REVIEW ARTICLE

Intraoperative neurophysiologic monitoring in spine surgery. Developments and state of the art in France in 2011

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Introduction

Intraoperative monitoring in spinal deformity surgery can reduce the incidence of postoperative neurological complications, including spinal cord deficits, cauda equina deficits and nerve root deficits. We will first review the different intraoperative neuromonitoring techniques. Several techniques are generally combined by the neurophysiologist to increase the sensitivity of intraoperative monitoring. Different monitoring alerts are then presented, illustrating the different responses to monitoring changes during spinal deformity surgery depending on the time of the alert during the surgery, the lesional level determined by the intraoperative monitoring, etc. A SFCR multicenter study contributes data on the use of monitoring techniques in France in 2011. After reviewing the use of intraoperative monitoring and its possible legal complications in the United States, suggestions for guidelines are proposed.

Monitoring techniques

Somatosensory evoked potentials (SSEP)

Somatosensory evoked potentials (SSEP) assess the functional integrity of sensory pathways leading from the peripheral nerve, through the dorsal column and to the sensory cortex. From a technical point of view, the posterior tibial nerves are stimulated (duration of stimulus, 0.2 ms; frequency, ~3 Hz; intensity, ~25 mA). Peripheral recordings are made at the level of internal popliteal sciatic nerves. A cortical recording is made in Cz, in regard of the primary somesthetic cortex of both lower limbs. SSEPs are the result of averaging. The acquisition time is on the order of 1 min.

An increase in latencies greater than 10% and a decrease in amplitudes greater than 50% constitute warning signals. SSEPs are altered by the surgical act due to a mechanical factor or secondarily by ischemia. SSEP alterations can also be related to systemic hypotension, hematocrit decrease, hypothermia, anesthesia (volatile agents such as isoflurane, halothane, nitrous oxide attenuate SSEP and should not be used if monitoring is employed).

The disadvantages of SSEPs are the following:

- they only assess the functional integrity of spinal cord dorsal columns. Few cases of postoperative paraplegia with preserved intraoperative SSEPs have been reported (ischemic neurologic injury in the anterior spinal artery territory) [1,2];
- SSEPs are sensitive to anesthetics. Halogenated gases should not be used except for a few minutes during induction. The anesthesia should be delivered continuously;
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- the acquisition time is a little long, approximately 1 min.

The advantages of SSEP are the following:

- based on a large series of 51,263 interventions, it was demonstrated that SSEP had 92% sensitivity and 98% specificity in detecting postoperative neurological complications [3];
- this technique is easy to implement;
- this technique has no contraindications;
- monitoring of the cervical spine is possible;
- SSEP can be combined with other monitoring techniques.

**Neurogenic mixed evoked potentials (NMEP)**

NMEP allow monitoring of the overall spinal cord. NMEPs are obtained by stimulating the spinal cord through electrodes inserted by the surgical team: either a flexible spinal electrode inserted into the epidural space at the rostral part of the operating field, either two needles electrodes (cathode in the epidural space at the rostral part of the operating field, anode in the interspinous ligament above the cathode). The stimulation parameters are the following: intensity, 20–50 mA; duration of stimulation, 1 ms; frequency, 4.1 Hz. Recordings are performed at the internal popliteal sciatric nerves or the posterior tibial nerves. NMEPs result from a short averaging of approximately 50 stimulations, performed in 10–15 s. NMEPs require patient curarization. NMEPs comprise an initial biphasic component and a polyphasic component. Neurophysiological collision studies have shown that the biphasic component corresponds to antidromic activation of the sensory pathways, whereas the polyphasic component corresponds to activation of the motor pathways [4].

The advantages of NMEP are:

- they are fast and easy to implement;
- they are resistant to most anesthetics;
- they are sensitive in detecting a lesion;
- in case of alert, the lesional level can be determined by displacing the stimulation electrode along the intervertebral spaces.

The disadvantages of NMEP are:

- their specificity remains relative because they correspond to the joined activation of motor and sensory pathways;
- they require curarization;
- the terminal medullary cone is not monitored.

**D waves**

D (direct) waves make it possible to monitor the motor pathways from the cortex to the level of the spinal electrode. D waves are obtained by transcranial electrical stimulation (intensity, 80–100 mA; duration of stimulus, 0.5–1 ms; frequency, 0.8 Hz) [5]. The recording is spinal, generally at the level of T11 (and at the caudal part of the operating field). An average of five to 10 stimulations generally suffices, for an acquisition time less than 10 s. This technique is preferentially but not mandatorily performed on a patient having undergone curarization. The advantages of D waves are:

- very rapid acquisition;
- D waves are specific of motor pathways;
- they can establish a lesional level by displacing the spinal electrode along the intervertebral spaces;
- D waves have prognostic value.

The disadvantages of D waves are:

- the recording electrode is in the surgical field and its use by the surgeon can produce artifacts;
- laterality cannot be distinguished;
- D waves cannot be used in small children, generally under 4 years of age (incomplete maturation of motor pathways).

**Motor evoked potentials (MEP) by transcranial electrical stimulation**

MEPs allow monitoring of motor pathways, from the motor cortex to muscles.

The transcranial electrical stimulations are made with corkscrew electrodes at C1 and C2. Five to seven pulses, 2–4 ms apart; intensity, 250–750 V; duration of each pulse, 0.5 ms [6–7]. Recordings are made in lower limb muscle groups.

MEPs allow selective and specific assessment of the functional integrity of descending motor pathways, from the motor cortex to muscles. Recordings are lateralized for each limb. There is no need for averaging.

The disadvantages of MEP are:

- they require at least partially functional motor pathways (preoperative data);
- they are incompatible with prolonged curarization;
- exceptional adverse effects have been described: tongue or lip laceration (29/15,000 monitoring sessions), mandibular fracture (1/15,000), cardiac arrhythmia (5/15,000), epileptic seizures (5/15,000), scalp burn (2/15,000) and intraoperative awareness (1/15,000) [8];
- they are often difficult to carry out on patients under the age of 6 years because of incomplete maturation of motor pathways, but response facilitation methods are currently being developed [9–13].

**Pedicle screw testing**

Neurophysiological monitoring aims to improve the safety of pedicle screw placement. Each pedicle screw is electrically stimulated with an increasing intensity from 5 to 30 mA (duration, 0.2 ms; frequency, 0.8 Hz). Recordings are made at the level of the lower limb muscles with or without the rectus abdominis muscles (depending on the root levels to test). The objective is to estimate the motor response threshold. There is no averaging. Neuromuscular blockades are prohibited. The recording of muscle activity at an intensity under 10 mA (the classically accepted threshold) argues

in favor of a medial breach (close proximity of the screw to the nerve root).

The advantage of pedicle screw testing is that it is a rapid and easy technique that can be combined with new surgical instruments used during screw placement.

The disadvantages of this test are:

- the technique is sensitive to a large number of anesthetics;
- it can be distorted by anterior curarization;
- this technique is less sensitive for thoracic pedicle screws than for lumbar pedicle screws.

Continuous electromyography (EMG)

Continuous electromyography (EMG) consists of continuous recordings of several muscle groups of the lower limbs chosen depending on the root levels at-risk. There is no stimulation. The neurophysiologist looks for the abnormal presence of discharges of rhythmic motor unit potentials. The patient should not have undergone curarization.

The advantage of the continuous EMG is that it provides immediate information potentially on multiple pathway recordings.

The disadvantages of the continuous EMG are the poor performance in terms of sensitivity and specificity. Moreover, the information is not retroactive, contrary to other monitoring techniques.

Intraoperative alerts and guidelines

Adapting reduction based on monitoring data

The observation of a 16-year-old boy presenting severe kyphoscoliosis was presented. Neurological examination was normal. After halo traction and discectomy through an anterior approach, a posterior instrumentation was planned. With placement of the rods, there was a complete loss of MEP signals and 10 min later of SSEP signals. The rods were removed and the intraoperative wake-up test demonstrated movements in both lower limbs. MEP and SSEP signals reappeared. The rods were remounted. Again, there was a complete loss of MEP signals and 5 min later of SSEP signals. Another intraoperative awakening with the rods in place demonstrated paraplegia. When the rods were removed, mobilization of the lower limbs was obtained, SSEPs and MEPs reappeared. The rods were remounted with a minor correction. SSEPs and MEPs remained normal. This observation illustrates several monitoring alerts corresponding to true-positive alerts and adaptation of the reduction based on intraoperative monitoring.

Determining lesional level with NMEP

The observation of a 13-year-old female patient presenting with 75° idiopathic scoliosis is presented. During the positioning of sub-laminar polyester bands, the patient presented bradycardia at 40/min and high blood pressure (20/12). There was a complete loss of spinal SSEPs (in T2) and of cortical SSEPs. Moving the spinal electrode along the intervertebral spaces, one by one, a T8 lesional level was established with NMEPs. Two sub-laminar links at T8 and T9 were removed. Opening the canal, there was no macroscopic anomaly of the spinal cord. Blood pressure was stabilized. Thirty minutes later, NMEPs (in T4) and SSEPs reappeared, with normal values. The instrumentation was pursued. This observation illustrates that in case of a monitoring alert, the lesional level can be determined with NMEPs by displacing the stimulation electrode along the intervertebral spaces.

Maintaining instrumentation during an alert for kyphosis

The observation of a 14-year-old boy with a T7 hemivertebra related to Goldenhar syndrome causing kyphoscoliosis (scoliosis 90°, kyphosis 80°) is presented. Osteotomy and posterior instrumentation were planned. At the end of the osteotomy, SSEPs and NMEPs in T4 lowered in amplitude and then were lost. This alert was interpreted as undoubt-edly being related to an imbalance in the sagittal plane induced by the osteotomy. The arthrodasis was pursued by positioning a rod to correct the hyperkyphosis. NMEPs then reappeared (spinal electrode in T4), as did the SSEPs [14]. The posterior arthrodasis was pursued and the postoperative neurological exam was normal.

A second observation of a 10-year-old boy presenting kyphosis secondary to achondroplasia was presented. Upon installation of the first rod, spinal SSEPs were lost. With a lesser correction, spinal SSEPs reappeared. The arthrodesis was pursued with a normal postoperative neurological examination.

In the first alert for kyphosis, occurring during an osteotomy, the monitoring alert was solved by pursuing the arthrodasis, which provided balance in the sagittal plane. In cases of osteotomy for kyphosis, the priority may be to maintain stability, with installation of a temporary rod preceding the osteotomy [15].

In the second case, this time occurring during the correction, the monitoring alert was solved by reevaluating the correction required. The “monitoring alert: remove instrumentation” concept should be adapted to the circumstances. Responses to monitoring changes during spinal deformity surgery must be adapted to what the surgeon did a few minutes earlier.

Thoracic hernia: anterior approach, SSEP and NMEP monitoring alert

The observation of a 30-year-old female patient presenting with a calcified T7-T8 thoracic hernia is presented. Resection of this calcified hernia via an anterior approach was planned. For monitoring, NMEPs were elicited by electrodes seated into intervertebral discs through thoracoscopy [4,16]. The calcified herniation appeared to adhere to the dura. During the release of the hernia from the dura, NMEPs suddenly disappeared and SSEP amplitudes lowered. The surgery was therefore interrupted. The patient presented postoperative Brown-Sequard syndrome, with complete clinical recuperation at 1 year. This observation again illustrates a true-positive monitoring alert. Moreover,
from a technical perspective, NMEPs were done during an anterior approach procedure.

**SSEP false-negative during a kyphoscoliosis surgery**

The observation of an 11-year-old girl presenting congenital kyphoscoliosis secondary to a T4 hemivertebrae in the context of Goldenhar syndrome is presented. An in situ T2/T6 convex epiphysiosis was performed with a posterior approach. The anesthesia was purely intravenous (propofol, sufentanyl). The patient was monitored with SSEPs alone. SSEPs had little amplitude and little reproducibility, but no intraoperative alert was raised. No deficit was observed upon awakening. Then return to walking was difficult at 1 week, with balance problems. At 2 weeks postoperative, the patient presented complete spastic paraplegia. Imaging demonstrated T4 spinal cord compression. A T4 laminectomy was performed with anterior disco-vertebral resection to widen the canal. Clinical recuperation was complete at 3 months. This observation demonstrates a progressively appearing deficit after surgery, undetected by the intraoperative monitoring with SSEPs alone. Multimodal monitoring provides better performance (better sensitivity and specificity values) than single-mode monitoring [17]. However, no monitoring technique can predict paraplegia with deferred onset, a few hours or a few days after the end of surgery [18].

**Alert on preexisting neurological deficit (medullary tumor)**

Surgery of spinal cord tumors can be monitored multimodally, combining MEPS and SSEPs [19]. A series of 10 patients is presented (four intramedullary tumors, one extramedullary tumor, one medullary hemangioma, three cavernomas, one syrinx). Preoperative data included SSEPs and MEPS. Only one patient had normal preoperative SSEPs and MEPS. MEPS could be monitored in nine out of 10 cases. Intraoperative SSEPs were useful in only four of 10 cases. No total abolition of responses was observed during surgery. In a single case, MEP was lowered on one side with no postoperative deficit. In five cases, alteration of intraoperative MEPS was correlated with a postoperative deficit but with walking recuperated within 6 months for eight of 10 patients. No paraplegia or monoplegia was observed when there was no intraoperative MEP modification (no false-negative). Other complementary techniques can be used such as medullary recording of D waves after electrical stimulation of the cortex or medullary stimulations with multilevel muscle recordings.

In conclusion, intraoperative monitoring of spinal cord lesions is more delicate than monitoring in spinal deformity surgery. Preoperative SSEPs and MEPS are often altered. MEPS and SSEPs cannot always be monitored. A reduction in the amplitude of responses with no abolition guides the surgeon but does not necessarily require interrupting the surgery. A reduction in amplitude most often means transitory aggravation of the postoperative motor deficit. Completing MEPS with D waves recordings and spinal cord stimulations allows the surgeon to better assess the functional integrity of descending motor pathways.

**Monitoring practices in 2011 in vertebral surgery**

A multicenter study was conducted by the SFCR in 2011. One hundred seventeen spinal surgeons responded to a survey on intraoperative monitoring. Sixty-nine of them practiced in public hospitals, 45 in private hospitals, and three worked in both types of institution. According to this survey, in France in 2011, 36% of spinal surgeons had intraoperative monitoring available. There was more intraoperative monitoring in public hospitals (42%) than in private hospital structures (27%).

Multimodal monitoring (associating SSEPs and MEPS or SSEPs and NMEPs) was found for the most part in public hospitals (60%), whereas it was exceptional in private hospitals. The difficulty having a neurophysiologist available in private hospitals was expressed.

Practicing an intraoperative wake-up test differed substantially between teams with or without monitoring. The teams without monitoring capability systematically used wake-up tests in case of vertebral deviation or systematically if severity criteria presented or never used them. In teams with monitoring facilities available, the wake-up test was for the most part carried out depending on monitoring data.

Concerning the indications of intraoperative monitoring, 78% of the surgeons indicated that they used it in vertebral deviation surgeries (scoliysty, kyphosis), 10% in arthrodesis surgery on one or two levels, 8% in canal decompressions, and 4% in disc surgeries.

Open comments were also made: monitoring was an undeniable plus, sufficient allocated personnel was not available, and given the prices allocated to these monitoring procedures, in private hospitals it was very difficult to recruit a neurophysiologist.

Several codifications for intraoperative monitoring are available but certain procedures (testing pedicle screws, D waves) are carried out without it being possible to assign them an existing medical procedure code. In France, the different CCAM (common classification for medical procedures) codifications related to intraoperative monitoring are:

- **AGQP004**: intraoperative monitoring of motor, sensory, or somesthetic evoked potentials, for more than 4h. Price of the procedure: € 0. Complementary procedure;
- **YYYY146**: SSEP during vertebral surgery, performed by a practitioner other than the physician performing the anesthetic procedure. Price: € 134. Complementary procedure;
- **AZQP002**: bedside evoked potentials. Price: € 78. Independent procedure;
- **AHQP004**: recording of motor potentials elicited by cortical and/or spinal stimulation. Price of the procedure: € 66. Independent procedure.

Prices of an intraoperative monitoring device range from € 35,000 to € 50,000. Concerning consumables, sterile flexible spinal electrodes cost € 220 each, sterile needle electrodes cost € 24 per pair, and the other consumables —cork-screw electrodes, subcutaneous needle electrodes, etc. — vary in price depending on the manufacturer. To
Intraoperative monitoring: summary of the techniques used, organizational methods, and networking

Several neurophysiological monitoring techniques are available, complement one another, and allow monitoring of spinal cord motor pathways, spinal cord sensory pathways, and some nerve roots. Motor pathway functional integrity is assessed using MEPS, D waves and NMEPs. Sensory pathways functional integrity is assessed using SSEPs and NMEPs. Nerve roots are monitored using pedicle screw testing and continuous EMG.

These different techniques require placement of many electrodes and immediate preoperative recordings. Reference curves are acquired so that the quality of the installation can be verified before surgery begins. Intraoperative monitoring then takes place by combining the methods, most particularly SSEPs and NMEPs or SSEPs and MEPs. These different techniques of intraoperative monitoring are redundant but complementary. Combining them provides optimal surveillance.

The value of neurophysiological monitoring has long been established. The effectiveness of SSEPs was the first described based on a large cohort [3]. NMEPs, MEPs, and D waves were later developed and widely used.

However, each technique in isolation can be responsible for false-negatives [1,2]. Certain techniques such as MEPS and D waves are very difficult to carry out in very young children because of the immaturity of the corticospinal pathways [9—13]. It is indispensable to verify that the motor and sensory spinal cord functions are intact with a multimodal monitoring associating several techniques in accordance with the patient’s age and the neurophysiologist’s experience.

The practical questions of organization and medical responsibility are always a challenge. Should monitoring be the responsibility of the anesthesiologist, the surgeon, a surgeon-guided automatic system, an unsupervised technician, a neurophysiologist trained in these techniques, or a neurophysiologist supervising several simultaneous surgeries? Automatic or surgeon-guided monitoring systems have been recently developed, including SSEPs, MEPS, and pedicle screw testing.

In principle, these automatic or surgeon-guided devices allow the surgical team to do without a neurophysiologist. These devices seem to be adapted for pedicle screw testing and in general are certainly preferable to the absence of monitoring. However, these devices are not adapted to patients under 6 years of age. Moreover, in case of monitoring alert, these devices cannot determine a lesional level. Monitoring is therefore under the surgeon’s responsibility, although he or she may not necessarily be competent in this domain. It has been demonstrated that experienced monitoring teams had fewer than one-half as many neurologic deficits per 100 cases compared to teams with relatively little monitoring experience [3]. What is known about these automatic devices in this domain?

These device characteristics in terms of the sensitivity and specificity remain undetermined. Currently there is no dedicated series or cohorts of patients monitored with this procedure.

Intraoperative monitoring can be partially network-based, with a technician in the operating room and the neurophysiologist remotely visualizing monitoring data, possibly of several simultaneous surgeries. However, we believe that this mode of operation is only efficient if the neurophysiologist is in the operating room to perform MEPS/NMEPs and in the operating room within a few minutes in case of monitoring alert, given that interactions with the surgeon and the anesthesiologist are maximum only if he or she is present.

In a recent Scoliosis Research Society (SRS) study on 108,419 spinal surgeries monitored between 2004 and 2007, the authors reported a 1% rate of new neurological deficit, including nerve root deficit, cauda equina deficit and spinal cord deficit [20]. These spinal surgeries were monitored in 65% of the cases. Intraoperative monitoring methods were not specified. Monitoring performance was extremely mediocre, with changes in monitoring reported in 11% of nerve root deficit, 8% of cauda equina deficit, and only 40% of spinal cord deficit. In other large studies published by experienced monitoring teams, monitoring sensitivity was greater than 80% for spinal cord deficits [21—23].

Several neurophysiologists responded to the above-mentioned SRS publication [18,23,24]. They explained that with the development of surgeon-guided monitoring devices, neurophysiologists were very likely absent from the operating room. These surgeon-guided monitoring devices probably have lower performance than monitoring by an experienced neurophysiologist. However, no monitoring technique can predict paraplegia with later onset, a few hours or days after surgery [18].

In conclusion, optimal intraoperative monitoring:

- includes close collaboration between the surgeon, the anesthesiologist, and the neurophysiologist;
- includes complementarity and redundancy of techniques between at-risk and tested structures;
- the techniques elected should be sensitive to the lesional mechanism;
- it must be possible to interact in case of an alert or a complication;
- the specialist should be in the operating room to perform MEPS/NMEPs and should be in the operating room within a few minutes in case of monitoring alert.

Current state of affairs and medical and legal aspects outside of France

In the legal context in the United States, any American citizen can sue for damages with no fees for the plaintiff. The justification for legal action is decided later. The patient must demonstrate negligence, breach of good practices. The plaintiff’s lawyer establishes the list of grievances, assesses whether there has been breach of good practices, and requests medical expertise. The practitioner’s lawyer requests medical expertise. There is no panel of medical
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experts. The depositions are made before trial (plaintiff and practitioner). There may be negotiations to find a financial settlement. If an agreement is not reached, a trial by civilian jury (with no medical knowledge) is organized. There are geographic variations, but in the majority of cases practitioners are victorious.

The mean cost of malpractice insurance for a surgeon is $42,200. According to a 2007 AAOS survey, 55% of surgeons refuse certain surgeries, 39% refuse to do spinal surgery, 21% refuse emergencies, 6% have stopped doing surgery altogether, and 5% take early retirement. From 1985 to 2005, compensation for hip surgery was $60.2 million (for 290 cases) and compensation for laminectomies was $51.7 million (for 160 cases).

The last SRS study is reviewed [20]. It states that multimodal monitoring is more effective than single-mode monitoring and that the role played by the neurophysiologist is essential. Finally, the ultimate objective should remain patient safety before operator safety.

Two examples of legal action are presented. The first is a 17-year-old patient presenting bone dysplasia with spinal canal stenosis that was treated with laminectomy and fusion. The patient experienced postoperative paraplegia and demanded $3.3 million in damages (evaluation of future medical expenses, $52 million). SSEPs had been planned but the device was not available at the beginning of surgery. During the intervention, SSEPs were nil. A wake-up test demonstrated paraplegia. The jury considered that a breach of good practices had not occurred, since the SSEPs had been planned and the wake-up test had been performed. The jury returned a verdict in favor of the practitioner.

The second observation presented is a 63-year-old woman presenting rheumatoid arthritis. A C1-C2 arthrodesis using a posterior approach was performed. The patient was tetraplegic at wake-up and died 15 months later of decubitus complications. The family demanded $3 million. No monitoring had been planned for the surgery and no wake-up test was performed. The jury considered that there had been a breach of good practices. A verdict against the practitioner was returned ($2 million).

Medical and legal foundations, or state of the art

The terms "state of the art", "professional standards", "good practices", "scientific knowledge", "medical guidelines", etc. are used. Several definitions of professional standards have been drawn up. All of them stem more or less precisely from "methods that have been proven in practice for the majority of professionals". The formulation of these references as "what should be done" has evolved with time to progressively reduce the proportion of practice and empirical experience, by progressively emphasizing the proportion of research, abusively considered as "scientifically acquired data", forgetting the uncertainty inherent to all scientific knowledge. These references remain subjective and therefore variable in their interpretation, and unwritten, which disturbs the judicial and political powers. What is currently called "good practices" is not established in relation to experience but corresponds most particularly to a rapid advance of administrative centralization, reflecting a will to standardize practices. This imposed standardization flouts the biases and approximations of certain publications, the uncertainty inherent in any proof, and the temporary nature of most knowledge.

What is the scientific value of the SFCR guidelines proposed today? This is only a professional agreement based on variable scientific levels of proof.

Will these guidelines have legal authority? What is the legal validity of such guidelines from a scientific society? The judge is not bound by the expert conclusions and decides according to his personal judgment. Legally, no written rule is opposable to a medical decision. For a magistrate, the only validity of guidelines of a learned society consists in information about the state of the art, at a given moment.

Proposition for guidelines

Monitoring techniques

We have seen that the notion of intraoperative neuromonitoring corresponds to heterogenic methods, both in the techniques used and in how they are used.

Intraoperative neuromonitoring techniques include SSEPs, NMEPs, MEPs, D waves and pedicle screw testing. Multimodal monitoring refers to combined techniques, most particularly SSEPs and MEPs or SSEPs and NMEPs.

Several modalities can be observed: with a neurophysiologist in the operating room, with a technician in the operating room and a neurophysiologist partially outside the operating room (network), without a neurophysiologist (anesthesiologist, automatic or surgeon-guided devices).

The use of multimodal monitoring (SSEPs and MEPs or SSEPs and NMEPs) in presence of a neurophysiologist seems to be the most reliable technique. To date, there is no dedicated study concerning patients monitored by automatic or surgeon-guided devices. However, results of the latest SRS study indicate that these automatic systems or surgeon-guided devices may have lower performance than multimodal monitoring performed by an experienced neurophysiologist [20,23,24].

Whatever the monitoring technique used, it remains preferable to the absence of monitoring. As a last resort, the intraoperative wake-up test can be considered as a non-continuous monitoring technique of motor functions.

Electrostimulation of pedicle screws is a useful EMG technique that can be performed routinely, providing complementary information to the surgeon.

Monitoring indications

Neuromonitoring in a patient who already has a neurological deficit contributes little information to the surgeon. This is the case in spinal cord lesion surgeries and in revision surgeries with abnormal reference potentials.

The monitoring methods should be adapted to the at-risk structures given the surgery planned and the patient characteristics. The neurophysiologist has to be competent in several intraoperative monitoring techniques.

The nerve roots that are easy to assess are S1 and to a lesser degree L5 on the condition of normal previous values.

Roots L1 to L4 are difficult to monitor. Concerning the detection of nerve root deficits, performance of neuromonitoring is poor in terms of sensitivity and specificity.

Intraoperative monitoring has no indication in degenerative disc surgery of the lumbar spine.

Spinal deformity surgery is the leading indication for intraoperative neuromonitoring. The data provided by monitoring are not absolute whatever technique is used. The absence of monitoring in thoracic and thoracolumbar vertebral deviations reduces the patient’s chances of a good outcome.

Concerning lumbar or lumbosacral deviation surgery, the at-risk structures are the cauda equina and/or the nerve roots. The monitoring techniques are much less effective here. S1 roots are usually monitored. L5 roots can be monitored with a particular protocol. The cauda equina is not adequately assessed.

Guidelines for monitoring alert

Any significant modification of the evoked potentials signifies an alert and should be interpreted taking several parameters into account:

- the technique used and the limit of the indications provided;
- the patient’s hemodynamic state and the anesthesia conditions;
- the lesional level if it can be established;
- the surgeon has to evaluate what he or she was doing 1–10 min earlier, notably if any instability was induced.

An adapted response to a neurophysiological alert during thoracic or thoracolumbar vertebral deviation surgery is not necessarily removal of the instrumentation. Two courses of action should be carried out:

- verification of hemodynamics and metabolic constants;
- on the surgical level, four responses are possible:
  - release the correction and pursue the instrumentation or detection if the potentials normalize rapidly;
  - reduce the correction to a level ensuring that the potentials normalize;
  - remove the material if normal values do not return;
  - leave the material in place in under correction so that instability that may compromise neurological recuperation is not induced.

In all cases, a wake-up test remains valuable during decision-making.

In case of monitoring alert, the presence of the neurophysiologist in the operating room and the collaboration between the surgeon, the anesthesiologist, and the neurophysiologist are highly recommended.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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