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Intraoperative neuromonitoring in paediatric spinal surgery

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Learning objectives

By reading this article, you should be able to:

- Discuss the common modalities for intraoperative neuromonitoring (IONM) and the evidence that supports their implementation in paediatric spine surgery.
- Explain the influence of anaesthetic agents and physiological variations on IONM monitoring.
- Work as a team with surgeons, neuromonitoring professionals, and anaesthetists to respond to changes in IONM signals.

Key points

- The most common indications for intraoperative neuromonitoring (IONM) in paediatric surgery are for spinal deformities, intra- and extramedullary tumour resection, and spinal dysraphisms.
- Modalities of IONM include motor-evoked potentials, somatosensory-evoked potentials, EMG, and EEG.
- Anaesthetic and analgesic agents can affect IONM signals and must be selected in consultation with the neurophysiologist.
- An IONM alert should prompt the surgeon to assess for possible mechanical injury and the anaesthetist to optimise MAP as first-line therapies.
- Communication between the anaesthetist, neurophysiologist, surgeons, and nursing staff is fundamental to the effective use of IONM.

Surgical procedures of the spine have an inherent risk of damage to important neural structures and may result in postoperative neurological deficits. In paediatric spinal scoliosis correction, this risk varies with the type and underlying aetiology of the scoliosis. Although the risks remain relatively low, severe neurological deficits are devastating.[1] Intraoperative neuromonitoring (IONM) techniques have been developed to provide feedback on the integrity of vulnerable neural structures and improve the safety of these surgical procedures.

The benefit of IONM has long been acknowledged. Some of the first modalities of IONM, including the ankle clonus and Stagnara wake-up tests, had limited clinical utility and required intraoperative emergence from anaesthesia, which may be fraught with danger and difficulty, especially in children.

The advent of newer and complementary intraoperative methodologies to assess specific, at-risk neural pathways, such as the corticospinal tracts, dorsal columns, and nerve roots, has made IONM standard practice in many paediatric and adult institutions. Nevertheless, a consensus on the use of

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IONM has not been established. There is a significant variation in practice between institutions; protocols vary depending on the technology and alert criteria used, and anaesthesia and surgical management. In this article, we review the methods, indications, and evidence for the use of the IONM techniques commonly used in paediatric spinal surgery. The considerations of IONM relevant to anaesthesia for spinal surgery in paediatric practice are discussed, with an emphasis on the impact of various anaesthetic and analgesic agents on IONM. Further information and figures describing IONM modalities, along with an additional bibliography, are provided in the accompanying online supplement. The clinical scenario presentation provides a review of IONM used commonly and a framework for dealing with intraoperative IONM alerts.

Clinical scenario: crisis resource management and intraoperative neuromonitoring alerts

A 15-yr-old with idiopathic scoliosis arrived for correction of her curvature. Before induction of anaesthesia, the surgeon, anaesthetist, nurses, and neurophysiologist participated in a preoperative huddle to confirm the intraoperative plan and discuss any concerns that may affect intraoperative neuromonitoring (IONM).

After induction of anaesthesia, appropriate upper-extremity IONM responses confirmed that prone positioning had not caused pressure or stretch on the brachial plexus.

As the case proceeded, the skull-femoral traction application corresponded with a reduction in motor-evoked potentials (MEPs) of 70%, suspicious for stretching of the anterior spinal artery. In response, the MAP was increased to >85 mm Hg. Despite this, the responses did not fully recover, prompting the surgeon to reduce the applied traction. With this manoeuvre, the responses recovered to their baseline values. Consulting a 'checklist for the response to IONM changes' (Fig. 1) was beneficial in identifying all possible causes of IONM alerts.

During insertion of a left-sided pedicle screw, a unilateral loss of the left lower-extremity MEPs and somatosensory-evoked potentials of 80% and 50%, respectively, were noted, raising concerns of a Brown-Séquard spinal-cord injury. In response, the surgeon paused all manipulations. The responses did not recover, despite working through the checklist and taking all measures to improve the situation. The patient was given steroids, and a decision was made to limit the extent of the surgery.

As the surgeons began their closure, the anaesthetist titrated the TIVA infusion to allow for prompt emergence based on the patient's depth of anaesthesia as interpreted from the EEG signal. The patient was returned to the supine position and the trachea extubated without complication. A postoperative examination revealed mild left-sided lower-extremity motor and sensory deficits, which recovered after a few weeks.

The dynamic perioperative exchange between the surgeon, anaesthesiologist, and neurophysiologist highlights the importance of good communication in order to mitigate the risk of neurological injury.

Electrophysiological methods

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

SEPs

SEPs were developed to monitor the posterior columns of the spinal cord by evaluating signals from sensory cortical neurones generated in response to stimulation of peripheral nerves, typically the ulnar, median, and posterior tibial nerves. Upon stimulation, the signal propagates up the dorsal spinal column with some contribution from the spinothalamic tract before moving through the medulla and thalamus to arrive in the somatosensory cortex. Notably, SEP monitoring does not provide any information on the descending corticospinal tract or spinal-cord grey matter.

The integrity of the sensory pathway is evaluated by intermittently monitoring the amplitude and latency of the SEP waveforms to assess for intraoperative changes from baseline. This procedure relies on averaging responses in order to improve reliability. Current technologies have mitigated, but not removed this limitation, which also inherently introduce some degree of feedback delay.

Changes in somatosensory-evoked potentials may arise from trauma to the dorsal columns. For example, insertion of a sublaminar hook can directly traumatise the spinal cord, producing a Brown-Séquard injury and an abrupt reduction in the SEP amplitudes on the affected side without affecting the contralateral signals. Supplementary Fig 1 shows a stereotypical example of these signal changes. Once an alert is identified, diagnosis of the underlying cause is paramount. Clinical response to a signal change can include removal of offending implants and increasing the mean arterial pressure in an effort to aide recovery.[2] A surgical pause may afford the spinal cord time to recover. A checklist, such as the one described in the clinical scenario accompanying this article (see Clinical scenario and Fig 1) can aid in the management of changes in IONM signals.

The alert criteria for changes in SEP amplitude vary. For example, alert criteria can range from a 50% decrease relative to a stable baseline to an abrupt amplitude alteration, to a trend clearly exceeding trial-to-trial variability without a technical cause (see online Supplementary data for references to several studies that examine signal sensitivity). There is no consensus about what magnitude in a change from baseline constitutes a meaningful abnormality. In one recent retrospective study of a large cohort mostly comprising children, a persistent 50% reduction in amplitude or a prolonged latency >10% proved to have a 95.0% sensitivity, 99.8% specificity, 95% positive predictive value, and a 99.8% negative predictive value.[4] Whilst the specificity of SEPs is uniformly high across studies, sensitivity may be low. There are several reports of patients waking from anaesthesia with neurological deficits that had been undetected by SEP monitoring (see online Supplementary data for references). The differential receiver operating characteristics between sensory and motor pathways emphasise the need to integrate multiple IONM modalities.

MEPs

MEPs achieve motor specificity without the need for signal averaging. The MEP is elicited using a high-voltage short-

Table 1 Intraoperative neuromonitoring modalities.

	SEP	MEP	EMG	EEG
Stimulation site	Peripheral sensory nerves	Transcranial motor cortex	Triggered (or none)	(None)
Recording site	Cortical	Extremity muscle	Muscle	Scalp
Advantages	Sensory specificity; continuous signal capture	Motor specificity; large-amplitude signal	Continuous monitor; allows for surgical correlation with pedicle screw stimulation	Monitors cerebral integrity and anaesthetic depth
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	

duration stimulus applied to the scalp overlying the primary motor cortex. The transcranial impulse generates multiple electrical waves that propagate down the spinal cord and synapse of the neuromuscular junction, leading to depolarisation and muscle contraction. Monitoring the amplitude, latency, and morphology of the resultant compound muscle action potential provides an assessment of the motor pathway.

Unlike SEPs, MEP monitoring in children has some unique differences to adult patients. Infants and toddlers require a greater delivered charge to obtain MEPs than adolescents, with reported reliability decreased in children aged <6 yrs. This is likely to be a result of the immaturity of the motor pathway, which does not fully develop until about 13 yrs of age.[5] More references describing motor pathway maturation are available in the online Supplementary data.

MEP monitoring during spine surgery is both efficacious and safe (see online see online Supplementary data for references). Compared with SEPs, MEPs are more sensitive to reduced blood flow secondary to vascular insult or hypotension.[6] In addition, MEPs change earlier than the SEP signal, which facilitates quicker diagnosis of impending spinal-cord injury.[6] For example, during the reduction of kyphosis, stretch of the anterior spinal artery can limit the spinal-cord blood flow, a frequent cause of changes to the MEP response.[7] In a case series, 19 of 37 instances of intraoperative skull-femoral traction were associated with MEP amplitude decreases greater than 50% related to the application of traction, all of which resolved with reduction of the traction weights.[7] Notably, there were no observable SEP changes in each of these traction-related MEP decreases, indicative of

Checklist for IONM alerts in patients with a stable spine

Gain control of the room
- ❑ Intraoperative pause: stop case and announce alert to the room
- ❑ Eliminate extraneous stimuli (e.g. conversations)
- ❑ Anticipate the need for additional intraoperative or perioperative imaging if not already available

Anaesthesiologist
- ❑ Verify that no change in anaesthetic administration has occurred (e.g. neuromuscular block)
- ❑ Asses depth of anaesthesia
- ❑ Optimise mean arterial pressure (e.g. goal of 90-100 mm Hg)
- ❑ Check and optimize haemoglobin
- ❑ Check and optimize blood pH and PCO_2
- ❑ Check and optimize temperature

Neurophysiologist
- ❑ Repeat trial of IONM to rule out potential false positive
- ❑ Check all leads and connections
- ❑ Assess pattern of changes (e.g. asymmetric *vs* symmetric changes)

Surgeon
- ❑ Stop current manipulation
- ❑ Discuss events and actions just before to signal loss
- ❑ Assess field for structural cord compression, examine osteotomy and laminotomy sites
- ❑ Consider reversing actions (e.g. remove traction, rods, screws or corrective forces)

Ongoing considerations if no interval improvement
- ❑ Revisit anaesthetic and systemic considerations and ensure they are optimized
- ❑ Consult experienced colleagues
- ❑ Consider steroid administration (e.g. methylprednisolone 30 mg kg^{-1} i.v.,)
- ❑ Consider wake-up test
- ❑ Discuss continuing with surgical procedure *vs* staging the procedure

Fig. 1 Checklist for responding to intraoperative neuromonitoring changes in patients undergoing spinal surgery (adapted from Vitale and colleagues and Ziewacz and colleagues).[2,3]

spinal-cord compromise specifically to the area supplied by the anterior spinal artery. MEP changes during acute hypotension and skull-femoral traction during posterior spinal fusion surgery are shown in Supplementary Fig 2.

Consensus guidelines recommend using a decrease in MEP signal >60% as a 'significant warning criteria' in spine deformity surgery.[2] However, published warning criteria have ranged from a decrease of 60% amplitude to complete loss.[6] Lack of concrete warning criteria unfortunately remains one of the principal limitations around the use of MEPs. This limitation partly reflects high sensitivity of MEPs to anaesthesia and marked trial-to-trial variability. The wide range of alert criteria highlight the difficulty in selecting optimal receiver operating characteristics and predicting new neurological deficits (NNDs): a low threshold leads to increased false-positive alerts; high thresholds risk false negatives and missed reversible NND.

Illustrating these difficulties, in a study of paediatric spinal fusion surgery, alert criteria included a persistent unilateral or bilateral loss of ≥65% of MEP amplitude or ≥50% SEP amplitude decrease relative to a stable baseline.[8] In this study, sensitivities were estimated as 93.5%, 92.2%, and 46.7% for MEPs, combination (either MEPs or SEPs), and SEPs, respectively; however, sensitivity analyses demonstrated that the receiver-operator characteristics varied markedly depending on different assumptions related to the number of patients that would have otherwise experienced an NND without intervention.[8] In contrast, others have established that a single MEP signal with an 80% decrease in amplitude during a surgical action is an important warning criterion for neurological damage, whereas the persistence of any MEP recording at the time of surgical closure is associated with normal postoperative neurological function.[9] Of note, the duration of MEP loss may be a predictor of outcome with weakness associated with MEP loss durations greater than 40–60 min.[10]

Adverse effects of MEP monitoring are infrequent, but include tongue laceration (mitigated by the use of a bite block), scalp burn, and seizures (see online Supplementary data for reference).

EMG

Continuous EMG monitors cranial nerve and nerve roots by placing needle electrodes into a given muscle group. Either visual or audible outputs are used to detect neurotonic discharges, which reflect irritation of a nerve innervating the muscle by mechanical, thermal, or metabolic stimuli. This modality is a sensitive indicator of nerve irritation, but not necessarily of injury, as innocuous surgical manoeuvres can cause irritation.[11] Accordingly, EMG has utility in providing the surgeon with information on nerve location. Notably, transection, avulsion, or severe nerve injury will abrogate firing. Therefore, the absence of an EMG signal does not necessarily preclude injury. For the anaesthetist, EMG activity may detect movement, which could represent inadequate depth of anaesthesia (DOA).

In spinal fusion instrumentation, electrical stimulus can be applied to each pedicle screw. A screw in close proximity to a nerve root will activate the EMG at a lower threshold current, indicating its misplacement. Multiple confounding factors alter the triggered EMG signal, including prior root injury, the use of neuromuscular block, screw type, and location within the spinal column. The reliability and validity of stimulated EMG results do not appear to change in paediatric patients. References that elaborate on the characteristics of intraoperative EMG changes with specific injury patterns are available in the online Supplementary data.

EEG

Raw and processed EEG monitors the integrity of the cerebral cortex to provide the operative team with information regarding cerebral perfusion and DOA. In the absence of cerebral blood flow, children may continue to display sustained low-amplitude EEG activity, and EEG should be interpreted with caution.[12]

Bispectral index (BIS) monitoring, a commercially available processed EEG monitor, is routinely used to evaluate DOA. It provides a dose–response relationship to anaesthetic depth with either hypnotic i.v. or inhalation agents. Processed EEG is most commonly used as a marker of DOA in the perioperative setting. Multiple conditions can preclude the BIS monitor from indicating the correct hypnotic state, including EMG activity, neuromuscular block, electrical interference, and patient-specific abnormal EEG patterns.[13] In children, EEG features are also a function of age, and so commercial devices should accordingly be used with caution.

Monitoring DOA in children can be achieved by using raw EEG waveforms. EEG waves are classified by frequency from high (8–15 Hz α-activity and 15–25 Hz β-activity) to low (1–3 Hz δ-activity and 4–7 Hz θ-activity). The progression from awake to anaesthetised follows a progression from a relative abundance of high-frequency components to a low-frequency prominence. This transition displays features that depend on both age and anaesthetic agent. Fig. 2 provides an illustration of the typical EEG changes seen under anaesthesia.

Importantly, raw EEG may be more predictive in paediatric patients. Raw EEG has additional advantages compared with processed EEG, as it is not limited by a processing delay. It also allows for easy identification of pollution from EMG and electrocautery interference, which can be excluded during interpretation. Multichannel or bilateral hemisphere recordings are possible without the use of proprietary electrodes or special equipment.

The accumulation of propofol after a prolonged exposure can cause motor neurone suppression and result in reduction of MEP responses. This will not only necessitate increased stimulating thresholds to elicit responses, but may also trigger false alerts. This phenomenon of 'anaesthetic fade' can be minimised by titrating to the appropriate DOA as indicated by the EEG response.[14] Monitoring DOA with EEG may also prevent excessively long emergence times.

Indications for IONM

The most common paediatric spinal surgical indications for IONM are spinal deformities, including kyphoscoliosis and spondylolisthesis, intra- and extramedullary tumour resection, and spinal dysraphisms. The online Supplementary data includes a brief history of the developments leading to our modern IONM methods.

Perioperative factors affecting IONM

Non-anaesthetic factors

Spinal-cord perfusion

MAP <60 mm Hg is an important risk factor for spinal-cord injury during spinal deformity surgery. Autoregulation may

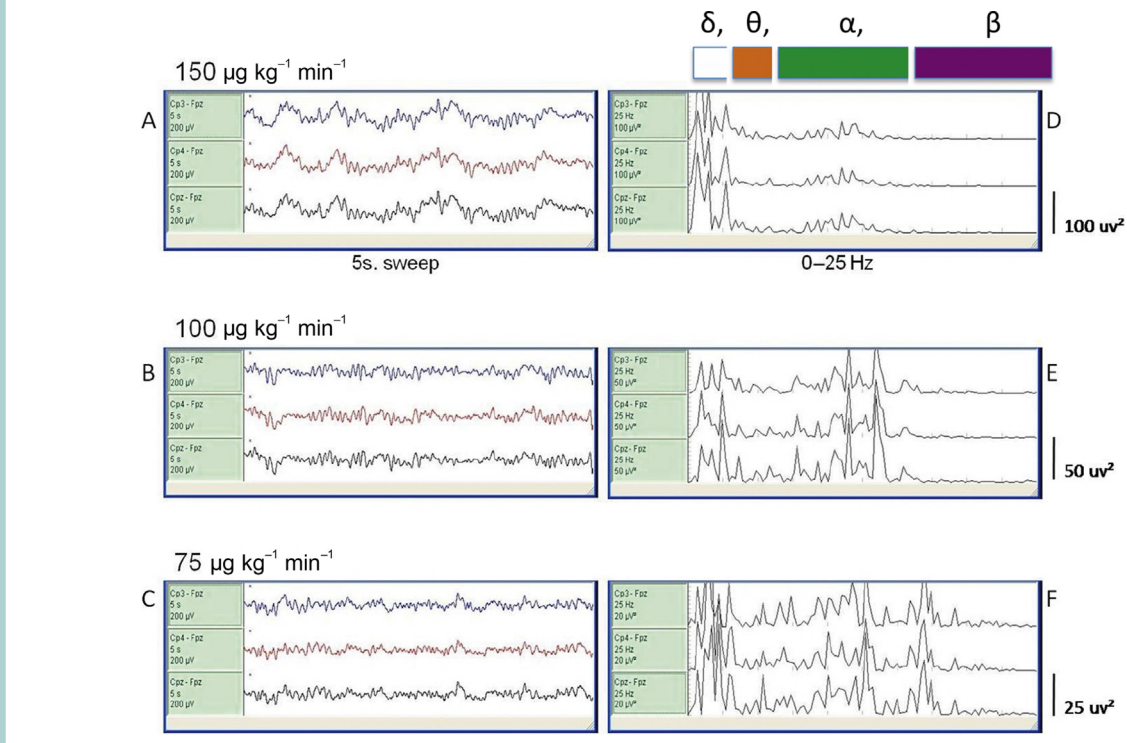

Fig. 2 EEG signals change with varying propofol infusion rates. EEG signal is shown in both the time (left) and frequency (right) domains at differing propofol infusion rates running in conjunction with a remifentanil infusion at 0.1 μg kg^{-1} min^{-1}. The EEG waves are classified by frequency from high (8–15 Hz α-activity and 15–25 Hz β-activity) to low (1–3 Hz δ-activity and 4–7 Hz θ-activity). Greater DOA is associated with a prominence of low-frequency components as demonstrated in the top recordings at propofol 150 μg kg^{-1} min^{-1} with low-frequency large-amplitude waves. In this case, the majority of the frequency power is in the δ and θ range. As the propofol infusion rate is decreased, there is a corresponding decrease in amplitude of the raw EEG and a shift towards higher-frequency activity (middle and bottom), indicative of lightening of anaesthesia. EEG recording: Cp3-Fpz (red trace), Cp4-Fpz (blue trace), and Cz-Fpz (black trace), and the filter settings are 0.5 Hz low-frequency filter (LFF) and 35 Hz high-frequency filter (HFF).

not ensure adequate spinal-cord perfusion during the increased stress placed on the spinal cord with corrective surgery. Anatomically, a single anterior spinal artery supplies the ventral two-thirds of the spinal cord, which includes the motor neurones and the corticospinal tracts. The dorsal one-third of the spinal cord, which houses the dorsal columns transmitting proprioception and light touch, is fed by a pair of posterior spinal arteries. There is limited collateral flow between the anterior and posterior circulations. A diagram of the vascular supply of the spinal cord is available in the online supplement (Supplementary Fig 3).

Patients with thoracic kyphoscoliosis are at particular risk for ischaemic cord injury during spinal deformity surgery. Almost 1% of patients undergoing scoliosis surgery have a degraded or complete loss of MEP responses caused by hypotension alone when the MAP decreases below 60 mm Hg. These changes resolve within 5 min of increasing the blood pressure.[6] SEPs are largely resistant to profound hypotension to MAP <40 mm Hg.[15]

The avoidance of low MAP during surgery and postoperative care is important for children with substantial thoracic kyphosis. In children older than 6 yrs old, the MAP is maintained at 70 (20) mm Hg.[16]

Oxygen tension and ventilation

Arterial blood gas tensions can affect IONM signals through changes in tissue blood flow patterns and oxygen delivery. For example, mild hypocapnia depresses SEP latencies in both awake and anaesthetised patients, whilst more severe hypocapnia will alter cortical SEPs by stimulating cerebral vasoconstriction.[17] Hypercapnia has not been shown to influence IONM.[18] Hypoxaemia, even before spinal-cord ischaemia, will compromise the IONM signal.[18] To optimise IONM, the anaesthetist must ensure adequate arterial-oxygen-carrying capacity whilst targeting normocapnic ventilation.

Anaesthetic techniques and medications

The most commonly used volatile anaesthetic agents produce dose-related decreases in the amplitude of MEPs. Therefore, TIVA techniques with propofol and opioid infusions are popular. Similarly, the neuromuscular block abolishes the MEP signal and is usually avoided when monitoring is in use. Regardless of the anaesthetic technique, a collaborative approach between anaesthetist and neurophysiologist is vital. Any changes in the choice or dosing of medications that can influence IONM should be communicated with the monitoring team so they can understand their impact on the signals. In the following sections, we provide a summary of the paediatric evidence for how commonly used perioperative medications impact IONM. We have limited our review to methods that have been studied in paediatric patients. The online Supplementary data reviews the use of lidocaine, magnesium and gabapentinoids, whose impact on IONM has not been

studied in children, and makes an effort to infer an approach to their use in children based on the adult literature.

Benzodiazepines

One study compared 30 paediatric idiopathic spine corrective surgeries. Anaesthesia was maintained with either propofol or midazolam. There were no differences in SEPs between groups.[19] Benzodiazepines are generally compatible with IONM modalities.

Ketamine

Ketamine is often used as an adjunct to prevent postoperative pain, an important consideration in patients with scoliosis. Ketamine will increase SEP and MEP amplitudes, and has been useful in cases that would otherwise be unsuitable for monitoring because of low-amplitude, poorly defined MEP responses.[20] One observational case series describes the impact of ketamine on MEP monitoring during paediatric spine surgery. Frei and colleagues report 134 consecutive MEP monitoring sessions in 108 children.[20] Based on their institutional experience, balanced anaesthesia with propofol had occasionally resulted in a gradual decline in MEP signal, more often in younger patients. Their practice pattern included an intraoperative switch to ketamine at an initial dose of 2–3 mg kg^{-1} followed by a continuous infusion of 4 mg kg^{-1} h^{-1} to ameliorate the propofol-related attenuation in signal. In their series, they describe the details for 13 patients requiring intraoperative switch from propofol to ketamine. In all but one scenario, MEPs returned. In the case where the MEPs failed to return, there was persistent motor deficit after surgery. They advocate a propofol-free ketamine-based anaesthetic approach for children. Notably, the changes in MEPs seen with propofol infusion in this study could potentially have been resolved by reducing the propofol infusion rates in order to prevent accumulation. It is important to note that ketamine does not have a reliable effect on EEG or BIS, and makes DOA based on these methods more difficult to interpret.

α_2-adrenergic agonists

Dexmedetomidine, an α_2 adrenergic agonist, is increasingly used as an adjunct to TIVA in procedures requiring IONM. A prospective clinical trial examining MEPs in 40 children that targeted various blood concentrations of dexmedetomidine and propofol using a factorial design demonstrated that the addition of dexmedetomidine caused a significant attenuation in amplitudes of MEP.[21] Recent unpublished data obtained from our institution show that infusion rates of 3 μg kg^{-1} h^{-1} caused significant reductions in MEPs in 14 of 28 patients undergoing spinal deformity correction for adolescent idiopathic scoliosis, with complete loss of signal in three cases. Clonidine administration has similarly been shown to depress MEPs significantly, but not SEPs.[22] Accordingly, α_2 adrenergic agonists should be used with caution whenever motor pathways are being monitored.

Intrathecal opioids and epidural analgesia

Two clinical studies have examined how intrathecal (IT) opioids influence IONM in paediatric scoliosis correction. In one study, 10 patients aged 15–18 yrs received sufentanil 50 μg with morphine 20 μg kg^{-1} intrathecally after induction of anaesthesia.[23] None of these patients had significant changes in SEP compared with their baseline measurements. Another study examining MEPs showed no significant difference in amplitudes and latencies compared to age-matched controls up to 30 min after injection of morphine 3–16 μg kg^{-1} IT at the end of the operation.[24] Thus far, the available clinical data suggest that any negative impact of IT opioids is marginal.

Conclusion

IONM is an important component of intraoperative management in paediatric spinal surgery. Nevertheless, anaesthetic and analgesic agents can impact on IONM signals, and must be selected in collaboration with the intraoperative neurophysiologist. As reviewed in the accompanying clinical scenario, any intraoperative IONM alert should prompt the surgeon to assess for possible mechanical injury and the anaesthetist to optimise MAP as first-line therapy. Effective communication between the anaesthetist, neurophysiologist, surgeons, and nursing staff is fundamental to the effective use of IONM and providing safe and optimal anaesthetic care to children undergoing spinal surgery.

Declaration of interest

The authors declare that they have no conflicts of interest.

MCQs

The associated MCQs (to support CME/CPD activity) will be accessible at www.bjaed.org/cme/home by subscribers to *BJA Education*.

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Supplementary data

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