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Best Practices in Intraoperative Neurophysiological Monitoring

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Introduction

Intraoperative neurophysiological monitoring (IOM or IONM) is now widely used in many surgical procedures. Modalities used in spine surgery include somatosensory evoked potential (SSEP), transcranial motor evoked potentials (TcMEP), D-wave, free run electromyography (EMG), and triggered EMG. The use of multimodality monitoring provides real-time information about the integrity of the spinal cord, nerve roots, and peripheral nerves, and can help minimize neurological defects.

Advances in anesthesiology and technology have increased the accuracy and potential applications for these techniques, while computer networks and communication systems have made them more generally available. However, best practices for maximizing the benefit of these technologies are not yet well established or described in the literature.

In order to better understand how these technologies are used in spine surgery, and to better understand their limitations, we put together a panel of expert spine surgeons from around the

world. These panelists were Stephen J. Lewis (SJL), Michael P. Grevitt (MPG), Kota Watanabe (KW), Oheneba Boachie-Adjei (OB), André Luís Fernandes Andújar (AA), and Kenneth MC Cheung (KC). The panelists shared their approaches to four case studies.

Case 1 involves an 18-year-old female with adolescent idiopathic scoliosis (AIS). Case 2 involves an 11-year-old female with congenital scoliosis and 80 deg kyphoscoliosis from hemivertebra at T8. Case 3 involves a 15-year-old male with a benign spinal tumor located at the right posterior wall of T12 causing anterior compression of the spinal cord. Case 4 involves a 38-year-old male with compression of the spinal cord at the T9/10 level by ossified yellow ligament (OYL).

For each case, we present a table of short responses for questions that arose during surgery, with an asterisk (*) indicating that a longer response is provided in the main text. The questions in the text and in the tables are labeled with the case number and question number. For example, Case 1 Question 1 is abbreviated (C1-Q01).

Case 1

An 18-year-old female with adolescent idiopathic scoliosis (AIS) with normal neurological status. The curve is flexible on bending x-rays. A posterior correction and fusion from T5-T12 is planned.

Case 1 Question 1 (C1-Q01 on Table 6.1)

Do you apply IOM in this case?

MPG:

Yes. IOM is mandatory for scoliosis. It is the standard of care; there is no medico-legal defense if IOM isn't used and there is a neurologic complication.

KW:

The risk of spinal cord injury may be low for correction. However, placing pedicle screws on the concave side still has a chance of damaging the spinal cord. Also, I do not know of any paper reporting that a flexible scoliosis curve has a lower chance of spinal cord injury during correction. Thus, I recommend IOM even in this flexible case.

Case 1 Question 2 (C1-Q02 in Table 6.1)

Do you perform IOM in all spine surgery? If not, what kind of surgery do you consider to operate without IOM?

MPG:

IOM is used in spinal deformity surgery where any corrective maneuver is performed (including reduction spondylolisthesis). Where there is a risk of neurological complication absent any deformity correction (e.g. positioning patient in ankylosing spondylitis fracture), IOM may be used on a case by case basis.

KW:

I always perform IOM in all spine surgeries, including herniotomy for patients with lumbar disc herniation. IOM may not influence the procedures during posterior decompression surgery for lumbar canal stenosis or during laminoplasty for cervical myelopathy. However, normal IOM can demonstrate that spinal cord injury did not occur during surgery, which can be relevant for patients who present with neurological deterioration after surgery. IOM benefits patient safety during deformity surgery or spinal cord tumor surgery. On the other hand, IOM protects doctors in decompression surgeries including laminoplasty.

AA:

I don't always have IOM available. When we don't have IOM available, we operate patients with neuromuscular scoliosis like cerebral palsy, myelomeningocele (aka spinal bifida), muscular dystrophy, and others. For some AIS cases with curves less than 70 degrees, we may also operate without IOM when it is not available.

KC:

Not all, I feel IOM is not mandatory in:

- 1) Lumbar spine—non deformity surgery, such as stenosis and disc herniation.
- 2) Patients with pre-existing complete paraplegia.

Case 1 Question 3 (C1-Q03 in Table 6.1)

What type of modalities would you use for this case?

- SSEP
- TcMEP
- D-wave
- Free run EMG
- Triggered EMG

MPG:

I use SSEP, TcMEP, and free run EMG. Multimodal IOM is the norm in our unit. The only time it is not used is where TcMEPs may be difficult (e.g. hereditary motor-sensory neuropathy (HMSN)/Charcot-Marie-Tooth).

KW:

I usually use only TcMEP for scoliosis patients with thoracic curve, since the problem will be spinal cord, not nerve root.

Case 1 Question 4 (C1-Q04 in Table 6.1)

When would you perform the baseline? Supine or prone?

KW:

I perform the baseline in prone position before surgery. I perform the baseline supine after anesthesia in patients with neurological symptoms.

AA:

For patients with idiopathic scoliosis, we perform baseline with the patient prone under anesthesia in the beginning of the surgery, but before infusing muscle relaxant to facilitate the exposure.

KC:

Prone generally, as muscle relaxant is used during intubation, so we want it to wear off before checking signals. The only exception to this is if we feel that there could be a signal change between supine and prone position. In these cases, we do a baseline in the supine position before turning. We will ask the anesthetist to avoid the use of muscle relaxants for intubation.

Case 1 Question 5 (C1-Q05 in Table 6.1)

Are there any specific anesthetic requirements or protocol that you routinely adopt for the purpose of IONM monitoring?

SJL:

Yes, I use TIVA (total intravenous anesthesia) after induction. Following baseline motors, muscle relaxants are used to facilitate the exposure of the spine. The muscle relaxant would be worn off prior to screw insertion. We maintain the patient's blood pressure near their baseline blood pressure measurement.

OB:

Total intravenous anesthesia. No gases and no paralytic agents. Hypotensive after baseline IOM for exposure then MAP at 80mmHg for rest of case.

The surgeon decided to perform IOM with SSEP and TcMEP.

The operation procedure went smoothly with normal anesthesia and IOM throughout the incision and surgical exposure. Pedicle screws were placed at T5, T7, T9-T12 on the convex and concave sides. Neurophysiology signals did not show abnormal changes. The operation and monitoring went well during surgery till the end of correction.

After the correction of deformity, SEP disappeared in the convex side (right) and significantly dropped in the concave side (left). MEP signals recorded from tibialis anterior, and abductor hallucis at the convex side disappeared (Fig 6.1a-b). Other issues related to neurophysiological signal changes like anesthesia and MAP were excluded. IONM signal changes were considered as operation related.

Case 1 Question 6 (C1-Q06 in Table 6.1)

Would you perform a wake-up test?

SJL:

No. I would remove the rod and perform a radiograph to assess screw placement and send blood to check the hemoglobin level. I would maintain the MAP at the patient's baseline or slightly higher.

KC:

No, I would activate our checklist. From a surgeon perspective, we would reverse the correction, bring in an image intensifier (I/I) to check screw positions, and irrigate the wound with warm saline to warm the patient and enhance local perfusion. We would also ask the anesthetist to raise MAP to above 90mmHg if it is low, and check Hb. While doing these, we would ask the anesthetist to prepare for a wake-up test.

Case 1 Question 7 (C1-Q07 in Table 6.1)

If you decide to do a wake-up test, do you perform it immediately after the warning or after a period of observation?

SJL:

I would expect some improvement with rod removal. I would assess the hemoglobin level and transfuse if the level is below 100. I would review the radiographs to assess screw placement, as one of my concerns would be that the spinal cord shifted into a medially placed screw with the correction maneuver.

Case 1 Question 8 (C1-Q08 in Table 6.1)

There is no improvement in the IOM signals. Do you change the surgical plan?

SJL:

I would leave the rods out. I would recheck all the pedicle screws for EMG threshold values. If there were concerning screws on the radiographs, I would remove them and palpate the holes. If the signals return after rod removal, I would complete the transfusion and try to reinsert the rods. If the signals were lost again after rod placement and the hemoglobin level was greater than 100, I would leave the rods out and close the wound. I would send the patient for cross sectional imaging to assess the implants and return on another day.

OB:

What was the result of the wake-up test? If positive then remove implants if you haven't done so already. If negative then ignore IOM even if no improvement and one side has responses. Convex side is not as critical as concave side IOM loss.

AA:

Yes. I would release the nuts of the convex rod and then of the concave rods. If, after 5-10 minutes, the signals don't rise, I would take the convex rod out, then the concave rod, waiting another 5-10 minutes.

KC:

Yes, I would do a wake-up test. If the wake-up test fails, I would check each screw position manually by removing it and probing the track to see if there is any misdirected screw. If none, I would close the wound and send the patient for MRI without putting in the rod.

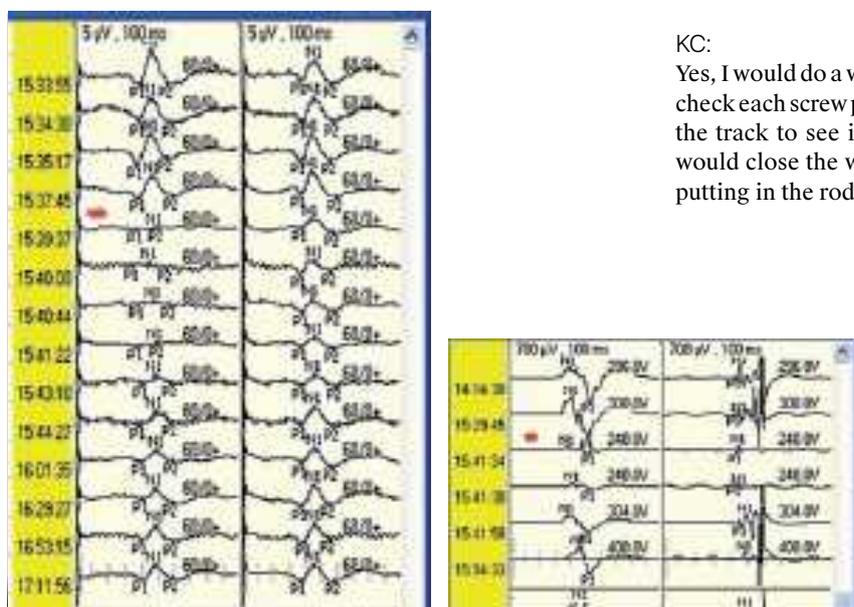


Fig 6.1

Case 1 Question 9 (C1-Q09 in Table 6.1)

Based on IONM signals, the surgeon reversed the correction and loosened the rods. MEP signals returned after 15 minutes, while SEP returned after 30 minutes. Now, what is your next step?

SJL:

I would check the radiograph and the blood work. I would transfuse the patient to get the hemoglobin over 100 and retry the correction after that.

MPG:

Follow with closure. I would abandon the surgery at this stage. Case precedent law in the UK suggests that defensible practice is to abandon and ensure that the child is moving legs and formal muscle testing of ALL muscle groups once she is awake. This also gives the opportunity to ask the parents for their views on a return to theatre for a later 2nd attempt at correction (some weeks later if no neuro deficit). Alternatively, if an immediate 2nd attempt is made, another loss of MEPs with some post-op deficit this would be considered indefensible.

AA:

I would finish the surgery with an “in situ” rod contouring, leaving the curve as it is. Then, I would return 1 week later to insert the rods again, making the final correction. In my experience, this plan always works.

KC:

I would finish the procedure using a more gentle correction technique.

Case 1 Question 10 (C1-Q10 in Table 6.1)

The surgeon decided to load the rods and accept less correction and close. Would you give this patient steroids and why?

SJL:

No steroids. I feel this case is a perfusion issue which needs to be addressed by improving perfusion through correction of anemia, maintaining a physiological blood pressure, and removing the rods.

MPG:

No. The British Association of Spinal Cord Injury Specialists (BASCIS) guidelines DO NOT recommend a NASCIS (National Acute Spinal Cord Injury Study) type steroid regimen.

KW:

If the patient was neurologically normal, I would not give steroids. But, if there is any neurological deficit, I will give steroids.

KC:

No—since the patient signals have recovered and there is no good evidence of the usefulness of steroids.

The surgeon did not give steroids for this case. The period from instrumentation fixation to patient wake-up after closure was about 1 hour. IONM was performed during this period and remained normal.

Case 1 Question 11 (C1-Q11 in Table 6.1)

In your center, when should neuromonitoring be discontinued?

SJL:

We discontinue monitoring at closure. Late loss of IONM is generally related to anemia. We repeat the hemoglobin level at closure and watch for any drops in blood pressure. By maintaining an adequate hemoglobin level, we can maximize our correction of the deformity.

KW:

I will discontinue after finishing skin closure, since I have a case whose MEP dropped during skin closure because of epidural hematoma.

Case 1 Question 12 (C1-Q12 in Table 6.1)

Do you always perform a wake-up test at the end of the procedure?

SJL:

After closure, the patient is woken up from anesthesia and taken to the recovery room or ICU extubated. A gross neurological examination is performed.

OB:

If IOM are stable then no. I will wait till the patient awakes in recovery to do wake up. If IOM does not return to baseline then I will wake up in the operating room (OR) before leaving for the recovery room (RR).

KC:

Yes, even if the patient is to go to ICU intubated and sedated, we would ask the anesthetist to do a wake-up test prior to discharge to ICU.

	Question	SJL	MPG	KW	OB	AA	KC
C1-Q001	Do you apply IOM in this case?	Yes. I perform IOM in all scoliosis patients.	Yes. IOM is mandatory for scoliosis.*	I recommend IOM even in this flexible case.*	IOM is optional for this case. We would ask IOM if the service is available.	If IOM is available, I would ask for. But it is possible to do the surgery if IOM is not available.	Yes, we always use IOM in scoliosis.
C1-Q002	Do you perform IOM in all spine surgery? If not, what kind of surgery do you consider to operate without IOM?	I use it for all spine cases with the exception of isolated implant removal.	IOM is used in spinal deformity surgery where any corrective maneuver is performed.*	I always perform IOM in all spine surgeries.*	Not all cases. All deformity cases. Patients with myelopathy. Patients requiring 3CO.	I don't always have IOM available.*	Not all.*
C1-Q003	What type of modalities would you use for this case?	I use SSEP, TcMEP, free run EMG, and pedicle stimulation (triggered) EMG.	SSEP, TcMEP, and free run EMG. Multimodal IOM is the norm in our unit.*	I usually use only TcMEP for scoliosis patients*	SSEP, TcMEP, and free run EMG are the modalities available to me.	SSEP, TcMEP, free run EMG, and triggered EMG	Mainly SSEP and TcMEP
C1-Q004	When would you perform the baseline IOM? Supine or prone?	I perform the baseline TcMEP prone prior to skin incision.	I perform the baseline at prone to confirm satisfactory IOM before knife to skin.	I perform the baseline in prone position before surgery.*	Prone for simple AIS	Prone under anesthesia in the beginning of the surgery.*	Prone generally.*
C1-Q005	Are there any specific anesthetic requirements or protocol that you routinely adopt for the purpose of IONM monitoring?	Yes, I use TIVA (total intravenous anesthesia) after induction.*	Yes, TIVA (total intravenous anesthesia) with propofol.	Intravenous propofol. No muscle relaxant, except for during intubation.	Total intravenous anesthesia. No gases and no paralytic agents.*	The anesthesia is totally intravenous, with propofol and remifentanyl.	Yes. We generally prefer TIVA.
C1-Q006	Would you perform a wake-up test?	No.*	Yes, as a final check.	No. First, I would immediately remove or loosen the rods, and wait for the recovery of MEP .	Reverse correction before wake up.	No. I don't think a wake-up test at that moment would help.	No. I would activate our checklist.*
C1-Q007	If you decide to do a wake-up test, do you perform it immediately after the warning or after a period of observation?	I would expect some improvement with rod removal.*	After all anesthetic adjustments (increase MAP, transfusion and volume replacement).	I will do wake-up test if the MEP does not recover to normal level even after removal of the rods.	Will do ASAP so as not to waste time if implant removal is being considered.	I usually don't perform a wake-up test. It does not change my approach.	Do the wake up after the above steps and if there is no signal return.
C1-Q008	There is no improvement in the IOM signals. Do you change the surgical plan?	I would leave the rods out.*	Yes, remove both rods and de-tension the spine.	I will immediately remove or loosen the rods, and wait for the recovery of MEP.	What was the result of the wake-up test?*	Yes. I would release the nuts of the convex rod and then of the concave rods.*	Yes, I would do a wake-up test.*
C1-Q009	Based on IONM signals, the surgeon reversed the correction and loosened the rods. MEP signals returned after 15 minutes, while SEP returned after 30 minutes. Now, what is your next step?	I would check the radiograph and the blood work.*	Follow with closure. I would abandon the surgery at this stage.*	I would gradually correct the deformity while checking MEP changes repeatedly.	Try to instrument but with less correction.	I would finish the surgery with an "in situ" rod contouring, leaving the curve as it is.*	I would finish the procedure using a more gentle correction technique.
C1-Q010	The surgeon decided to load the rods and accept less correction and close. Would you give this patient steroids and why?	No steroids. I feel this case is a perfusion issue.*	No*	If the patient was neurologically normal, I would not give steroids.*	I always give a single bolus of steroids for transient loss of IOM.	No. There is no evidence for that.	No*
The surgeon did not give steroids for this case. The period from instrumentation fixation to patient wake-up after closure was about 1 hour. IONM was performed during this period and remained normal.							
C1-Q011	In your center, when should neuromonitoring be discontinued?	We discontinue monitoring at closure.*	Once the total intravenous anaesthesia (TIVA) is being turned off.	I will discontinue after finishing skin closure.*	IOM is discontinued after wound closure and final readings.	Just before the patient wakes up from anesthesia.	We continue until the time of wound closure.
C1-Q012	Do you always perform a wake-up test at the end of the procedure?	After closure, the patient is woken up from anesthesia.*	No	No	If IOM are stable then no.*	No, we ask the patient to move her/his feet after wake up from anesthesia.	Yes*

An asterisk (*) indicates that a longer response is provided in the main text.

Table 6.1 Case 1: An 18-year-old female with adolescent idiopathic scoliosis (AIS)

Case 2

An 11-year-old female with congenital scoliosis and an 80 deg kyphoscoliosis from hemivertebra at T8. Normal neurology and MRI. A hemivertebra excision is planned at T8, posterior deformity correction and fusion T4-12.

Case 2 Question 1 (C2-Q01 in Table 2)

Do you apply MEP in patients under 12 years old and why?

SJL:

Yes. We perform MEP on all patients. Perfusion deficits to the spinal cord will not be recognized by SSEP monitoring.

The operation procedure went well with normal anesthesia and IOM throughout the incision and surgical area exposure. Pedicle screws were placed to T4, T6-12. EMG signals did not show burst during screw placement. Trigger EMG did not show abnormal value of stimulation current along any pedicle screws. Only, the trigger EMG tested with 10.1mA on right T8 pedicle screw, which was lower than others but within the threshold of 10mA. However, right sided SSEP and MEP suddenly dropped after placement of T8 pedicle screw on the right.

Case 2 Question 2 (C2-Q02 in Table 2)

What warning criterion do you use for free EMG?

Case 2 Question 3 (C2-Q03 in Table 2)

What warning criterion do you use for triggered EMG?

SJL:

We use 7mA in the lumbar and 8mA in the thoracic. However, we remove and check the lowest recorded screw, especially if it is significantly less than the others (e.g. all tests over 15 except for one test at 8).

Case 2 Question 4 (C2-Q04 in Table 2)

What is the relative importance of SSEP and MEP versus EMG? Do you always consider a warning from SSEP and MEP, or sometimes not consider a warning because of normal EMG and trigger EMG?

SJL:

We consider SSEP a recording of the dorsal columns, and the MEP as a recording of the anterior cord (corticospinal and spinothalamic tracts). All perfusion deficits to the cord will manifest as loss of MEP alone. Direct trauma to the cord will have associated unilateral or bilateral deficits and often involve both MEP and SSEP. If the screw were medial as to impinge on the spinal cord, we would expect to see unilateral SSEP and/or MEP changes, however, severe breaches can cause bilateral changes especially on the concave apex of the curve. Triggered EMG is used to rule out breach of the pedicle screw so that it impinges on the traversing or exiting nerve root. Free run EMG would be indicative of direct contact of the screw with the nerve root.

MPG:

Rank order MEP>SSEP>EMG. Burst activity in EMG often occurs when there is no surgical maneuver. MEPs monitor the

perfusion of the cord—however, our positive predictive value for a post op neuro deficit is only 11%.

AA:

SSEP and MEP show the condition of the spinal cord, and the EMG tells if the screw may be touching some root or spinal cord when it breaks the pedicle. We consider a warning from SSEP and MEP even if the EMG is normal.

Case 2 Question 5 (C2-Q05 in Table 2)

Would you consider a wake-up test before proceeding with further actions?

SLJ:

No, I would remove the screw and palpate it carefully for any breaches. I would consider leaving the screw out if there are any concerns.

MPG:

No. Remove screw; anesthetic adjustment (increase MAP, transfuse, etc)—pause—any return of MEPs? If not—then start wake-up test.

OB:

Depends on how much of a drop. If it meets the warning criteria of a 50% loss of amplitude, then I perform a wake-up test.

AA:

No. We proceed with further actions. The next step would be the removal of the T8 pedicle screw.

KC:

No. I would immediately reverse the last step, which is the T8 screw and check the screw track. If there is no obvious perforation, I would check the next screw track bearing in mind that the signal change may be from an event up to some 15mins prior.

Intra-operative imaging was obtained to check for placement of screws (Fig 6.2). The right T8 screw appeared to have breached the medial pedicle wall and was removed. Subsequently, both SSEP and MEP signals returned.

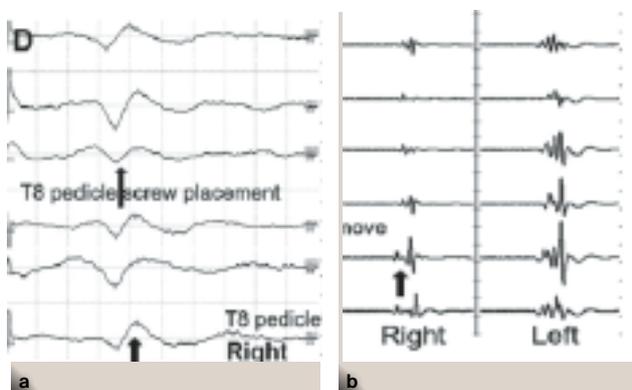


Fig 6.2

Case 2 Question 6 (C2-Q06 in Table 2)

Now, do you change the surgical plan or proceed with hemi-vertebra excision?

KW:

I need an explanation for placing the pedicle screw at T8 hemi, in spite of trying to resect T8 hemi. Anyway, I would not change the strategy, since the MEP recovered to normal levels.

AA:

I would proceed with HV excision, but I would check the position of the screw with imaging, as the signals dropped just after its insertion.

KC:

Since T8 is the hemi, I would not change the plan. However, if it is a screw that is important for structural stability after resection, we may need to change the plan.

The surgery continued after T8 screw removal. Hemivertebra excision was performed and IOM remained normal. Then, during the osteotomy closure, IOM signals presented significant loss in some channels of MEP. Significant reductions of 70% presented in the left rectus femoris, right rectus femoris, and tibialis anterior. SSEP showed small changes with an amplitude decrease of about 30%.

Case 2 Question 7 (C2-Q07 in Table 2)

In this scenario when MEP and SSEP changes do not corroborate, how would you interpret the changes?

SJL:

As described previously, SSEP and MEP do not test the same regions of the spinal cord and are therefore complementary. In the setting of perfusion injuries to the spinal cord, SSEP would be expected to remain normal despite significant loss in MEP signal. With a significant drop in MEP, I would be concerned of an anterior cord syndrome and concentrate on improving spinal cord perfusion by maintaining hemoglobin over 100, and maintaining the MAP at or above the patient's baseline. With some loss in the SSEP, the possibility of a central cord syndrome exists. I would recheck the decompression to ensure it was adequate and that I was not compressing the cord during osteotomy closure.

KW:

I would check the osteotomy site to check the status of dural (spinal cord) compression. If the dura or spinal cord was 360 degrees free from compression, I would continue the procedure.

OB:

MEPs more important here than SSEP. However, if MEP loss is accompanied by SSEP loss then there is a big problem for recovery. I would decompress the osteotomy site to make sure there is no cord impingement or buckling. When done and no changes, then do wake up.

AA:

There should be some compression or hypoperfusion of the spinal cord, especially on the anterior half of the spinal cord. Does not matter if the reduction of the signals it is not symmetrical.

Case 2 Question 8 (C2-Q08)

In this case, part of the muscles presented abnormal MEP. What is your decision?

SJL:

As long as there is normal signal in some of the muscle groups distal to the suspected level of injury, I would be reassured that I was not dealing with an anterior cord syndrome. This is more in keeping with a central cord syndrome where the cord may have been compressed with osteotomy closure. I would expand the decompression. If this was not sufficient, I would reopen the osteotomy and redo the decompression with the osteotomy open prior to reclosing the osteotomy.

MPG:

Release closure of osteotomy—pause—if MEPs improve then fix in that position—if not then restore to pre-resection position & wake-up test.

KW:

I would check the osteotomy site to check the status of dural (spinal cord) compression. If the dura or spinal cord was 360 degrees free from compression, I will continue the procedure.

OB:

So long as there are some muscle with MEP, especially the distal muscles, I would proceed.

AA:

I would compress the osteotomy site, trying to relax the spinal cord, and look for some compression on the spinal cord, especially on the concave side, and wait. I would also check the MAPs, asking the anesthesiologist to raise it to over 80mmHg and also check if the patient needs blood transfusion.

KC:

I would still consider this as positive and activate our checklist.

Case 2 Question 9 (C2-Q09 in Table 2)

If the abnormal MEP presented on abductor hallucis, while the other two muscles (rectus femoris, tibialis anterior) are normal, what is your decision?

SJL:

In this case, all these muscle groups are distal to the osteotomy level, and the injury is in keeping with a central cord syndrome. I would do the same as the previous answer.

KW:

Again, I would check the osteotomy site to check the status of dural (spinal cord) compression. If the dura or spinal cord was 360 degrees free from compression, I will continue the procedure.

Case 2 Question 10 (C2-Q10 in Table 2)

In high risk surgeries like VCR, as well as in young patients, would you consider different criteria for IOM?

SJL:

I use the same criteria for all, which is loss of MEP or SSEP amplitude to less than 50% of baseline. In VCR cases, the injury to the cord is more likely to be mechanical as opposed to perfusion. Mechanical injuries to the cord need to be recognized and reversed. Mechanical injuries will likely cause either a central cord syndrome, a Brown Sequard syndrome, or a complete cord pattern of signal loss, which would have both SSEP and MEP changes. Perfusion based changes will be exclusively MEP, and adjustments to the hemoglobin, blood pressure, and correction would be the method needed to restore IONM signal.

OB:

Not really, but because IOM alerts are more common I will accept signal changes so long as some signals are present and I know there is no offending agent or translation. The cord and canal manipulation can lead to IOM changes which may not necessarily imply actual neuro deficit.

The surgical maneuver was halted for 10 minutes observation. IOM with MEP and SSEP signals were performed continually. SSEP remained normal. For several minutes, MEP returned to normal. However, MEP dropped again without further surgical manipulation. There is total loss of rectus femoris MEP, as well as a drop in all other lower limb MEP.

Case 2 Question 11 (C2-Q11 in Table 2)

How would you interpret the variable signal loss?

SJL:

This represents a perfusion-based signal change. I would transfuse the patient, maintain an adequate MAP, and observe. If the signals do not return or improve, I would release the rod, and allow the hemoglobin level to rise before attempting to reinsert the rod.

OB:

Check the MAP, temperature, and hemoglobin. Decompress the osteotomy site again if not done.

AA:

This means that there is no damage (contusion) to the spinal cord, but there should be some compression or tension over the anterior part of the spinal cord. So it is necessary to continue the surgery to align the spine, releasing and relaxing the spinal cord.

Case 2 Question 12 (C2-Q12 in Table 2)

Do you suggest a wake-up test now?

KW:

Not yet. First, I would loosen the rods and correction, then meticulously explore the compression of dura and spinal cord.

If I could not find any abnormal intraoperative findings, I would do a wake-up test.

Case 2 Question 13 (C2-Q13 in Table 2)

After each maneuver in an attempt to regain IOM signals, in your experience, how long does it take to have signals return to normal, and when would you be happy to continue with the surgery?

SJL:

Perfusion based changes recover within 5 to 10 minutes. Changes secondary to mechanical injury to the cord can take longer depending on the injury, but I would expect to see some improvement within 15 minutes

MPG:

With partial (single or dual) muscle loss—sometimes 15 minutes. With profound (bilateral multi-muscle loss) & reversal of surgical maneuver, then as long as 40 minutes.

KW:

It very dependent to the situation. In my experience, a few minutes if the factors were adequately removed. If it recovers, I will soon restart the procedures.

OB:

I have waited for as long as 1 hour, then stabilized and quit, making sure there was no canal compromise or translation.

AA:

Around 10 minutes. I would be happy to continue the surgery if signal is at least 50% of baseline.

KC:

Signal return is variable and can be up to 30mins.* Usually if we can take quick reversal steps, signal return is quicker.

Case 2 Question 14 (C2-Q14 in Table 2)

The surgeon did not want to do a wake-up test because the surgery course was impossible to stop at this stage. What is your suggestion for next step?

KW:

I would loosen the rod and reduce correction to the point where IOM is normal, then fix in that position and close the wound. Take CT, myelo CT, or MRI after surgery.

OB:

The drop in MEP implies traumatized cord. Decompress, stabilize and close, and give steroids for 24 hours. Any signal in any muscle no matter how small is a good sign of potential recovery, especially if SSEP are stable.

AA:

I would do the same, which is to continue the surgery, with complete excision of the HV and correction of the kyphoscoliosis in order to align the spine and relax the spinal cord.

KC:

Finish the procedure as quickly as possible after rechecking

that there is no obvious dural compression at the osteotomy site, and also that all screws are properly placed. Then wake the patient up after surgery.

The surgeon decided to continue to close the osteotomy with minimal correction and fixed the rod and fusion in situ. IOM was continued to 30 minutes after closure. A wake-up test was performed after closure.

Case 2 Question 15 (C2-Q15 in Table 2)

Usually, when should IOM be discontinued?

KC:

At the time of wound closure. I am not sure that it is appropriate to do minimal correction after excising a hemivertebra, since there could be quite a gap that may not fuse in the long term. I agree with the principle of reduced correction, but would only do so after a wake up test is positive, and if reduced correction leads to a return of signal.

The wake-up test showed bilateral lower limb movement, but in later and more detailed testing, there was weakness in lower limb muscle power (Grade 3). Sensory function was normal.

Case 2 Question 16 (C2-Q16 in Table 2)

Is there anything else the surgeon could have done? Would you give steroids? When and what dosage?

SJL:

Maximize cord perfusion through transfusion. I only give steroids (one dose Decadron 4 to 10 mg, depending on weight) if I am concerned over a mechanical injury. For perfusion injuries, I am more concerned about correcting anemia and blood pressure (BP).

OB:

As expected in this case. Always give steroid during IOM alert and continue for 24 hrs if baseline is not recovered. Dosage is 35mg/kg stat and 5.4mg/kg/hour for 24 hrs.

AA:

I would ask the ICU to maintain the MAP over 80mmHg for at least 24hs and would use dexamethasone 10mg attack dose plus maintenance dose of 4mg 8/8hs for 2 days (adult dose).

Question	SJL	MPG	KW	OB	AA	KC
C2-Q01 Do you apply MEP in patients under 12 years old and why?	Yes. We perform MEP on all patients.*	Yes, multimodal monitoring is our standard of practice.	Yes, I use MEP for all deformity patients even in EOS.	Yes, and for all deformity cases.	Yes. It is our protocol.	Yes, why not?
C2-Q02 What warning criterion do you use for free EMG?	We check for sustained runs of EMG activity.	Usually warned if there is a sustained burst of activity.	I basically do not use EMG for evaluating malposition of pedicle screw.	Any activity with spike train or neurotonic discharge	05mA	We do not have good experience with free EMG.
C2-Q03 What warning criterion do you use for triggered EMG?	We use 7mA in the lumbar and 8mA in the thoracic.*	Not used.	I have no idea for triggered EMG.	10mA	10mA	We do not have good experience with this.
C2-Q04 What is the relative importance of SSEP and MEP versus EMG? Do you always consider a warning from SSEP and MEP, or sometimes not consider a warning because of normal EMG and trigger EMG?	We consider SSEP a recording of dorsal columns, MEP a recording of anterior cord.*	Rank order MEP>SSEP>EMG.*	I only rely on MEP.	SSEP and MEP alerts are relatively more important than normal EMG.	We consider a warning from SSEP and MEP even if the EMG is normal.*	I feel that MEP is most important in thoracic and cervical monitoring.
C2-Q05 Would you consider a wake-up test before proceeding with further actions?	No, I would remove the screw and palpate it carefully for any breaches.*	No. Remove screw; anesthetic adjustment (increase MAP, transfuse, etc)*	I would do a wake-up test if abnormal MEP continues even after removal of pedicle screw.	Depends on how much of a drop.*	No. We proceed with further actions.*	No. I would immediately reverse the last step.*
Intra-operative imaging was obtained to check for placement of screws. The right T8 screw appeared to have breached the medial pedicle wall and was removed. Subsequently, both SSEP and MEP signals returned.						
C2-Q06 Now, do you change the surgical plan or proceed with hemivertebra excision?		Proceed, but have a low threshold to abandon resection if MEPs drop again.	I would not change the strategy, since the MEP recovered to normal levels.*	If IOM returns to baseline, then proceed with hemivertebra resection.	I would proceed with HV excision, but I would check the position of the screw with imaging.*	Since T8 is the hemi, I would not change the plan.*

An asterisk (*) indicates that a longer response is provided in the main text.

Table 6.2 Case 2: An 11-year-old female with congenital scoliosis and an 80 deg kyphoscoliosis from hemivertebra at T8

Question	SJL	MPG	KW	OB	AA	KC	
The surgery continued after T8 screw removal. Hemivertebra excision was performed and IOM remained normal. Then, during the osteotomy closure, IOM signals presented significant loss in some channels of MEP. Significant reductions of 70% presented in the left rectus femoris, right rectus femoris, and tibialis anterior. SSEP showed small changes with an amplitude decrease of about 30%.							
C2-Q07	In this scenario when MEP and SSEP changes do not corroborate, how would you interpret the changes?	SSEP and MEP do not test the same regions of the spinal cord and are therefore complementary*	Always follow the MEPs – our published results for SSEPs were not as good as for MEPs.	I would check the osteotomy site to check the status of dural (spinal cord) compression.*	MEPS more important here than SSEP.*	There should be some compression or hypoperfusion of the spinal cord.*	I would still consider this a positive and activate our checklist.
C2-Q08	In this case, part of the muscles presented abnormal MEP. What is your decision?	*	*	*	*	*	*
C2-Q09	If the abnormal MEP presented on abductor hallucis, while the other two muscles (rectus femoris, tibialis anterior) are normal, what is your decision?	I would do the same as the previous answer.*	Wake-up test – if move feet then proceed to conclude operation	Again, I would check the osteotomy site to check the status of dural (spinal cord) compression.*	Any muscle group with MEP is fine.	Would be the same.	I would still consider this as positive and activate our checklist.
C2-Q10	In high risk surgeries like VCR, as well as in young patients, would you consider different criteria for IOM?	I use the same criteria for all*	No – currently MEP alert at drop to < 20%	Basically the same	Not really*	Usually not, but in some very hard cases, we may be more tolerant during the surgery.	No
The surgical maneuver was halted for 10 minutes observation. IOM with MEP and SSEP signals were performed continually. SSEP remained normal. For several minutes, MEP returned to normal. However, MEP dropped again without further surgical manipulation. There is total loss of rectus femoris MEP, as well as a drop in all other lower limb MEP.							
C2-Q11	How would you interpret the variable signal loss?	This represents a perfusion-based signal change.*	Variable perfusion	This may be a true positive.	Check the MAP, temperature, and hemoglobin.*	This means that there is no damage (contusion) to the spinal cord.*	This could be a vascular issue. I would check blood pressure, body temperature, and Hb.
C2-Q12	Do you suggest a wake-up test now?	I would expect improvement with the above maneuvers and not do a wake-up test.	Absolutely	Not yet.*	Decompress before wake up.	No. I don't think it would help at that moment. Much more important is to relax the spinal cord.	Once the above are excluded and there is still signal loss, yes do wake up.
C2-Q13	After each maneuver in an attempt to regain IOM signals, in your experience, how long does it take to have signals return to normal, and when would you be happy to continue with the surgery?	Perfusion based changes recover within 5 to 10 minutes.*	With partial (single or dual) muscle loss – sometimes 15 minutes.*	It is very dependent on the situation.*	I have waited for as long as 1 hour.*	Around 10 minutes.*	Signal return is variable and can be up to 30 minutes.*
C2-Q14	The surgeon did not want to do a wake-up test because the surgery course was impossible to stop at this stage. What is your suggestion for next step?	I would transfuse the patient as stated previously to maximize the cord perfusion.	Release the correction and repeat MEPs	I would loosen the rod and reduce correction to the point where IOM is normal.*	The drop in MEP implies traumatized cord.*	Continue the surgery, with complete excision of the HV and correction of the kyphoscoliosis.*	Finish the procedure as quickly as possible.*
C2-Q15	Usually, when should IOM be discontinued?	I generally discontinue the IONM at closure.	Usually 20 minutes after the last corrective maneuver and/or 2nd rod applied.	After finishing wound closure.	After closure.	When the patient is waking up, at the end of anesthesia.	At the time of wound closure.*
The wake-up test showed bilateral lower limb movement, but in later and more detailed testing, there was weakness in lower limb muscle power (Grade 3). Sensory function was normal.							
C2-Q16	Is there anything else the surgeon could have done? Would you give steroids? When and what dosage?	Maximize cord perfusion through transfusion.*	No – our SCI society has given guidelines that state NO steroids.	I would give a dose of 500mg steroids and 200ml Glyceol.	Always give steroid during IOM alert and continue for 24 hrs if baseline is not recovered.*	I would ask the ICU to maintain the MAP over 80mmHg for at least 24hs.*	Yes. I would give steroids using high dose methylpred as recommended by NACIS study.

An asterisk (*) indicates that a longer response is provided in the main text.

Table 6.2 (cont.) Case 2: An 11-year-old female with congenital scoliosis and an 80 deg kyphoscoliosis from hemivertebra at T8

Case 3

A 15-year-old male with a benign spinal tumor located at the right posterior wall of T12 causing anterior compression of the spinal cord presented incidentally on MRI with no neurological deficit. Surgery with posterior laminectomy, facet joint excision, and tumor excision is planned.

Before surgery, clinical electrophysiology tests showed normal SSEP and EMG, but transcranial magnetic MEP did not present responses in the low limb muscles.

Case 3 Question 1 (C3-Q01 in Table 3)

Do you select whether to do IOM based on pre-operative electrophysiology tests?

- Yes
- Not at all
- In some cases

Case 3 Question 2 (C3Q2 in Table 3)

If a patient is paraplegic before surgery, do you still use IOM?

- Yes
- Not at all
- In some cases

AA:

In some cases. If IOM is available, I would use it because it may guide me to avoid more damage to the spinal cord, and also to confirm the improvement of signals after decompression of the spinal cord. On the other hand, I would not cancel or postpone the surgery if I didn't have IOM available, because the patient needs decompression of the spinal cord and stabilization of the spine.

In this case, intraoperative SSEP and TcMEP monitoring were set up. MEP signals were recorded from the thenar, tibialis anterior, and abductor hallucis muscles.

Case 3 Question 3 (C3-Q03 in Table 3)

Would you consider other monitoring modalities like EMG, D-wave?

AA:

Yes. In this case D-wave would be useful, but it is possible to use only for surgeries above T9T10, which is not the case.

After induction of anesthesia, SSEP and TcMEP were recorded while patient was supine and then prone. With the patient in prone position, SSEP amplitude is a little reduced while MEP remained the same as in supine position.

Case 3 Question 4 (C3-Q04 in Table 3)

Do you perform baseline IOM in supine as well as in prone position?

- Always
- Not at all
- In some cases

SJL:

I only do in prone position unless the spine is unstable, as in trauma. The leads are not in place until the patient is fully positioned.

AA:

In some cases. We perform baseline in supine in cases with some instability of the spine, otherwise we perform only in prone.

Case 3 Question 5 (C3-Q05 in Table 3)

If yes, which of the following modalities do you perform during positioning?

- SSEP only
- SSEP and MEP

MPG:

SSEP and MEP. MEPs give a more rapid response, particularly when the neck is being adjusted in the Mayfield clamp in the case of a fractured ankylosed spine.

KC:

I always do SSEP and MEP. I think it is generally accepted that MEP is more important, but it is good to have SSEP as confirmatory evidence.

Case 3 Question 6 (C3-Q06 in Table 3)

If the signal drops significantly after positioning, what is your action?

- Adjust position
- Return supine for retest
- If signal returns after adjusting position and/or returning to supine for retest, start surgery. If not, abandon the operation.
- If signal remains suboptimal, start surgery with IOM conducted from prone position as baseline.
- Other

SJL:

Adjust position. Occasionally, especially when there is spinal cord compression, positioning the patient extended in the prone position may not be tolerated. In these cases, I consider using a Wilson frame to maintain the patient in a more kyphotic position and reassess the IONM.

MPG:

Adjust position, and/or return supine for retest. If signal returns, then start surgery. If not, abandon the operation. To proceed with less than ideal IOM would probably be medicolegally indefensible if there was a later IOM loss and/or post op neuro deficit. The abandonment would allow a Montgomery-compliant discussion¹ with the family to determine their appetite for risk and a 2nd attempt at a later date.

KW:

If signal returns after adjusting position and/or returning to supine for retest, then start surgery. If not, abandon operation.

OB:

Return supine for retest and wake up if abnormal. If normal in supine but abnormal in prone, abort case and discuss with family.

AA:

Adjust position. If the patient has no other option and needs surgery to decompress the spinal cord, we have to position the patient as best as possible and perform the surgery, using the signal from prone position as baseline.

KC:

I would readjust position, although in my experience that has not helped. If signal does not return, I would abandon the procedure, wake the patient up and counsel the patient on risk of surgery.

Total intravenous anesthesia (TIVA) using propofol and opioid was used. Additional drugs with ketamine, etomidate, and benzodiazepines were used. Baseline of TcMEP was recorded before muscle relaxants were used, prior to skin incision and exposure. The baseline of SSEP was recorded after exposure and before laminectomy.

Case 3 Question 7 (C3-Q07 in Table 3)

Do you use muscle relaxants during exposure?

- Yes
- No, never
- Not in this case

Case 3 Question 8 (C3-Q08 in Table 3)

At what point before or during surgery do you perform SSEP and TcMEP to use as your baseline?

AA:

Just after induction in some cases (when we expect some instability), but usually after prone positioning and before exposure.

After muscle exposure, muscle relaxation was stopped, and the surgeons began to perform the laminectomy and decompression. SSEP was normal. TcMEP dropped by 20%. Anesthesia and MAP variables remained stable.

Case 3 Question 9 (C3-Q09 in Table 3)

Is a 20% drop in MEP significant? What do you use as the warning criterion and cut-off point for TcMEP?

AA:

No. A 20% decrease in MEP is not significant. Also, the muscle relaxation may still be in effect. I use a drop of 50%.

The surgeon did not take the reduction of TcMEP as significant, and slowly performed the operation as planned. 15 minutes later, TcMEP returned to baseline. SSEP remained normal.

After laminectomy of T12, TcMEP of the right tibialis anterior dropped to 60% of baseline. Right side SSEP showed a 15% decrease in amplitude, while left side SSEP remained

normal. Technical issues related to monitoring and anesthesia were checked and excluded.

Case 3 Question 10 (C3-Q10 in Table 3)

Do you consider this drop in MEP significant?

Case 3 Question 11 (C3-Q11 in Table 3)

Do you consider it as a warning based on TcMEP?

- No, SSEP is normal
- No, MEP decrease is 40% only
- Yes, MEP is the priority for consideration
- Yes, either SEP or MEP drop is considered

SJL:

While a 50% drop is the threshold, if a lesser drop is associated with a surgical maneuver, close observation of the signals is performed to ensure no further drop occurs.

KC:

No. I do not consider this significant, since it does not reach the cut off of a 50% drop. However, I would be concerned and would ask for more frequent checks to ensure that other factors such as MAP and Hb are optimized, etc.

TcMEP of the right lower tibialis anterior dropped to 0% of baseline after 3min, while MEP in the right abductor hallucis (AH) and the left-sided MEP did not decrease a lot (only a 10% reduction in the right AH, and no change in the left side MEP). SSEP showed a 30% reduction in the right side.

Case 3 Question 12a (C3-Q12a in Table 3)

What is your response regarding the discrepancy between MEP and SEP signals?

Case 3 Question 12b (C3-Q12b in Table 3)

What is your response regarding the discrepancy in lateral MEP?

Case 3 Question 12c (C3-Q12c in Table 3)

What is your response regarding the discrepancy in MEP of the distal and proximal muscles?

MPG:

Not significant—context of the loss is more important. If there was a sustained (>15 minute) loss of a single muscle group I would still consider that important.

Case 3 Question 13 (C3-Q13 in Table 3)

Please comment on questions C3-Q12a–c.

SJL:

I do not consider a drop in a single muscle group, with the remaining groups normal in the setting of a surgery well proximal to all these muscles, as a significant issue. It may however be a warning that more drops in other muscle groups may be coming. SSEP (dorsal columns) and MEP (anterior cord) monitor different parts of the spinal cord so a change in one can occur without a change in the other.

KW:

The MEP did not decrease except for the one at rTA. This is not an indicator of the completeness of neurological function after surgery.

After 15min, SSEP monitoring reported a gradual drop of amplitude in right lower limb, and reached 50% of baseline. Two channels of right side lower limb MEP were abnormal.

Case 3 Question 14 (C3-Q14 in Table 3)

Do you use a checklist?

SJL:

I do not use a checklist (even though I am one of the authors on the paper!)² but I review with the monitoring team whether the upper extremity controls are normal, when they tested the last motor prior, go over all the surgical maneuvers/events that may have been performed since the last MEP was tested, review with anesthesia the blood pressure and hemoglobin and whether any other drugs were given.

KW:

Yes. Have a rest for 10 minutes without any surgical intervention, and then, evaluate the SSEP and MEP again. If the potentials are not normal, we might quit curative resection of the tumor.

Case 3 Question 15 (C3-Q15 in Table 3)

Do you perform a wake-up test after an IOM warning? If so, when?

SJL:

I generally do not do a wake-up test unless there is a significant discordance between the surgery and the IONM in the presence of a bilateral complete loss of MEPs.

MPG:

Significant IOM (MEP) loss—anesthetic adjustment—no improvement—wake-up test—failed wake-up test—remove rods/detension spine—imaging survey +/- intra-op ultrasound—removal of screws +/- additional decompression, etc.

Case 3 Question 16 (C3-Q16 in Table 3)

Do you act differently when the monitoring signal drops gradually compared to rapidly?

SJL:

Yes. Gradual is most often associated with perfusion while rapid is most often a result of a direct injury to the cord. I treat these types of injuries differently.

KW:

We very carefully perform surgical procedure not to damage the spinal cord until all the signals become flat waves.

AA:

Yes. If it drops rapidly, it is probably related to the last maneuver done, so we have to immediately take a step back. If the signal drops gradually, it is probably related to some degree of ischemia and not related to some surgical step.

Surgeon asked anesthesiologist for a wake-up test. During the waiting time, SSEP returned to normal, and the right MEP reappeared. Surgeon decides to continue surgery and quickly relieve the anterior compression.

Case 3 Question 17 (C3-Q17 in Table 3)

If the monitoring signals returned to normal before wake-up, would you abandon the wake-up test?

MPG:

No—oftentimes the additional stimulus and increased blood pressure are helpful in increasing cord perfusion.

AA:

Yes. During the process of waking up, the blood pressure rises and gives better perfusion for the spinal cord. So, this is a signal that it is necessary to give blood to the patient and/or maintain a higher MAP.

KC:

I may abandon wake up if there is a known reason why the signal should return to normal, such as increasing blood pressure. Otherwise I would still do the wake-up test.

At the end of the procedure, after laminectomy and instrumentation, the neurophysiologist reported that SSEP gradually returned to 70% of baseline, and TcMEP returned to 50% of baseline although the latency was still prolonged.

Case 3 Question 18 (C3-Q18 in Table 3)

Do you perform a wake-up test?

- No, I trust the return of monitoring signals
- Yes, there was a change of monitoring signal
- Yes, I always do wake-up test at the end of surgery.

SJL:

No, I trust the IONM. I generally extubate and wake the patient at the conclusion of the case. In cases of perfusion-based changes (bilateral MEP, normal SSEP) we aggressively monitor the hemoglobin after the surgery and maintain the level greater than 100, at least for the first day.

MPG:

No, probably better to complete the surgery and reverse anesthesia—when awake do a formal assessment of quads, etc. Keep instrumentation sterile in case of need for rapid removal if profound neuro deficit.

AA:

No, I trust the return of monitoring signals. This is a signal that the decompression is good and the spinal cord will progressively return to normal.

Case 3 Question 19 (C3-Q19 in Table 3)

If no wake-up test, when would you discontinue monitoring?

	Question	SJL	MPG	KW	OB	AA	KC
C3-Q01	Do you select whether to do IOM based on pre-operative electrophysiology tests?	I do not do pre-operative clinical electrophysiological tests.	Yes, we do pre-op SSEPs but not TcMEPs.	Yes	Not at all. Not outpatient. Only under anesthesia.	Yes	Not at all. We do not normally do preop studies.
C3-Q02	If a patient is paraplegic before surgery, do you still use IOM?	Yes	Not at all, there seems little point unless there is some protective sensation that is worth preserving.	Yes	Not at all because IOMs are usually absent.	In some cases.*	Depends if its partial or complete. If complete and known to be permanent, no.
In this case, intraoperative SSEP and TcMEP monitoring were set up. MEP signals were recorded from the thenar, tibialis anterior, and abductor hallucis muscles.							
C3-Q03	Would you consider other monitoring modalities like EMG, D-wave?	We routinely use EMG in all cases. I do not use D-wave.	Yes, free running EMG	No	No, not at all because IOMs are usually absent.	Yes*	No
After induction of anesthesia, SSEP and TcMEP were recorded while patient was supine and then prone. With the patient in prone position, SSEP amplitude is a little reduced while MEP remained the same as in supine position.							
C3-Q04	Do you perform baseline IOM in supine as well as in prone position?	I only do in prone position unless the spine is unstable, as in trauma.*	In some cases. Ankylosing spondylitis fractures with no neurological deficit.	In some cases.	In some cases. In myelopathics and patients going into intra op traction.	In some cases. We perform baseline in supine in cases with some instability of the spine.*	When I am concerned that there could be a change between supine and prone, I do supine.
C3-Q05	If yes, which of the following modalities do you perform during positioning? - SSEP only - SSEP and MEP		SSEP and MEP*	SSEP and MEP	SSEP and MEP. Both are needed.	MEP is more important than SSEP.	I always do SSEP and MEP*
C3-Q06	If the signal drops significantly after positioning, what is your action?	Adjust position.*	Adjust position, and/or return supine for retest. If signal returns, then start surgery*	If signal returns after adjusting position and/or returning to supine for retest, then start surgery.*	Return to supine for retest.*	Adjust position.*	I would readjust position, although in my experience that has not helped.*
C3-Q07	Do you use muscle relaxants during exposure?	After baseline signal is established, I use muscle relaxants for the exposure.	No, never. Exposure is fine without muscle relaxation.	No, never.	Not in this case.	Yes. We routinely use muscle relaxants for exposure, so the baseline is taken before infusing it.	Yes
C3-Q08	At what point before or during surgery do you perform SSEP and TcMEP to use as your baseline?	After positioning and prior to skin incision, I obtain baseline IONM.	Once the majority of the diathermy use for exposure is over and decompression/instrumentation starts.	Our discretion	After prone positioning and before incision.	Usually after prone positioning and before exposure.*	Same as mentioned previously.
C3-Q09	Is a 20% drop in MEP significant? What do you use as the warning criterion and cut-off point for TcMEP?	No. I use a 50% drop in MEP amplitude as criteria for warning.	No. I use a drop to <20%.	No. I use a 30% decrease	No. I use a 50% drop or 100mV of voltage increase to obtain recording.	No. A 20% decrease in MEP is not significant. I use a drop of 50%.*	No. Not significant. I use a drop of 50%.
After laminectomy of T12, TcMEP of the right tibialis anterior dropped to 60% of baseline. Right side SSEP showed a 15% decrease in amplitude, while left side SSEP remained normal. Technical issues related to monitoring and anesthesia were checked and excluded.							
C3-Q10	Do you consider this drop in MEP significant?		No	Yes	We use 50% as the warning criterial	Maybe. MEP is the priority, but SSEP is also considered.	
C3-Q11	Do you consider it as a warning based on TcMEP?	A 50% drop is the threshold.*	No, SSEP is normal.	Yes, MEP is the priority for consideration. Meets warning criteria at 60%.	Yes, MEP is the priority for consideration, but SSEP is also considered.	Yes, MEP is the priority for consideration.	No, it does not reach the cut off of a 50% drop.*

An asterisk (*) indicates that a longer response is provided in the main text.

Table 6.3 Case 3: A 15-year-old male with a benign spinal tumor located at right posterior wall of T12 causing anterior compression

Question	SJL	MPG	KW	OB	AA	KC
TcMEP of the right lower tibialis anterior dropped to 0% of baseline after 3min, while MEP in the right abductor hallucis (AH) and the left sided MEP did not decrease a lot (only a 10% reduction in the right AH, and no change in the left side MEP). SSEP showed a 30% reduction in the right side.						
C3-Q12a	" What is your response regarding the discrepancy between MEP and SEP signals?"		Not uncommon - loss of SSEP late event - has less sensitivity than MEPs		There is still anterior cord compression that should be decompressed.	I would still take the MEP drop seriously and activate the checklist.
C3-Q12b	What is your response regarding the discrepancy in lateral MEP?		Again - not uncommon - unilateral still potentially important		There is asymmetric compression.	Cannot explain, perhaps related to the surgery being at the conus.
C3-Q12c	What is your response regarding the discrepancy in MEP of the distal and proximal muscles?		Not significant – context of the loss is more important.*		Cord irritation with incomplete signal recording proximal to distal muscle groups.	Cannot explain, perhaps related to the surgery being at the conus.
C3-Q13	Please comment on questions C3Q12a-c	I do not consider a drop in a single muscle group. . . a significant issue.*		The MEP did not decrease except for the one at rTA.*		The response for all of them would be the same.
C3-Q14	Do you use a checklist?	I do not use a checklist*	Yes. We have adapted Mike Vitale's published checklist. (Ref #2)	Yes*	We have an algorithm for IOM.	Yes
C3-Q15	Do you perform a wake-up test after an IOM warning? If so, when?	Generally no*	Yes, if anesthetic adjustment produces no improvement.*	In most cases, at the end of surgery.	We do a wake-up test when all interventions have been taken and there is no response or improvement.	No, we don't usually perform wake-up tests.
C3-Q16	Do you act differently when the monitoring signal drops gradually compared to rapidly?	Yes*	Yes, if there is a precipitous loss I would de-tension the spine immediately.	We very carefully perform surgical procedure.*	Same treatment approach regardless of rate	Yes*
C3-Q17	If the monitoring signals returned to normal before wake-up, would you abandon wake up test?	Yes, I would abandon the wake up.	No*	Yes, I would abandon the wake up.	Yes, I would abandon the wake up.	Yes.*
At the end of the procedure, after laminectomy and instrumentation, the neurophysiologist reported that SSEP gradually returned to 70% of baseline, and TcMEP returned to 50% of baseline although the latency was still prolonged.						
C3-Q18	Do you perform a wake-up test?	No, I trust the IONM.*	No, probably better to complete the surgery and reverse anesthesia.*	Yes, I always do wake-up test at the end of surgery.	No, the return is a good indication of neuro recovery and we will do wake up after surgery.	No, I trust the return of monitoring signals.*
C3-Q19	If no wake-up test, when would you discontinue monitoring?	We discontinue the monitoring at closure.	20 minutes after the last surgical maneuver.	Just before skin closure	After wound closure	I would continue until the end of the procedure, finishing before the patient wakes up.

An asterisk (*) indicates that a longer response is provided in the main text.

Table 6.3 (cont.) Case 3: A 15-year-old male with a benign spinal tumor located at right posterior wall of T12 causing anterior compression

Case 4

A 38-year-old male with compression of the spinal cord at the T9/10 level by ossified yellow ligament (OYL). Lower limb neurological deficit of grade 3 motor power, and a corresponding sensory level but no sphincter disturbance. His walking ability is impaired and requires a frame with 2 assistants. Posterior laminectomy, excision of the OYL, and 1 level instrumented spinal fusion is planned.

Case 4 Question 1 (C4-Q01 in Table 4)

Is there any preoperative planning or precautions one can take to minimize injury to the spinal cord during decompression?

- Prone test (awake in ward)
- Pre-operative medication (e.g. riluzole, steroids)
- Other

KC:

I would always do a prone test, and have the patient lie on a bed in the prone position for as long as tolerable. I have found this helps to inform us about safety, since there is a high chance that the signal will be lost when this patient goes from supine to prone position, or that the signal may not even be monitorable intraop due to his existing neurology.

Case 4 Question 2 (C4-Q02 in Table 4)

What standard monitoring modalities would you use for this case?

- SSEP
- TcMEP
- D-wave
- Free run EMG
- Triggered EMG

AA:

It is not possible to use D-wave because the surgery should finish at T9T10, as the catheter should be positioned in T10.

Case 4 Question 3 (C4-Q03 in Table 4)

When would you perform the baseline IOM? Supine or prone?

KW:

In OYL or ossification of the posterior longitudinal ligament (OPLL) patients, MEP sometimes changes soon after turning to prone position, especially in patients with neurological deficits.

AA:

Supine after anesthesia and prone. In this case, it is recommended to perform baseline with patient both supine and after turn to prone.

Case 4 Question 4 (C4-Q04 in Table 4)

IOM was not performed before turning prone. On turning prone, SSEP showed low amplitude but was obtainable, whilst TcMEP was not obtainable. What would your response be?

- Wake-up test
- Abandon surgery
- Proceed with surgery
- Other

MPG:

Proceed with surgery. All the above dependent on patient consent and discussion about the need for wake-up test, etc.

KW:

I would turn the patient to supine position, and check if MEP recovers. In patients with neurological deficits, MEP is sometimes not obtainable. Even if MEP is not obtainable, I would turn the patient and proceed with surgery.

OB:

Turn supine and repeat IOM. If normal try prone again and if no response abort. If no responses supine then you can proceed with wake-up test.

AA:

Proceed with surgery. Patient is already with motors grade 3, so he needs to decompress the spinal cord to get better. There is no other option.

KC:

I would accept this and proceed to surgery. However, I feel that the better way to manage this patient is with a preop prone test and intraop baseline in the supine position.

Case 4 Question 5 (C4-Q05 in Table 4)

The surgeon decided to take this as the baseline and proceeded with surgery. After a laminectomy was performed, SSEP dropped to 50% of baseline whilst TcMEP remained unrecordable. What is the significance of a 50% SSEP drop in this setting?

- True positive
- False positive
- No significance
- Other

KW:

It may be a true positive, but we only need to do decompression and fixation. This is different from correction surgery or spinal cord tumor resection. In these surgeries, the options may include stopping surgery and closing the wound. However, in this situation, the surgeon has already passed the point of no return.

Case 4 Question 6 (C4-Q06 in Table 4)

What is your response in this situation? State all the parameters you would like to know and adjust to, including the values you would accept.

SJL:

I am more concerned with the loss in MEPs. I would improve perfusion by maintaining adequate blood pressure and transfusing packed red cells if hemoglobin is less than 100. I would bring MAP to 80 mmHg.

AA:

I would proceed with the decompression of the spinal cord, resecting all the yellow calcified ligament and stabilizing the spine, maintaining the MAP over 80mmHg during the entire procedure.

Case 4 Question 7 (C4Q7 in Table 4)

The signal remained similar for 10 minutes despite all the rescue procedures above. How long before you would consider signal loss to be final and therefore stop waiting?

SJL:

I would be resuscitating throughout and not just wait. I would continue with the laminectomy. I would complete the surgery in an expedited fashion and close the wound and wake up.

KW:

I would not stop surgery. I would proceed with the surgery to decompress the spinal cord and stabilize the spine. I think this is the only way to save the spinal cord.

Case 4 Question 8 (C4Q8 in Table 4)

What is your next step?

- **Wake-up test**
- **Proceed with surgery without wake-up test**
- **Other**

SJL:

Proceed with surgery without wake-up test. The patient requires the decompression and fusion. I would complete as soon as possible and close.

KC:

In this patient, since there are no surgical steps that can be done to reverse the procedure, I would proceed as quick as possible and finish the procedure.

Case 4 Question 9 (C4Q9 in Table 4)

The surgeon decided to perform a wake-up test. The patient was unable to move his lower limbs. Which of the following will you consider?

- **High dose steroids**
- **Proceed with surgery**
- **Abandon surgery**
- **Other**

SJL:

Proceed with surgery. The laminectomy is completed already. If instrumentation is necessary, I would complete it and close. If not necessary, just close. I provided steroid prior to incision.

Case 4 Question 10 (C4Q10 in Table 4)

How would you estimate the prognosis for lower limb motor recovery after this surgery? What is the basis for your prognostication?

SJL:

I do not feel you can prognosticate the neurological findings based on the IONM in this case. No evidence of any MEP signal is worrisome. As long as no spinal cord infarct occurred, I would expect some recovery and perhaps near complete recovery. However, if a cord infarct occurred, the prognosis is guarded.

KW:

I would expect some recovery but I am sure not complete. The surgical result of cord decompression with or without fixation in the lower thoracic level tends to be unfavorable. I always inform patients about the deterioration of neurological status.

AA:

After decompression of the spinal cord and stabilization of the spine, I believe the spinal cord will recover its function, to better than before the surgery. I state this on the basis of my experience from other cases.

Case 4 Question 11 (C4Q11 in Table 4)

Is there anything you would do differently in this case from the surgeon?

SJL:

This is a case that requires some baseline MEP signal to safely perform the procedure. If no prone baselines could be established, the patient should have been flipped back supine and attempts made to obtain signal. Care must be taken by the anesthesiologist to maintain adequate blood pressure during induction and to ensure that adequate hemoglobin is present. If signal cannot be established supine, I would wake up the patient to test neurological function. If TcMEP are present when supine, I would flip the patient on a Wilson frame and maintain kyphosis during the procedure. IONM would be re-tested in the prone position prior to skin incision.

KW:

The purpose of the surgery is to decompress the spinal cord by removing the ossified ligament. Thus, even if I notice the deterioration of IOM during the procedure, the only thing I need to do is proceed with surgery. If the IOM is normal, I will keep my usual pace during the procedure, but if IOM is abnormal, I will hurry the surgery as much as possible.

OB:

Supine IOM is critical to know if changes were related to position, at which point surgery could have been aborted.

	Question	SJL	MPG	KW	OB	AA	KC
C4-Q001	Is there any preoperative planning or precautions one can take to minimize injury to the spinal cord during decompression?	Generally give Decadron 10 mg prior to incision & position patient on Wilson frame if some kyphosis.	Prone test (awake in ward). We have on occasion done this with preop SSEPs.	I usually do a prone test.	Pre-operative medications, protective agents.	In this case I would do a prone test.	I always do a prone test*
C4-Q002	What type of standard monitoring modalities would you use for this case?	SSEP, TcMEP, free run EMG	SSEP, TcMEP, and free run EMG. Standard multimodal IOM.	I basically use only TcMEP	SSEP, TcMEP, and free run EMG	It is not possible to use D-wave.*	SSEP and TcMEP
C4-Q003	When would you perform the baseline IOM? Supine or prone?	Supine after anesthesia	Prone. After the preop tests are normal then straight to prone IOM before commencing surgery.	In OYL or OPLL patients, MEP sometimes changes soon after turning to prone position.*	Supine after anesthesia	In this case, it is recommended to perform baseline with patient both supine and prone.*	Supine after anesthesia
C4-Q004	IONM was not performed before turning prone. On turning prone, SSEP showed low amplitude but was obtainable, whilst TcMEP was not obtainable. What would your response be?	Flip back supine, and obtain baseline supine. If signal returns, reflip on Wilson frame in kyphosis.	Proceed with surgery.*	I would turn the patient to supine position, and check if MEP recovers.*	Turn supine and repeat IOM.*	Proceed with surgery.*	I would accept this and proceed to surgery.*
C4-Q005	The surgeon decided to take this as the baseline and proceeded with surgery. After a laminectomy was performed, SSEP dropped to 50% of baseline whilst TcMEP remained unrecordable. What is the significance of a 50% SSEP drop in this setting?	May represent some injury to the dorsal column during the decompression.	It is not possible to say, the only way to determine is to wake the patient and do a full neurological assessment.	It may be a true positive, but we only need to do decompression and fixation.*	True positive	True positive. The SSEP is the only parameter we have to orient ourselves.	I would take a 60% drop as being significant. So I would consider this change not significant but I would be careful.
C4-Q006	What is your response in this situation? State the parameters you would like to know and the values you would accept.	I am more concerned with the loss in MEPs.*	Adjust anaesthetic (MAP > 80mmHg, Hb>10g/dL, CVP elevated, etc)	The same as mentioned above. Only need to do decompression and fixation.	Give steroid if you haven't already, raise MAP to >80 and complete decompression.	I would proceed with the decompression of the spinal cord.*	I would raise the MAP to above 90mmHg.
C4-Q007	The signal remained similar for 10 minutes despite all the rescue procedures above. How long before you would consider signal loss to be final and therefore stop waiting?	I would be resuscitating throughout and not just wait.*	15 minutes	I would not stop surgery to stabilize the spine.*	I can wait for 1 hour before making a decision to quit.	10 minutes	Difficult, not sure there is a correct answer. I would wait at least 30mins.
C4-Q008	What is your next step? - Wake-up test - Proceed with surgery without wake-up test - Other	Proceed with surgery without wake-up test.*	Wake-up test. Our published data for SSEP indicates a 30% positive predictive value .	Proceed with surgery without wake-up test. Same as mentioned above.	Do wake-up test and finish surgery.	Proceed with surgery without wake-up test, as commented two questions above.	I would proceed as quick as possible and finish the procedure.*
C4-Q009	The surgeon decided to perform a wake-up test. The patient was unable to move his lower limbs. Which of the following would you consider? - High dose steroids - Proceed with surgery - Abandon surgery - Other	Proceed with surgery. The laminectomy is completed already.*	Abandon surgery. To continue is medico-legally indefensible.	Proceed with surgery to stabilize the spine. Same as I mentioned above.	High dose steroids and PRAY.	Proceed with surgery, as I commented above.	Proceed with surgery and high dose steroids, since there are no reversible steps.
C4-Q010	How would you estimate the prognosis for lower limb motor recovery after this surgery? What is the basis for your prognostication?	I do not feel you can prognosticate the neurological findings based on the IONM in this case.*	Sacral sparing has a good prognosis for some motor recovery.	I would expect some recovery but I am sure not complete.*	He can still recover but it may take a while.	I believe the spinal cord will recover its function, to better than before the surgery.*	I do not know, but if he exhibits early and fast recovery, the chance of him improving is high.
C4-Q011	Is there anything you would do differently in this case from the surgeon?	This is a case that requires some baseline MEP signal to safely perform the procedure.*	No	The purpose of the surgery is to decompress the spinal cord by removing the ossified ligament.*	Supine IOM is critical.*	I would not lose time doing the wake up test.	Yes, the preop prone test and supine baseline.

An asterisk (*) indicates that a longer response is provided in the main text.

Table 6.4 Case 4: A 38-year-old male with compression of the spinal cord at T9/10 level by ossified yellow ligament (OYL)

Discussion

There is substantial variation in how our six spine surgeons would choose to address the issues in these four cases, as well as points of consensus. To correct the adolescent idiopathic scoliosis in Case 1, three surgeons consider IOM mandatory, while three would use IOM if available (C1-Q01). One surgeon uses IOM in all spine surgeries, two in surgeries with any corrective maneuver, and three in some but not all spine surgeries (C1-Q02). Exceptions include surgeries where the risk of spinal cord injury is deemed low (e.g. implant removal) or in neuromuscular scoliosis where there is no distal neural function. One surgeon indicates that if curves are less than 70 degrees, he may operate without IOM if it is not available. From the discussion of Case 2, there is unanimous consensus that MEP should be used in all early onset scoliosis (EOS) cases (C2-Q01).

As for modalities used, most surgeons choose multimodal monitoring that includes SSEP, TcMEP, and free-run EMG (C1-Q03, C3-Q03, and C4-Q02). For thoracic scoliosis, two surgeons also use triggered EMG, and one surgeon only uses TcMEP (C1-Q03). One surgeon finds D-wave useful, but it is only possible for surgeries above T9/T10 (C1-Q03 and C3-Q03).

Three surgeons use pre-operative electrophysiology tests in deciding whether to use IOM, while three surgeons do not perform routine outpatient electrophysiology (C3-Q01). Two surgeons use IOM in paraplegic patients, two use it when available to avoid further damage or to detect recovery of signal, and two surgeons do not use IOM with paraplegic patients since signals are normally absent (C3-Q02).

Baseline IOM is typically performed prone prior to skin excision (C1-Q04 and C3-Q08). In cases with spinal instability, compression of the spinal cord, or other additional risks, surgeons perform baseline IOM with the patient supine and again after turning to prone (C3-Q04 and C4-Q03). Surgeons use SSEP and MEP during positioning, with two surgeons finding MEP more important than SSEP (C3-Q05).

If the signal drops significantly after positioning, surgeons will typically adjust position and/or return to supine for retest (C3-Q06 and C4-Q04). If IOM is normal after turning prone, reflip on Wilson frame in kyphosis; if no response, abort. In some cases, some surgeons would proceed with the surgery even if MEP is not obtainable (C3-Q06 and C4-Q04).

Anesthesia preferences include total intravenous anesthesia (TIVA) with propofol (C1-Q04). Three surgeons use muscle relaxants for exposure, while three do not (C3-Q07). For intraoperative neuromonitoring, one surgeon has a systematic approach but does not use a checklist. All other surgeons use a checklist or a set algorithm developed within their own institution (C3-Q14).

After loss of IOM signals in Case 1, one surgeon suggests transfusion to maximize cord perfusion (C1-Q09). All surgeons would release the nuts and take out the implants (C1-Q06 and C1-Q08). All surgeons would remove both rods, but one surgeon would release the nuts and wait for 5–10 minutes before

first removing the convex rod, and then the concave rod. One surgeon considers concave side IOM loss to be more critical. The general strategy is to release the correction until MEP returns to normal. However, if the MEP does not return or drops further, all surgeons would choose to abandon surgery (C1-Q08).

When IOM signals return after loosening the rods, three surgeons would continue the surgery but with less correction or with “in-situ” rod contouring. One surgeon would abandon surgery, and wake the patient up to ensure neurology is normal, which also allows for a discussion with the parents about a 2nd stage correction (C1-Q09).

For warning criteria, there is no universal consensus. For free EMG, three surgeons check for any activity with sustained runs of EMG or neurotonic discharge, one suggests 0.5mA, and two don't use free EMG (C2-Q02). For triggered EMG, two surgeons suggested 10mA, one suggested 7mA in the lumbar and 8 mA in the thoracic, and three don't use triggered EMG (C2-Q03). For a change in MEP that merits immediate action, four surgeons use a 50% drop, one uses a 30% decrease, while another waits until the signal drops to less than 20% (C3-Q09, C3-Q10, and C3-Q11). Two surgeons agree that MEP signal changes distal to the osteotomy level are more significant than proximal MEP changes (C3-Q12). For SSEP, a drop to 50% of baseline is considered a significant drop by 3 surgeons, while another uses a 60% drop (C4-Q05). As for the relative importance of SSEP versus MEP signals (C2-Q04), three suggest a rank order with MEP being more important than SSEP. Three think MEP and SSEP signals are both significant (C2-Q04).

While there is no universal consensus for IOM warning signals, none of the six surgeons change their criteria for high risk surgeries (C2-Q10).

Three surgeons consider a rapid drop in monitoring signals to be a direct result of a recent maneuver, and a slow drop in monitoring signals to be the associated with perfusion (C3-Q16). In contrast, three surgeons treat rapid drops and slow drops the same.

For the variable signal loss in Case 2 (C2-Q11) when SSEP remained normal, and MEP returned to normal and then dropped again without further surgical manipulation, three consider this a perfusion-based signal change; they check the MAP, temperature, and hemoglobin, and then take appropriate measures and observe. One considers this a problem due to compression or tension in the cord, which requires spinal cord decompression or relaxation. After attempts to regain IOM signals, surgeons may wait between 10 minutes and an hour for signals to return (C2-Q13 and C4-Q07).

As for the use of steroids in Case 1, 2, and 4, there is no consensus. Three surgeons never give steroids, citing the lack of evidence (C1-Q10). Two surgeons would give if there was a neurological deficit or transient loss of IOM (C1-Q10). In Case 4, after the patient was unable to move his lower limbs, three would give steroids (C4-Q09). For Case 1, one surgeon would

address it as a perfusion issue (C1-Q10). For mechanical injury, 4 surgeons are more inclined to give steroids. However, the dosage and frequency vary from one stat dose to bolus plus infusion over 24–48hrs (C2-Q16).

All surgeons continue IOM/MEP until the end of anesthesia. One surgeon cited anecdotal evidence of a MEP drop due to epidural hematoma during closure. One surgeon suggests MEP can be discontinued 20 minutes after the final surgical maneuver. (C2-Q15, C3-Q19)

None of the surgeons routinely perform intraoperative wake-up tests (C1-Q06 and C3-Q15). Most feel that a wake-up test would waste time or not help with decision making. Four surgeons will conduct a wake-up test if other adjustments (reversal of previous surgical steps, removal of implants) do not correct an IOM warning and there are reversible steps, while two surgeons usually do not perform wake-up tests (C1-Q06, C1-Q07, C3-15, and C4-08). Five specifically mention increasing MAP to above 80 or 90 mmHg (C4-Q06). After anesthesia or other adjustments, if signals are stable or return to baseline, they will wait for the patient to wake up from anesthesia to perform a gross neurological examination. All surgeons trust a return of signals indicating neurological recovery (C3-Q17 and C3-Q18). Only one of the six surgeons on the panel routinely performs a wake-up test as a final check (C1-Q06, C1-Q12, C2-Q15, and C3-Q18).

Conclusion

There is a consensus that neuromonitoring is mandatory for high-risk spine surgeries, and at least preferred for lower-risk spine surgeries. The most commonly used modalities are SSEP, TcMEP, and free-run EMG. Baseline IOM is performed in the prone position, unless there is reason to believe that the signal may change when the patient is moved from supine to prone. Different surgeons have different views on what IOM changes merit immediate action, and often have different views on the appropriate action. All of these differences point to the need for further study to establish best practices for maximizing the benefits of IOM.

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