesses**
SSEP	• Allows continuous monitoring throughout the surgery • Does not preclude the use of neuromuscular blockade	• Its interpretation requires temporal summation, which can delay the detection of a signal change by up to 16 minutes • Unable to detect motor changes • Individual nerve root function is not effectively monitored by SSEPs
tcMEP	• Allows monitoring of the entire motor pathway (cortex, corticospinal tract, nerve root, peripheral nerve) • Sensitive in the detection of postoperative motor deficits • Sensitive for detecting spinal cord ischemia	• Does not allow for continuous monitoring • Precludes use of neuromuscular blockade • Highly sensitive to inhalational anesthetics, demanding rigid anesthetic protocols
Spontaneous EMG	• Sensitive for nerve root injury • Provides real-time information about nerve root function throughout surgery • May be combined with SSEPs to improve specificity	• Sensitive to temperature changes • High rate of false positive alarms • Precludes use of neuromuscular blockade
Triggered EMG	• High sensitivity for medial pedicle wall breach • Useful in minimally invasive surgery where anatomical landmarks may be challenging to visualize • Relatively easy technique	• Accepted set thresholds not firmly established • Less sensitive for thoracic pedicle screws than for lumbar pedicle screws • High rate of false positive alarms

IONM, intraoperative neurophysiological monitoring; SSEP, somatosensory sensory evoked potential; tcMEP, transcranial motor-evoked potential; EMG, electromyography.

The indications for neuromonitoring in children

MEP can be used to monitor nearly every type of clinical situation. This is a precious interventional tool for surgeons. However, the indications differ depending on the information expected. There are several “levels” of indications.

Absolute indications are those involving patients who have a spinal deformity without any neurological deficit, no matter the level of severity. The aim is to achieve good three-dimensional correction, using all possible technical aids, which contributes to the best possible function in the long-term. In this context, osteotomy (posterior, Ponte or transpedicular) or vertebral column resection is sometimes indicated, but are associated with a considerable number of neurological complications, up to 30% in some studies (**10).**

An IONM alert during a vertebral resection step or when reducing the deformity should interrupt the procedure, with the surgeon releasing the correction until the responses re-appear. Sometimes, one must stop short of the desired amount of correction to prevent irreversible neurological damage. In a different context, surgical correction of a moderate and reducible idiopathic scoliosis cannot tolerate a loss of chance due to poor implementation, whereas monitoring is just as essential. The same goes for a kyphotic deformity, which is known to be associated with more neurological complications **(11).**

Other indications are not as obvious. The central nervous system (CNS) is said to be fully mature after 4 years of age. This would make surgery in a younger patient more difficult to monitor. But we have shown differences between patients: some children younger than 4 can benefit from effective multimodal or MEP monitoring. If MEP recruitment curves are obtained at the start of the procedure, they will be reliable for the remainder of the procedure. However, given that the CNS is often immature in a child less than 4 years, the absence of initial responses should not stop one from doing the procedure **(12).**

Other options are to do a preoperative multimodal analysis or to delay the procedure for a few years if the spinal malformation is stable (e.g., hemivertebra). But one must be certain that waiting will not compromise the prognosis. IONM is harder to do in patients with central or peripheral neurological diseases. In this case, and particularly in children who can walk, an analysis can be done before the procedure. If the border line responses are present — even if they are asymmetric or altered — they can be used as a reference during the surgical procedure. Here again, like in children less than 4 years, IONM is questionable and not essential (**10).**

A 2011 symposium of the French Spine Surgery Society (SFCR) established the first "rules of the Art" (*lege artis*) for monitoring. Remember that in the legal context, these are "methods that have proven themselves in practice for the majority of professionals". These references are subjective and variable in their interpretation. They change over time. A judge is not bound by the conclusions of an expert; *lege artis* is information that tells the judge about the state of the Art at a given moment in time. Ultimately, the judge has the final say (**13).**

The 2011 symposium concluded that multimodal monitoring was high quality when using a combination of techniques to monitor motor and somatosensory pathways (MEP + SEP or NMEP + SEP + D-wave) in the presence of an experienced neurophysiologist. As mentioned previously, this ideal situation is not, or only rarely, feasible in the French medical system. Conversely, automated or surgeon-guided systems have greatly improved since 2011, even if they are less impressive. But in practice, they are limited to monitoring MEPs (**13).**

In all cases, the intraoperative wake-up test is an essential tool that anesthetists must master (**10**):

- when using MEP, intraoperative wake-up will theoretically contribute little because it is superimposed on the recruitment curves. Nevertheless, experience has revealed two benefits. The first is that it eliminates questions about an artefact linked to the device (asymmetric responses, responses with atypical amplitudes or reproducibility without cohesive interpretation, etc.). The second is to lighten the depth of the anesthesia and to observe the return of normal amplitudes even before complete clinical awakening occurs. We call this "electrophysiological awakening". The origin is in the depth or the patient's susceptibility to anesthesia, probably sometimes associated with a period of transient spinal cord pain. In any case, this electrophysiological awakening procedure conducted by a trained anesthesiologist often makes it possible to preserve all the benefits of an intervention;
- on the other hand, when using mixed (NMEP) or sensory potentials (SEP) without MEP, the information provided by the intraoperative wake-up test is essential because NMEP and SEP do not provide useful information about motor function.

Technical incidents before the first incision managed

This is an important question because these incidents often happen in daily practice. Technical incidents can occur during the preoperative period, up to the first incision. Each time, they bring up uncomfortable questions and difficult decisions. These incidents are listed in chronological order (**10**):

- before anesthesia: if the system is down or defective and cannot be replaced, the procedure must be cancelled if there was an absolute indication for monitoring. This is the correct decision most of the time, except in an emergency situation. This decision must be clearly explained to the family. In the absence of replacement material in due time, the decision is made by the surgeon. The situation is more complex for relative indications, such as neuromuscular scoliosis and those causing a neurological deficit. The discussion is then open, given the low risk-benefit ratio of MEP monitoring in these indications. In this particular situation of associated neurological deficit, the family must be given clear information and must participate in the decision;

- after anesthesia but before the procedure starts: absence of curves during monitoring is common when using MEP. The electrodes are placed on the upper and lower limbs, and the responses do not appear as they should:

- if the monitor goes into alarm or standby mode, the situation is tricky in a patient who has been anesthetized, intubated, received infusions and an indwelling catheter. However, and if a second monitor is not available, it is preferable to wake the patient up if there is an absolute indication for monitoring. This is why at least two monitors should be available at the facility,

- if the curves are absent in the upper and lower limbs, an anesthesia-related reason should be suspected. If this happens in a patient who has no preoperative neurological deficit, the surgical procedure does not need to be stopped. The anesthesiologist is asked to check the depth of the anesthesia, the absence of halogenated compounds, nitrous oxide, muscle relaxants, the maintenance of satisfactory hemodynamics and the absence of hypothermia. Generally, the MEPs re-appear after the anesthetic protocol has been modified,

- special attention is required in children who have instability of the vertebral column. Some conditions with large instability are such that positioning the child prone on an operating table can cause the responses to disappear. In these circumstances, the responses are still visible in the upper limbs but disappear in the lower limbs. This observed this once in a patient who had mucopolysaccharidosis type II. The responses were present when the patient was supine but disappeared when they were prone, then reappeared when they were returned to a supine position. The procedure was cancelled and the child awakened. The subsequent steps (rescheduled surgery) must be determined during a multidisciplinary meeting: use of multimodal monitoring with neurophysiologist present in the OR, modification to anesthesia protocol, change in patient position, change to surgical approach with patient in lateral decubitus, etc. This type of instability is likely the limit of simplified MEP monitoring managed solely by the surgeon.

During such technical incidents, the family should never be summoned on an emergency basis and asked to choose between a surgical option or a cancellation. The family must be informed in real time of the technical difficulty; however, it is not conceivable nor ethical to encourage them to ask for the surgery to be continued when there is an absolute indication for IONM, not an emergency. This decision would have little value given how emotionally charged the moment would be (**10**)

The steps when there is a neurophysiological alert during the procedure

This implies that the responses in the lower limbs disappear while the ones in the upper limbs are still present. This is a “true” neurophysiological alert. Conversely, if all the curves disappear (upper and lower limbs), the depth of anesthesia should be questioned and it should be lightened, and if necessary, lead to a near-awakening situation to see all of the responses re-appear (electrophysiological wake-up).

If we look sequentially at the surgical steps for pediatric spinal deformity, several alerts raise questions and require an appropriate response.

1. Alert during the surgical approach

During the surgical approach, several patients have specific spinal cord susceptibility (especially at the thoracic spine level) or have unstable lesions that can explain a loss of MEP at the start of the procedure (Fig. 1). The surgical approach can destabilize the spine, interrupt the blood flow due to a spasm or a vascular bleed, even a small one. The surgeon should be extremely careful if the MEP curves in the lower limbs disappear in this situation. If the alert persist for more than 20 minutes, the surgical procedure must be interrupted. During this pause, all the usual anesthesia and technological parameters must be checked. If only the surgical approach has been completed, the patient can be awakened (**10**)

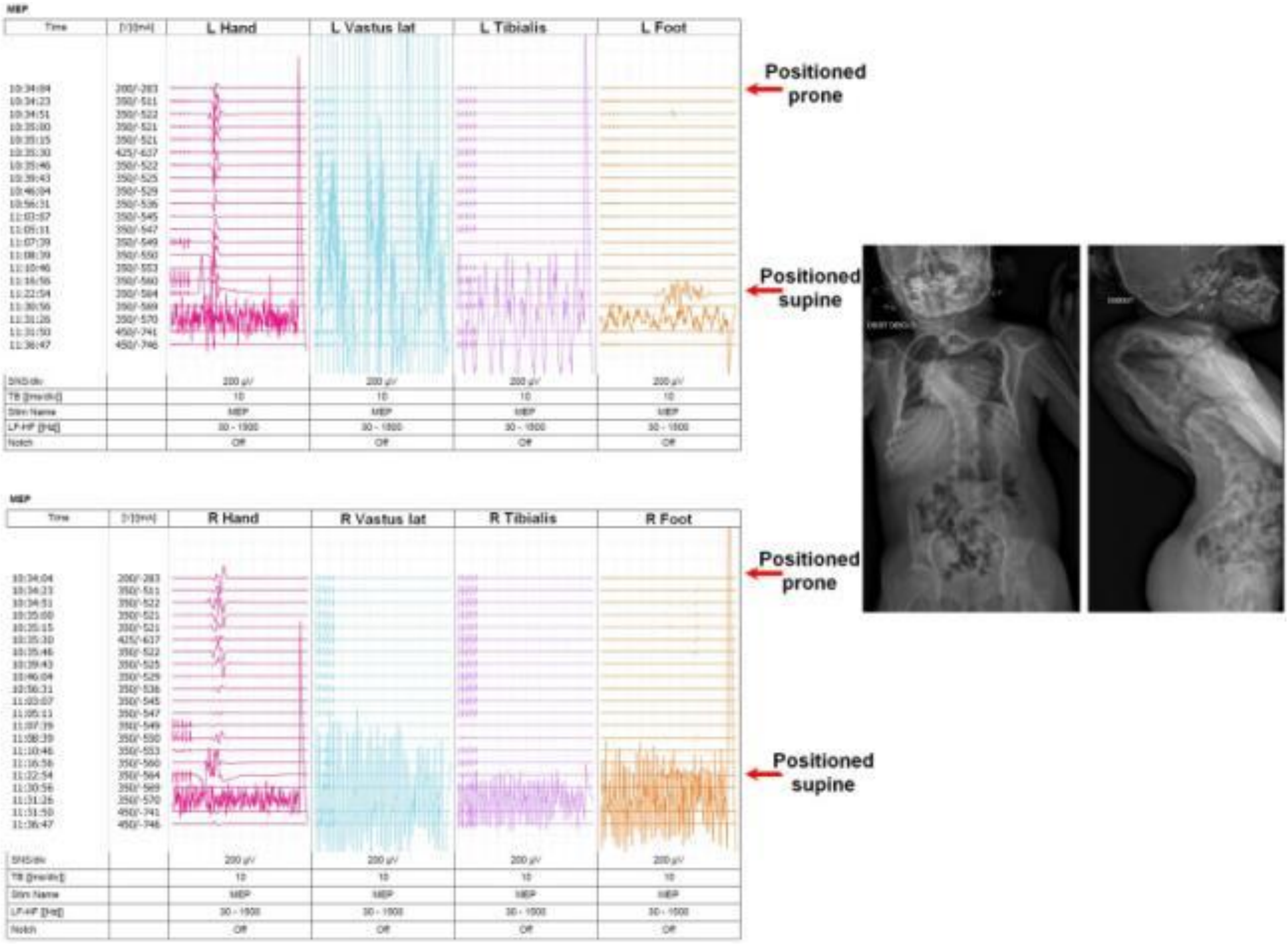


Figure 1. A 5-year-old girl with severe kyphotic scoliosis with arthrogryposis; the decision was made to apply distraction without fusion. After induction, the patient was positioned prone. MEP base line responses present in both upper limbs but not in the lower limbs. The decision was made to cancel the surgical procedure. MEPs re-appeared in the lower limbs once the patient was turned over (supine). No deficit upon waking (**10**)

2. Alert when inserting the implants

When the alert occurs while the implants are being inserted, this can be due to a contusion, vascular spasm or temporary inhibition when passing the implant (sublaminar band or hook). When inserting a pedicle screw, the spinal cord might have suffered direct trauma (Fig. 2). In this situation, the curves in the lower limbs can disappear in both legs or in only one leg. If the latter occurs, the cause of the trauma is clear (**10**)

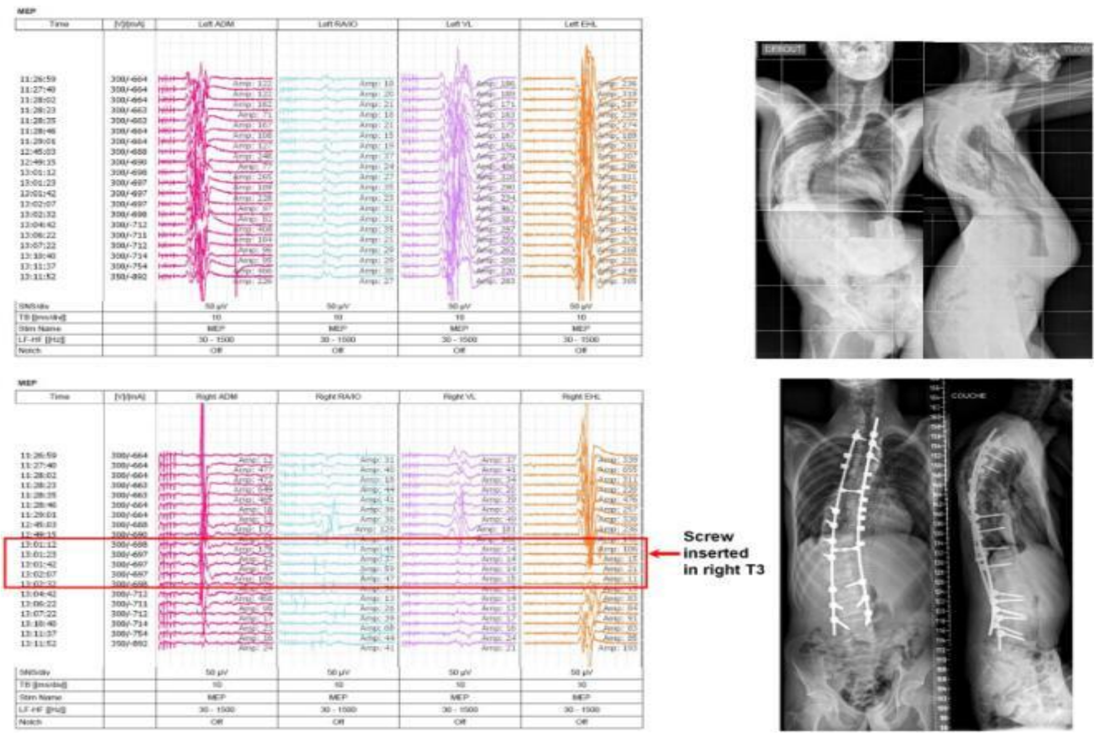


Figure 2. Scoliosis of 125° in a 16-year old male patient with Glass syndrome. Unilateral disappearance of the MEP curves in the right lower limb when inserting the right proximal pedicle screws. The persistence of a signal in the right upper limb rules out a general problem (anesthesia depth, technical problem, etc.). After the screws that were being inserted when the MEP curves disappeared were removed, the curves re-appeared. The surgery was continued while closely monitoring the curves; the correction was achieved with no neurological deficit. No neurological deficit upon waking (**10)**

Like with any alert, the hemodynamic and anesthetic constants should be verified next, although normal curves in the hands leave little doubt about an intrinsic spinal cord origin. At the same time, any implant that was being inserted when the alert sounded must be removed. D-wave monitoring is very useful in this indication, when available. This device, by an electrode in the epidural space, can determine which level is damaged. If no surgical incident is detected, the next step is to take radiographic images to check the position of the pedicle screws (**14).**

The depth of the anesthesia will be reduced with the goal of restoring the curves in the context of a neurophysiological wake-up test. If it is impossible to specifically evaluate the motor pathways (MEP or D waves), that is to say if the monitoring was carried out with SEP or NMEP only, a clinical intraoperative wake-up test is initiated the same way (**10)**:

- if the MEP curves re-appear or if motor function is found during the wake-up test, there is still no clear path forward. Some teams will continue the surgery while relying on clinical findings. Others go to the fallback position — stopping the intervention and applying in situ fixation if the spine is unstable. Both of these strategies can be defended from a medical viewpoint. We are at the limits of our knowledge of spinal cord pathophysiology;

- if the MEP curves do not re-appear or no motor function is found upon clinical awakening, a fallback solution is needed. Two scenarios are possible:

- the pathology is a stable vertebral column lesion (hemivertebra, moderate idiopathic scoliosis), which has two possible solutions (**10)**:

– remove all the implants and perform arthrodesis in situ, then have the patient wear a corset for several months,

– use a bipolar construct at the proximal and distal ends of the curvature, which will stabilize the lesion, in combination with arthrodesis. This is the logical option if an extensive and potentially destabilizing surgical approach was used;

- conversely, if the lesion was already unstable, it has been shown that it would be harmful to remove all the implants and to leave the unstable lesion as is, even with a graft and corset. A patient's spinal cord lesion must be stable for them to have the best chance at full recovery. A bipolar construct without reduction, or with only minimal reduction, appears to be the best option. Non-instrumented in situ fusion risks becoming an imbalanced deformity over time.

3. Alert during reduction of the deformity

This is a critical point of the intervention. There is a clear reason for the curves disappearing at this point (Fig. 3). Appropriate action is needed. The typical checks are done, namely the hemodynamic and metabolic (especially temperature) parameters. Surgically, the correction must be released without removing the implants. The absence of spinal cord compression should be confirmed at the correction level, especially when performing vertebral osteotomy (Fig. 4). A sharp intra-canal bone fragment (posterior wall) may still be present, or closing the osteotomy may have compressed the spinal cord posteriorly. One solution may be to widen the laminectomy and insert an anterior expansion cage. Even when motor pathways can be evaluated specifically using MEP or D-waves, this must be done at the same time as a wake-up test initiated immediately by the anesthetist. The aim is to achieve neurophysiological awakening, which would be reassuring **(15).**

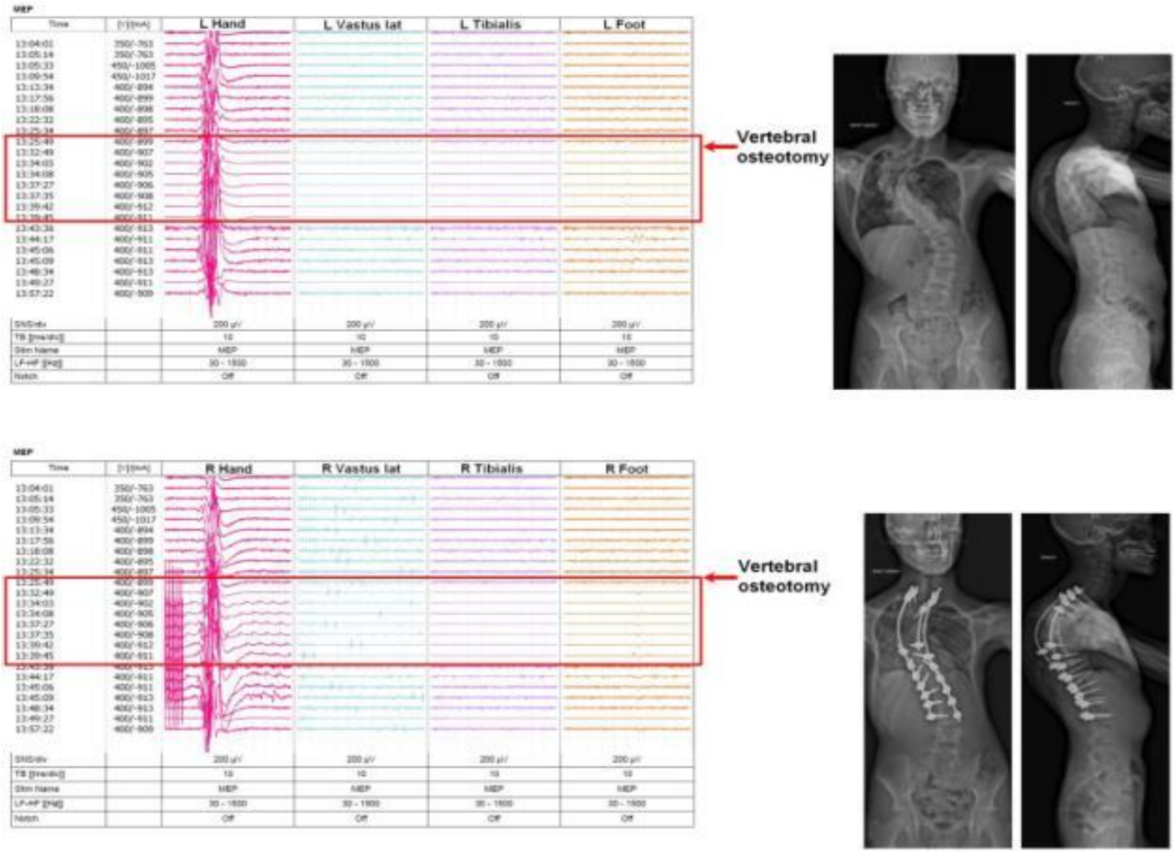


Figure 3. Congenital scoliosis without dysraphism or neurological deficit in a male 14-year-old patient. Decompensation during puberty led to the decision to perform vertebral osteotomy. Implants inserted while using surgical navigation. During the vertebral osteotomy, the curves disappeared. Fixation was done in the

spontaneous reduction position on the table. The curves re-appeared as the site was being closed. No clinical deficit upon waking (**10**).

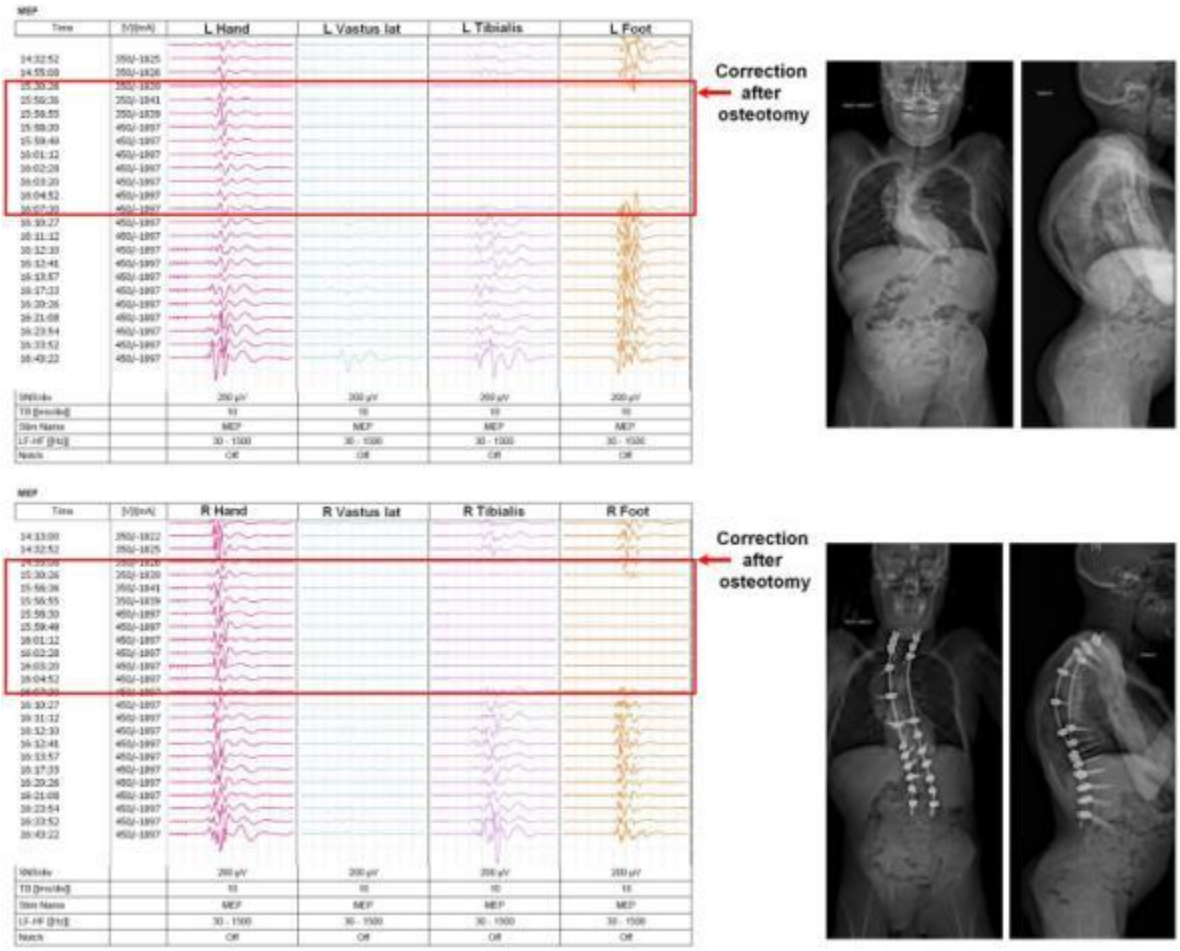


Figure 4. Severe scoliosis with double curvature in a 16-year-old boy with lipodystrophy. The decision was made to perform vertebral fusion and vertebral osteotomy. No neurological incidents during the osteotomies. Gradual disappearance of the curves upon reduction, suggesting an ischemic mechanism. Fixation applied in position on table. No deficit upon waking (**10**).

The curves might quickly return to normal. The notion of a "return to normal" introduces a time limit which remains subjective, but which can reasonably be set at 20 minutes. This corresponds to the time needed for the anesthesia team to check the hemodynamic parameters, improve them and evaluate the depth of anesthesia. This is also the time needed for a surgeon to recheck the local hemostasis and verify the implant positions using a fluoroscopy unit in the OR. During this time, the monitor and electrode parameters are verified, and several new stimulations are done (**10**).

Rapid return of the curves means that the surgical procedure can be continued, with three options (**10**):

- the first is to try the complete reduction again, moving gently and gradually. In practice, this option must be used carefully and not repeatedly as the spinal cord is now susceptible, which means there is a risk that repeated attempts will make the curves disappear permanently, with no recovery possible;
- the second option is to accept a partial correction up to a level that ensures the MEPs are normalized. In practice, this strategy is often difficult to quantify but has a practical benefit in that it both corrects the main deformity and fulfills the treatment contract;

- the third option is to leave the hardware in place without correction, so as to not induce instability that would negatively affect neurological recovery.

If the MEP curves do not return and the clinical wake-up test is negative (SEP, NMEP), we are at a point in the surgical procedure where the spine is already unstable or has been destabilized even more by the surgery. It seems logical to fix it in situ using a bipolar construct at a minimum. These are the main changes relative to the SFCR report issued in 2011. If the lesion is unstable, it is strongly advised not to remove all the hardware. Stability is one of the elements that will encourage neurological recovery, if it is still possible **(16).**

In the immediate postoperative period, and if the neurological exam is abnormal, MRI is justified to ensure there is no intracanal hematoma and to verify the implants are positioned correctly. If MRI is not available, CT scan can be done at a minimum to check the implant positioning and to ensure the compression is not being caused by a remnant bone fragment (**11).**

Recently, Lenke et al. published good practice guidelines on the actions to take following a neurophysiological alert during spine surgery. Jouve et al propose a pragmatic decision tree which summarizes the steps to take in the most common scenarios (Fig. 5) (**17).**

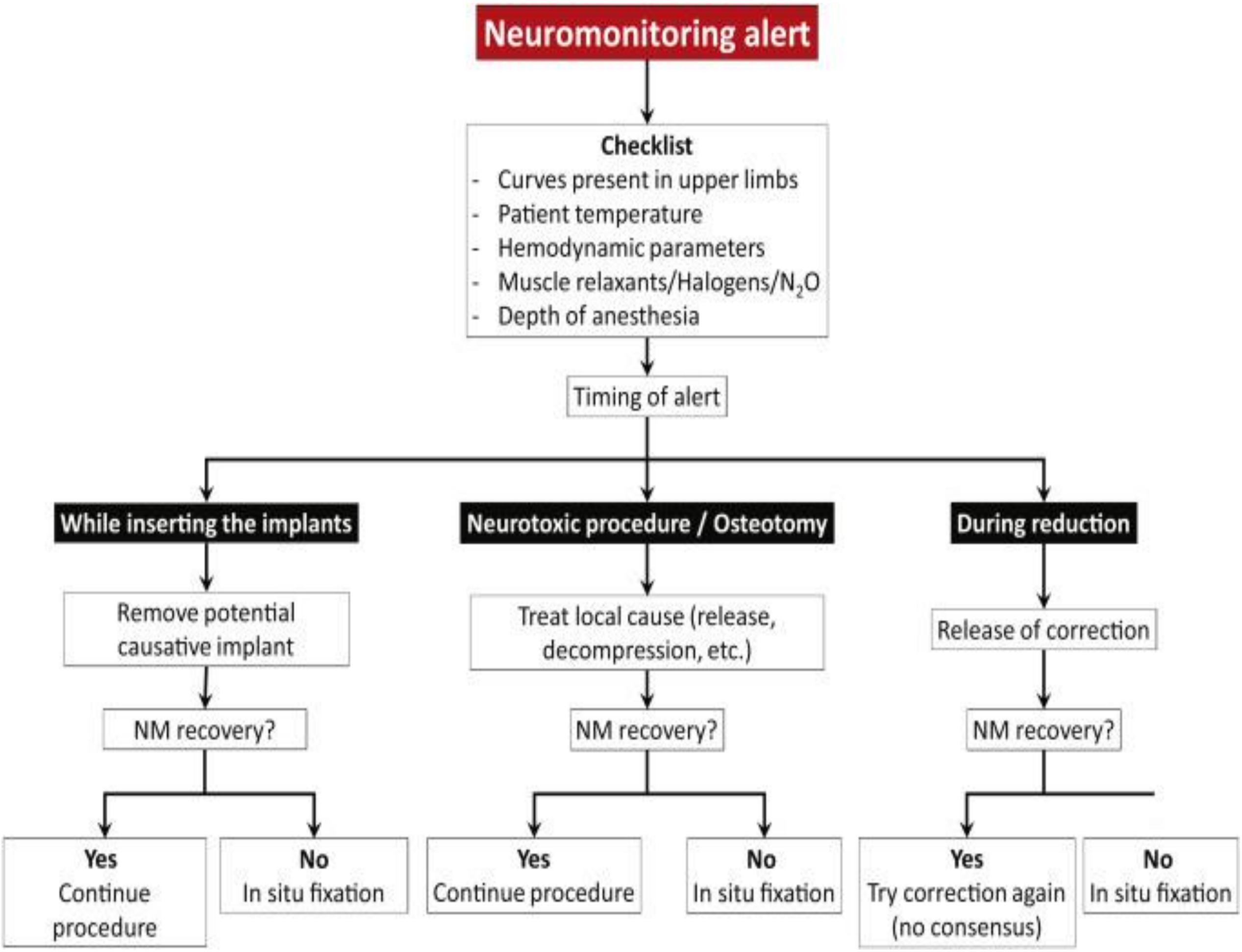
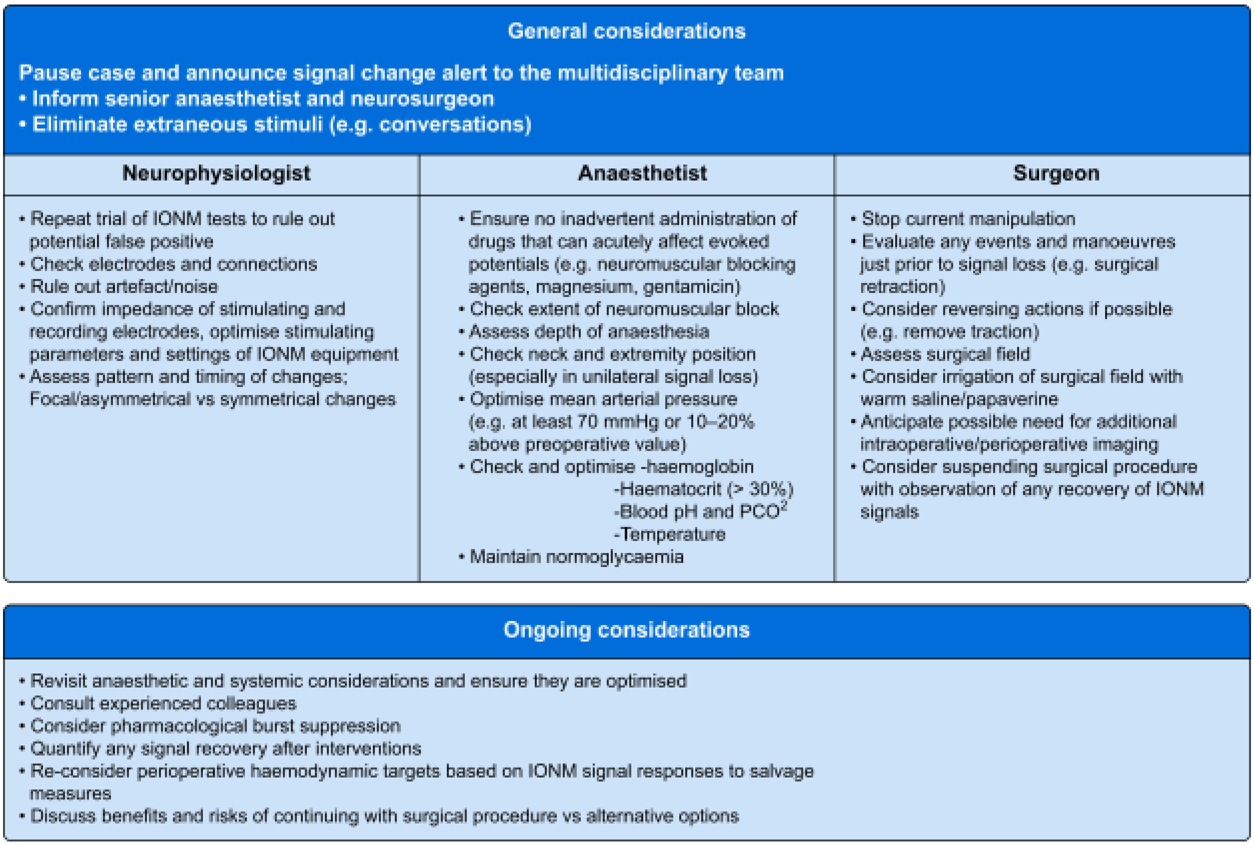


Figure 5. Suggested steps to take when there is a true neuromonitoring alert (NM: neuromuscular) the level of surgery dorsolumbar and the alert absence of lower limb responses (**10)**

Multidisciplinary management of intraoperative neuromonitoring signal change

The importance of a coordinated response to IONM signal alert criteria involving neurophysiologists, anaesthetists and neurosurgeons, cannot be overemphasised. No UK consensus guidance currently exists regarding the multidisciplinary response to IONM signal change in intracranial surgery. That present as local guidance used at King's College Hospital NHS Foundation Trust, which outlines proposed actions to be taken according to role, and those actions coordinated as an intraoperative team (**18**).

Furthermore, this checklist enables the consideration of possible causes of IONM alerts. A shared mental model of the key steps in the planned procedure undertaken in advance is invaluable, as is knowledge of the intended IONM modalities to be used and the patient's baseline neurological status (to inform expected tolerance to changes in physiology). Open and dynamic communication within the entire intraoperative team is needed throughout each procedure (***19)*.**



General considerations

Pause case and announce signal change alert to the multidisciplinary team
- **Inform senior anaesthetist and neurosurgeon**
- **Eliminate extraneous stimuli (e.g. conversations)**

Neurophysiologist	Anaesthetist	Surgeon
• Repeat trial of IONM tests to rule out potential false positive • Check electrodes and connections • Rule out artefact/noise • Confirm impedance of stimulating and recording electrodes, optimise stimulating parameters and settings of IONM equipment • Assess pattern and timing of changes; Focal/asymmetrical vs symmetrical changes	• Ensure no inadvertent administration of drugs that can acutely affect evoked potentials (e.g. neuromuscular blocking agents, magnesium, gentamicin) • Check extent of neuromuscular block • Assess depth of anaesthesia • Check neck and extremity position (especially in unilateral signal loss) • Optimise mean arterial pressure (e.g. at least 70 mmHg or 10–20% above preoperative value) • Check and optimise -haemoglobin -Haematocrit (> 30%) -Blood pH and PCO^2 -Temperature • Maintain normoglycaemia	• Stop current manipulation • Evaluate any events and manoeuvres just prior to signal loss (e.g. surgical retraction) • Consider reversing actions if possible (e.g. remove traction) • Assess surgical field • Consider irrigation of surgical field with warm saline/papaverine • Anticipate possible need for additional intraoperative/perioperative imaging • Consider suspending surgical procedure with observation of any recovery of IONM signals

Ongoing considerations

- Revisit anaesthetic and systemic considerations and ensure they are optimised
- Consult experienced colleagues
- Consider pharmacological burst suppression
- Quantify any signal recovery after interventions
- Re-consider perioperative haemodynamic targets based on IONM signal responses to salvage measures
- Discuss benefits and risks of continuing with surgical procedure vs alternative options

Figure 6: King's College Hospital NHS Foundation Trust protocol for the multidisciplinary response to intraoperative neuromonitoring signal changes in intracranial neurosurgery (**18**).

Relevant to the anaesthetist, IONM signal suppression caused by an anaesthetic agent or change in technique tends to result in global signal change, whereas surgical injury may manifest as focal or asymmetrical change. Recovery of IONM signals may take time to resolve irrespective of cause, and with changes related to anaesthesia, may take 30 min or more. During this time, the anaesthetist can assist by supporting the nervous system, through increasing MAP and oxygen delivery (**18**).

IONM Strategies and Challenges

In patients with severe myelopathy or in- stability, 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 per- formed (Table 3). (Figs. 7A– D). Patients with neuromuscular disorders represent a continued challenge because useful monitoring is impossible in at least 10% of patients, especially those with cerebral palsy or severe motor atrophy (Figs. 8A–D). Spondylolisthesis is also challenging to monitor because it is a single-level abnormality with a very distal location (**7).**

Table 3. Recommended Neuromonitoring by Level of Spine Surgery* (**11**).

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 7. 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 (**11).**

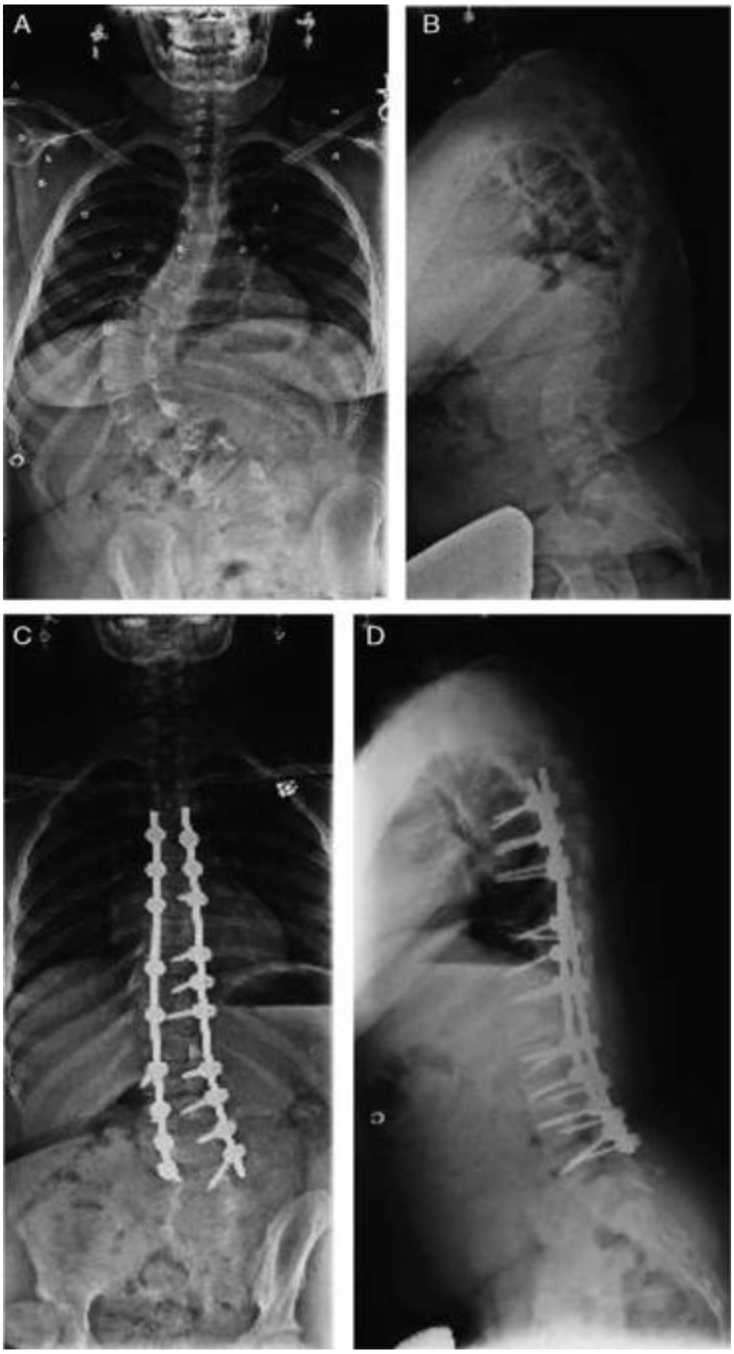


Figure 8. This 13-year-old girl with myelodysplasia and a 75-degree curve was ambulatory at baseline. She underwent posterior spinal fusion with an asymmetrical pedicle subtraction osteotomy at the apex of her curve and spinal cord untethering. Motor evoked potentials were lost at the time of rod insertion and returned with removal of the rod. To remedy concerns for canal translation and screw placement on the concave side of the curve, they 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 **(11).**

References:

1. Iskandar, B. J., & Finnell, R. H. (2022). Spina bifida. New England Journal of Medicine, 387(5), 444-450.
2. Sahinovic MM, Gadella MC, Shils J, et al. (2021). Anesthesia and intraoperative neurophysiological spinal cord monitoring. Current Opinion in Anesthesiology. Oct 1;34(5):590-6.
3. Levin DN, Strantzas S, & Steinberg BE. (2019). IONM in paediatric spinal surgery. BJA Educ. 19(5): 165-171. https://doi.org/10.1016/j.bjae.2019.01.007
4. Charalampidis, A., Jiang, F., Wilson, J. R., et al. (2020). The use of intraoperative neurophysiological monitoring in spine surgery. Global spine journal, 10(1_suppl), 104S-114S.
5. Sloan, T. B., Janik, D., & Jameson, L. (2008). Multimodality monitoring of the central nervous system using motor-evoked potentials. Current Opinion in Anesthesiology, 21(5), 560-564.
6. Cottone, C., Kim, D., Lucasti, C., et al. (2024). Causes of Intraoperative Neuromonitoring Events in Adult Spine Deformity Surgery: A Systematic Review. Global Spine Journal, 14(8), 2399-2407.
7. Wilson, J. P., Jr, Vallejo, J. B., Kumbhare, D., et al. (2023). The Use of Intraoperative Neuromonitoring for Cervical Spine Surgery: Indications, Challenges, and Advances. Journal of clinical medicine, 12(14), 4652. https://doi.org/10.3390/jcm12144652
8. Gupta, M. C., Lenke, L. G., Gupta, S., et al. (2024). Intraoperative neuromonitoring predicts postoperative deficits in severe pediatric spinal deformity patients. Spine deformity, 12(1), 109-118.
9. Jouve JL, Choufani E, Peltier E, et al. (2024). Neuromonitoring for spine surgery in children. Orthop Traumatol Surg Res. 110(1s): 103-180. https://doi.org/10.1016/j.otsr.2023.103780
10. Strike SA, Hassanzadeh H, Jain A, et al. (2017). Intraoperative neuromonitoring in pediatric and adult spine deformity surgery. Clinical spine surgery. Nov 1;30(9):E1174-81.
11. Nassef, M., Splinter, W., Lidster, N., et al. (2021). Intraoperative neurophysiologic monitoring in idiopathic scoliosis surgery: a retrospective observational study of new neurologic deficits. Canadian Journal of Anesthesia/Journal canadien d'anesthésie, 68(4), 477-484.
12. Gavaret, M., Jouve, J. L., Péréon, Y., et al. (2013). Intraoperative neurophysiologic monitoring in spine surgery. Developments and state of the art in France in 2011. Orthopaedics & Traumatology: Surgery & Research, 99(6), S319-S327.
13. Vucicevic, R. S., Asher, D. P., Hasan, S. S., et al. (2024). SPINE SURGERY.
14. Fustes, O. J. H., Kay, C. S. K., Lorenzoni, P. J., et al. (2021). Somatosensory evoked potentials in clinical practice: a review. Arquivos de neuro-psiquiatria, 79(09), 824-831.
15. Lenke, L. G., Fano, A. N., Iyer, R. R., et al. (2022). Development of consensus-based best practice guidelines for response to intraoperative neuromonitoring events in high-risk spinal deformity surgery. Spine deformity, 10(4), 745-761.
16. Adkins, G. B., Pescador, A. M., Koht, A. H., et al. (2024). Intraoperative neuromonitoring in intracranial surgery. BJA education, 24(5), 173-182.
17. Seubert, C. N., & Balzer, J. R. (Eds.). (2022). Koht, Sloan, Toleikis's Monitoring the Nervous System for Anesthesiologists and Other Health Care Professionals. Springer Nature.