The diagnostic value of multimodal intraoperative monitoring (MIOM) during spine surgery: a prospective study of 1,017 patients

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Abstract A prospective study of 1,017 patients who received MIOM during spine surgery procedures between March 2000 and December 2005. To determine the sensitivity and specificity of MIOM techniques used to monitor spinal cord and nerve roots function during spine surgery. MIOM has become a widely used method of monitoring neural function during spine surgery. Several techniques only monitor either ascending or descending pathways and thus may not provide sensitive or specific results. MIOM aims to monitor both ascending and descending pathways therefore giving immediate feedback information regarding any neurological deficits during the operation. Intraoperative sensory spinal and cortical evoked potentials, combined with monitoring of EMG and motor evoked potentials recorded from the spinal cord and muscles elicited by electrical motor cortex, spinal cord, cauda equina and nerve root stimulation, was evaluated and compared with post-operative clinical neurological changes. One thousand and seventeen consecutive patients underwent a total of 4,731 h of MIOM to evaluate any neural deficits that may have occurred during spine surgery. Of these, 935 were true negative cases, 8 were false negative cases, 66 were true positive cases and 8 were false

positive cases, resulting in a sensitivity of 89% and a specificity of 99%. Based on the results of this study, MIOM is an effective method of monitoring the spinal cord functional integrity during spine surgery and therefore can lead to reduction of neurological deficit and consequently improve postoperative results.

Keywords Spine surgery · Intraoperative monitoring · Sensitivity · Specificity

Abbreviations

cm-EP	Cerebro-muscular evoked potentials
cs-EP	Cerebro-spinal evoked potentials
ns-EP	Neuro-spinal evoked potentials
nc-EP	Neuro-cerebral evoked potentials
sm-EP	Spino-muscular evoked potentials
ss-EP	Spino-spinal evoked potentials
BCR	Bulbo-cavernosus reflex
BAR	Bulbo-anal reflex
AEP	Acoustic evoked potentials

Introduction

With the rapid development of imaging techniques and better understanding of structural and functional pathology of the spine and spinal cord, there has been an increasing number of spine surgeries, particularly in specialized interdisciplinary spine centres where spine surgeons (orthopaedic and neurosurgeons) work closely with neurologists, rheumatologists and anaesthetists to offer optimal care to patients with spinal disorders. In addition to the congenital and/or acquired deformities of the spine, the

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increasing age of the general population leads to an increasing number of pathologies with myelopathies due to degenerative changes.

Spinal tumours, particularly intradural and intramedullary, are not that common; however, surgical treatment in these areas places the functioning spinal cord at risk. The intraoperatively obtained online functional status of the spinal cord offers crucial information to guide the surgical technique.

Somatosensory evoked potentials (SEP) were introduced for IOM in the 1970s [11]. However, a large multi-center survey conducted by the Scoliosis Research Society [12] showed that 0.127% of patients had postoperative neurological deficits in spite of unchanged intraoperative SEP findings. The same study showed the rate of true positive SEP of 0.423% but these findings did not prevent a neurological deficit. It is a well-established fact [3, 4, 13] that SEP alone are not a reliable tool for assessment of the descending motor pathways: damage will therefore not be primarily recognised by SEP. After basic physiological research in the 1950s [14] motor evoked potentials (MEP) with spinal cord recording were introduced for clinical diagnostic examinations and for monitoring scoliosis surgery [1] in the 1980s. Tamaki [17] and Kurokawa [9] introduced direct spinal cord stimulation and recording techniques spinal cord evoked potentials (SCEP) in the early 1970s. Spinal electrodes allow the simultaneous recording of spinal somatosensory evoked potentials (SSEP) and cortical somatosensory evoked potentials (CSEP) yield various sensory level diagnoses. Cerebro-muscular and spino-muscular evoked potentials reveal information about the functioning of the upper and lower motoneuron as well as neuromuscular transmission. They are recorded by compound muscle action potentials (CMAP). This technique has become possible using modern electrical stimulators delivering a short repetitive trains of single stimuli, with the introduction of intravenous anaesthesia such as propofol or ketamine in combination with short acting opioids [20].

The evaluation of various evoked potential techniques during scoliosis surgery [10] showed the advantage of routine monitoring of the ascending and descending pathways. However this study, performed on 30 patients, did not allow for the calculation of specificity or sensitivity of the method. Owen pointed out the influence of the performing technologist's qualifications during intraoperative monitoring, by analysing 22 lawsuit reports involving patients who had surgically induced neurological deficit undetected by intraoperative monitoring [13]. It was found that if the appropriate test had been administered correctly the onset of the deficit would have been detected. The failures highlighted in Owen's analysis were caused by human error, and, as such, he emphasized the fact that the monitoring

programme must have professional supervision by neurologists or neurophysiologists with the appropriate higher education and who are trained and experienced in IOM.

The review papers published by well experienced experts [3, 4, 13, 15] conclude that spinal cord monitoring is a team effort involving the surgeon, the neurophysiologist/neurologist and the anaesthetist to improve surgical outcome, primarily for the patient, but also for the surgeon and the spine centre in general.

Study aims

To determine sensitivity and specificity of multimodal intraoperative monitoring in spine surgery.

Patient population, materials and methods

Patient population

The surgeon determined the need for intraoperative monitoring and thus the patient related inclusion criteria for the study. The decision was taken based on the complexity of the surgical procedure and the potential risk of iatrogenic neurological damage. Also patients were included, where IOM was expected to aid the technical procedure such as appropriate placement of pedicle screws ("Electronavigation"). All patients ($n = 1,017$) underwent spinal surgery between March 2000 and December 2005. The patients were selected out of a total of 11,536 patients who received spine surgery at the institution during the study period. Exclusion criteria was determined by the neurologist and included epilepsy, stroke within the previous 6 months and infectious diseases of the CNS. All patients underwent preoperative clinical examination by the surgical spine team which included in the majority of the cases additional neurological and electrophysiological examinations by the first two authors. Following the operation, all monitored patients were examined by both the neurologist and spine surgeon to assess possible new neurological deficits or document of the postoperative neurological status. The same anaesthesia protocol was utilized in all cases, as it was important not to use any substances that would significantly alter or abolish evoked potentials [19].

The patient population consisted of 599 females and 418 males with an average age of 55.4 years (range 0.6–87 years). The surgical interventions were performed by the spine unit chiefs (Orthopaedic Surgery and Neurosurgery) in 929 cases (91%), by chief residents in 81 cases and residents in seven cases. The main diagnoses were (in decreasing order of frequency): lumbar spinal stenosis; with or without instabilities; cervical or thoracal spinal

stenosis; deformities such as scoliosis and kyphosis; and spinal cord, spine and sacral tumours (Table 1).

Materials

For the study two Keypoint® 8-channel workstations and two Keypoint® 4 m/4c devices (Medtronic-Dantec™ Denmark) were used with integrated electrical stimulators and custom software. Stimulation of peripheral nerves for obtaining SEPs and recording of CMAPs for MEPs was carried out using surface electrodes (Medtronic-Dantec 901L0202), except in the case of EMG from the anal sphincter and bulbocavernosus muscles, for which monopolar or bipolar needle electrodes were used (Medtronic-Dantec, 9013L0202 resp. 9013S0021). For transcranial motor stimulation as well as for the recording of cortical sensory evoked potential monopolar needle electrodes (Medtronic-Dantec, 9013L0202) were placed at C3' and C4' according to the international EEG 10–20 System. Bipolar spinal electrodes (Inter Medical™, IMC-KG-102, Japan) were placed subarachnoidal or epidural for electrical spinal stimulation or recording. They were introduced either preoperatively by lumbar puncture with a Tuohy needle 18G (Portex™ Ltd. UK) or intraoperatively by the surgeon. Nerve stimulator devices (Inomed™ GmbH, 79331, Germany) were used for direct nerve, root or tumour stimulations.

The placement of stimulating and recording electrodes and continuation cables was carried out at the same time as induction of anaesthesia. On average, it prolonged the presurgical procedure by 5–15 min, depending on whether a spinal electrode had to be inserted by lumbar puncture for monitoring the spinal cord at the onset of surgery.

Anaesthesia protocol

The use of complete intravenous anaesthesia was used instead of gas narcotics. This was usually accomplished using propofol or ketamine in combination with short acting opioids, as described in the methodology paper in

this supplement [16]. Muscle relaxants were only used for intubation, but usually not during surgery.

Method and principles of multimodal intraoperative monitoring

As conventional nomenclature of evoked potentials has misleading abbreviations for multimodal use of motor and sensory evoked potentials as well as continuous EMG, a new nomenclature with clear labelling of stimulation and recording sites is suggested here and was used in the present study (Fig. 1).

Fig. 1 **a** Principles of stimulation and recording sites of descending pathways. **b** Principles of stimulation and recording sites of ascending pathways

Table 1 Frequency of clinical diagnosis in all 1,017 monitored cases

Diagnosis	Frequency	Percentage
Lumbar spinal stenosis with, or without instability	409	40.2
Cervical/thoracic/spinal stenosis	282	27.8
Deformities	217	21.3
Tumours	109	10.7
Total	1017	100.0

The neural structures to be stimulated and the recording sites (brain, spinal cord, nerves, muscles), were chosen in accordance with any anticipated injury caused by surgical site or procedure. Monitoring was always done on both sides with simultaneous recording on the right or on the left sides of proximal and distal site of risk, to distinguish systemic changes (anaesthetic, perfusion, temperature, etc.) from direct surgery-related changes. The same scalp needle electrodes used for transcranial electrical motor stimulation C3'–C4'/C4'–C3' in cerebro-muscular evoked potentials (cm-EP; previous nomenclature: MEP, Br-CMAP) and cerebro-spinal evoked potentials (cs-EP; previous nomenclature: D-wave monitoring) were also used for recording nc-EP (neuro-cerebral evoked potentials; previous nomenclature: SEP, SSEP, CSEP). The same epidural or subarachnoidal spinal electrode were used rostrally for recording neuro-spinal evoked potentials (ns-EP; previous nomenclature: SSEP), spino-spinal evoked potentials (ss-EP; previous nomenclature: SCEP) and also for stimulating spino-muscular evoked potentials (sm-EP; previous nomenclature: SCMEP, SCEP, MEP) as well as for control recordings for cortico-spinal evoked potentials (cs-EP). The same caudal spinal electrode, primarily used for monitoring the cortico-spinal tract in cs-EP, was also used as a control for recording the ns-EP and as the stimulation site in ss-EP. In cervical spine surgery, the recording of CMAP from peripheral muscles in cm-EP and sm-EP yielding information in the upper extremities about anterior root innervation and at the legs about the corticospinal tract. The peripheral nerves and dermatomes were selected to provide information about the dorsal sensory roots and the dorsal columns at the site of risk. The tests were usually repeated at 5-min intervals for accurate trend analysis and at any further time upon surgical demand. Continuous EMG recordings were done with the same surface muscle electrodes as those used for cm/sm-EP. During intraoperative irritation or compression of nerve roots, so called myotonic discharge (repetitive pseudorhythmic firing of motor units) was analysed as an indicator of nerve root dysfunction. In lumbar fusion surgery, stimulation of pedicle screws was considered to provide useful information regarding the distance of the screw to the neural tissue in an unaffected root ("Electronavigation"). A threshold stimulation level of more than 8 mA was considered normal, 5–8 mA critical and less than 5 mA pathological, indicating that there was not enough distance between the screws and the neural tissue as well as the cracked pedicle.

Results

The MIOM was performed in 1,017 (9%) of 11,536 spine surgery procedures at the Schulthess Clinic during the

5 year study period. All monitorings were performed by two experienced neurologists with 10 years of clinical experience in neurophysiology (first two authors). The average time dedicated to monitoring was 4 h and 39 min, which included an average of 30 min preparation and establishment of baseline data and 15 min for removal of the electrodes. In addition, an average of 1.5 h was required for case preparation and data analysis. This made a total of 4,731 h' hands-on intraoperative monitoring time and 1,526 h' data analysis, including reporting and data management, which accounted for a total of 6,257 h by the responsible neurologists (first two authors). The minimal monitoring time was 60 min for a simple decompression and dorsal stabilisation at the L2/3 level and maximum time of 18 h and 15 min for the total resection of chordoma spreading from C3 to clivus followed by 360° stabilisation of occiput to C5.

The monitoring modalities and selection of muscles and nerves to be recorded respectively stimulated were applied according to clinical situation and any needs that occurred during surgical procedures. In order to be successful, unconstrained communication between the surgeon, the neurophysiologist and the anaesthetist was crucial. Epidural and subarachnoidal electrodes for stimulation and recording were placed either by the neurophysiologist or surgeon at the appropriate place in 318 cases (31%). Special attention was paid to the recording of bulbocavernosus and anal reflexes during operations on the cauda equina. Based upon the structural and functional diagnostics of the spine problem, the neurophysiologist decided the MIOM strategy prior to the operation. This comprised a combination of motor and sensory evoked potentials as well as continuous EMG recording. On average, 6.5 different monitoring tests were applied per patient with a minimum of two and a maximum of 24 tests. The amount of monitoring tests was defined as the sum of recorded muscle pairs in c/s/t/nm-EP, the sum of stimulated nerve pairs in ns-/nc-EP and the cs-EP and ss-EP.

A baseline examination was performed on each patient under general anaesthetic before the operation. Table 2 shows how often the different modalities were applied during all operations, how often the potentials were considered normal, abnormal or not recordable for intraoperative diagnostic use. For the spino-muscular, spino-spinal, neuro-spinal and the reflex examinations, there are no normative data in the literature. Thus, for assessment during the intraoperative monitoring in the particular patient, the baseline of these modalities was given by the starting value and any significant change (increase of latencies more than 10%, decrease of amplitudes more than 50%) during the operation was diagnostically seen as a warning signal.

Table 2 Different monitoring modalities applied for the entire population, and the proportion of normal and/or abnormal neurophysiological findings at the baseline recording

Monitoring modality	Monitorings applied		Baseline recordings		
	Out of 1,017 cases	Mean tests ^a per patient	Normal potential	Abnormal potential	No potentials
cm-EP	1006 (99%)	2.6	357	634	15
sm-EP	166 (16%)	2.2	166 (NVM ^a)		0
cs-EP	291 (29%)	1.2 (i.e. 22% additional rostral control)	108	148	35 ^b
ss-EP	53 (5%)	1	53 (NVM)		0
nc-EP	943 (93%)	1.4 (19% with additional ns-EP)	378	559	6
ns-EP	217 (21%)	1.0 (84% with additional ncEP)	158 (NVM)		0
BCR, BAR	16 (1.6%)	1	16 (normative values missing)		0
F-wave	14 (1.4%)	2.6	2(no NV)		12
H-reflex	2	1	1(no NV)		1
AEP	2	2	2	0	0
EMG	919 (90%)	2.6	No spontaneous activity		

NVM normative value missing

^a Tests: recorded muscle pairs or stimulated nerve pairs in a given modality,

^b In 33 cases impossible or inappropriate positioning of spine electrode

Specificity and sensitivity of multimodal intraoperative monitoring

Using this multimodal monitoring approach, there were 935 true negative (91.9%), 8 false negative (0.8%), 66 true positive (6.5%) and 8 false positive (0.8%) findings, comparing preoperative to postoperative clinical neurological status. The detailed analysis of the false negative cases are presented in Table 3. Only one of these patients with false negative findings (i.e., the neuro-monitoring did not predict an occurrence of a neurological deficit) had permanent radicular deficits. All of the other patients recovered in less than 3 months and most of them within hours after the operation.

The group of true positive findings includes patients for whom the MIOM expert predicted a neurological deterioration; this was immediately communicated to the surgeon who then adequately adapted his procedure. Although these cases included some serious pathologies (tumours, deformities, myelopathies), the postoperative, neurological deterioration was minor, mostly involving monosegmental motor and/or sensory radicular deficits or pain. None of the patients in the study sustained a severe neurological complication such as incomplete or complete paraplegia. One patient who suffered severe arthrogryposis multiplex due to disseminated intravascular coagulopathy died during the operation.

Characteristics of false positive results are shown in Table 4.

Using the standard formula, the sensitivity of MIOM in this series of 1,017 examinations was calculated at 89% (95% confidence interval: 79.3–94.9%) and the specificity

including all 8 false positive cases was 99% (95% CI: 98.2–99.6%).

Discussion

The advancement of spine surgery (i.e., the correction of deformities, decompressive procedures for stenosis in the different regions of the spine and the resection of intramedullary and extramedullary tumours) created the demand for monitoring the function of the spinal cord and/or the nerve roots intraoperatively. The first regular attempt to functionally monitor the spinal cord was the “wake up” test introduced in the 1970s [18]. Although the use of the wake up test decreased the incidence of postoperative neurological deficits, it did not allow for the continuous monitoring of spinal cord function. Further more, it cannot be performed on young children, demented or mentally retarded patients.

Following the animal model of Croft [2] and the development of well-established neurological methods, continuous monitoring of the spinal cord was introduced [13, 17]. The wide application of sensory evoked potentials to monitor spinal cord function was conceptually insufficient, as later demonstrated by Nuwer [12]: sensory evoked potentials only give information regarding the function of ascending pathways and not of the descending motor pathways, which is more important for the patient and spine surgeon. After basic physiological research since the 1950s [14], MEPs were introduced to regular monitoring of spinal cord function [17]. A major advancement in the multimodal intraoperative monitoring has been achieved

Table 3 Description of false negative MIOM with postoperative neurological deterioration

Patient	Region	Pathology	Surgery	Op-time	IOM Modalities	IOM-baseline	IOM-changes	Neurological deterioration	Duration	Recovery
False negative cases										
f, 61 years	L4–S1	Prosis L5/S1, secondary progressive lumbar kyphosis	dorsal decompression, correction and fusion	12.8 h	cm _{IP} , VM, TA, AH-EP n _{IP} , TNc-EP Ped. screw stimulation cont. EMG	All potentials normal	None	Radiculopathy L5 + S1 left	Persistent partial deficit	No
f, 55 years	C2–C5	Spondylotic cervical myelopathy and deformity	Corpectomy C3 + C4, Correction and Fusion, dorsoventral	9.3 h	cs _{C8} -EP cm _{BB} , ADM-EP n _{MNC} -EP cont. EMG _{BB} , ADM	All potentials available, but pathologic	Loss of all potentials after C4/5 distr., completely recovered after reduction	Radiculopathy C5 left	6 weeks	Completely
f, 70 years	C5–C7	Spondylotic cervical myelopathy	Dorsal decompression	3.3 h	cs _{T1} -EP cm _{ADM} , AH-EP n _{MNC} -EP cont. EMG _{ADM} , AH	All Potentials available, but pathologic	None	Radiculopathy C5 left	1 week	Completely
m, 39 years	T9–L2	Achondroplasia, multisegmental stenosis and kyphosis	Laminectomy T9–L1, osteotomy and corrective Spondylodesis	11.8 h	cs _{T7/L1} -EP cm _{VM} , TA-EP s _{L1} , s _{T7} -EP n _{TNC} -EP n _{S/T7} -EP sn _{VM} , TA-EP EMG _{VM} , TA	All available, but pathologic	None	Radiculopathy L2, L3 left	3 months	Completely
f, 51 years	L5–S1	Pseudo-arthritis (5 operation)	Decompression and stabilisation	2.3 h	cm _{TA} , AH-EP n _{TNC} -EP	All available but pathologic	None	Weakness foot extension	3 months	Completely
f, 62 years	L1	Mama-CA-metastasis, fracture	Vertebrectomy fusion vertebroplasty	5 h	cm _{pect} , VM, TA-EP EMG _{pect} , VM, TA n _{IP} , nc-EP	All available	None	Sensory deficit L2	7 days	Completely
f, 72 years	L2–L5	Degenerative stenosis and instability	Dorsal decompression and fusion	4.5 h	cm _{VM} , TA, AH-EP s _{L2} , sn _{VM} , TA, AH-EP n _{IP} , nc-EP cont. EMG _{VM} , TA, AH	cmEP right not available, other EP severe pathologic	None	Urinary and bowel incontinence	3 months	Completely
f, 70 years	C2–C4	Chordoma	Decompression, total resection and Fusion, dorso-ventro-dorsal	17 h	cs _{T8} -EP cm _D , ADM, TA-EP sn _D , ADM, TA-EP n _{MN} , TNc-EP n _{TN} , s _{T8} -EP cont. EMG _D , ADM, TA	All available, but csEP and ncEP pathologic	Slowly reduction of all amplitudes	Sensory radiculopathy C5 left	5 days	Completely

by the group of Epstein [8] as well as Tamaki [7] by applying the different modalities to monitor motor pathways during spine surgeries. Luk then presented the major advantages of multimodal evaluation of the spinal cord [10]; however, with their small patient population of just 30 cases, the sensitivity and specificity could not be determined. Owen pointed out the importance of the professional performance needed to accurately interpret the intraoperative findings and stressed that, for this method to be useful to the spine surgeon's decision making process, it should be performed by an experienced neurologist/neurophysiologist; unprofessional monitoring leads to disputes in liability cases [13].

It is more than obvious that the surgeon who undertakes technically demanding procedures, such as excision of intradural tumours or correction of severe spine deformity, will rely on the results of the intraoperative monitoring of the spinal cord functional integrity to follow the concept of functional spine surgery, should the false negative findings of the monitoring procedure be at a magnitude to justify such an approach, ideally zero which is almost impossible to reach in biological sciences. However, the surgeon does not appreciate a constant disturbance during the procedure by being confronted with false positive findings. Following the recommendations by Owen [13] the spine unit in our hospital developed a closely collaborating team consisting of spine surgeons, anaesthetists and two experienced neurologists/electrophysiologists dedicated to fulltime monitoring with a good understanding of the surgical procedures and its specific risks. Following the experience of Deletis and collaborators (1996, 1999/personal communications) the neurologist was introduced to intraoperative monitoring directly by Tamaki and co-workers (Dr. H. Nishiura, 1999, 2000/personal communication).

The setting of each individual intraoperative monitoring was intended for the highest diagnostic accuracy. The aim of this study was to calculate the sensitivity and specificity of MIOM to facilitate the advancement of the surgical procedure and to either allow the surgeon to correct deformity as much as the functional status of the spinal cord allowed, or to resect the tumour completely/subtotally without damaging the healthy neural structures of the spinal cord.

Over the period of 5 years, the experienced spine surgeons selected 9% (1,017 patients) out of 11,536 spine procedures that were considered appropriate candidates for MIOM due to the severity of structural pathology and/or expected difficulties during decompression or correction procedures and potential risk of occurrence of iatrogenic damage of neural structures. Each case was discussed within the interdisciplinary spine team prior to the operation. An understanding of the pathology, the related

neurological disturbances and the function of the spine and spinal cord prior to the operation was crucial to interpret the analysis and the continuous recorded findings of the neurologist during the surgical procedure in order to inform the surgeon when true positive findings in the different modalities indicated that potential neurological deterioration could or had occurred.

The multimodal approach as used allows for online analysis of the function of ascending and descending spinal cord pathways and for the sensory and motor functions of the nerve roots. The neurophysiologist must be as specific as possible when presenting his findings to the surgeons and describe only those findings that he is actually measuring in order to allow the surgeon to adapt the procedure accordingly. The introduction of sequential analysis of nerve tracts with the help of additional epidural or subarachnoidal spine electrodes is a major advancement as the cm-EP, which measures global motor function of the descending pathways, reacts immediately to functional disturbances, but cs-EP and sm-EP allow more precise localisation of possible surgical related conduction blocks of the corticospinal tract and/or the lower motoneurons at nerve roots. The same is true for nc-EP in sequential analysis of ascending pathways performed by additional ns-EP, that can differentiate true dorsal tract and/or sensory nerve root conduction blocks from systemic changes. An understanding of these different monitoring methods allows the neurophysiologist to appropriately monitor the neural structure according to the immediate needs of the surgical procedure. In the study population an average of 6.5 different monitoring tests were used, with a maximum of 24 as well as widely overlapping modality techniques (Table 2). It is quite difficult for obvious ethical reasons, to calculate or estimate the number of operations that would not be possible to perform without monitoring or that would not allow the surgeon to achieve optimum results ("go to the limit"). The fact that in this 5-year period only one single serious neurological complication occurred may be seen as an indirect indicator of this assumption.

Some papers in the literature have reported the sensitivity and specificity of intraoperative monitoring, but all of them are related to single procedures which explains the low values derived [5, 6]. In this study, in applying the multimodal approach, the overall sensitivity was 89% and a specificity of 99%. The 8 false negative cases (0.8%—as shown in Table 3) with minor neurological deficits (all of which fully recovered except one patient with permanent radicular deficit) illustrate that, if patients are carefully selected and the monitoring is performed by an experienced neurophysiologist with special training in IOM, the spine surgeon can rely on the neurophysiological findings presented by the monitoring expert. The false positive findings

Table 4 Description of false positive MIOM with postoperative neurological deterioration

False positive cases								
Patient	Region	Pathology	Surgery	Duration	IOM modalities	IOM-baseline	IOM-changes	Expected neurological deficit
f, 69 years	C0–T1	Congen. Malformation with sec. compressive myelopathy	Dorsal decompression and fusion	3.8 h	CS _{T5} -EP cm _{BR,ADM} -EP n _{MNC} -EP EMG _{BR,ADM}	all MEP's and SEP's pathological	Alteration of cm _{ADM} -EP left	Radiculopathy C8 left
f, 83 years	C6–C7	Spondylotic cervical myelopathy	Ventral and dorsal decompression and fusion	5.3 h	CS _{T12} -EP cmEP _{BR,ADM} n _{MN} , TN C-EP n _{TN} S-EP EMG _{BR,ADM}	all MEP's and SEP's severely pathological	Alteration of n _{MNC} -EP left	Ataxia left arm
f, 12 years	T4–S1	Scoliosis, idiopathic	Corrective surgery ventral and dorsal	10.3 h	CS _{T11,T7} -EP c/sm _{TA,AH} -EP ssEP n _{TNC} /n _{TNS} -EP	Normal potentials	Loss of all signals	Metabolic disorder or hypovolaemic shock syndrome
f, 21 years	C5–S1	Scoliosis, neuromuscular	Corrective surgery from dorsal	7 h	CS _{T11} -EP cm _{VM,TA,AH} -EP sm _{VM,TA,AH} -EP n _{TNC} -EP cont.EMG _{VM,TA,AH}	Normal potentials	Unilateral loss of all signals correlated with hypovolaemic shock syndrome	Stroke
f, 59 years	L2–L3	Degenerative Stenosis and Instability	Dorsal decompression and fusion	5.5 h	cm _{P,VM,TA,AH} -EP, EMG _{P,VM,TA,AH} n _{PNC} EP	All motor and sensory potentials pathological available	Screw L5 right pathological threshold	Radicular irritation L5 right
f, 79 years	L1–L5	Scoliosis, degenerative	Decompression and corrective spondylodesis from dorsal	7 h	cm _{P,VM,PL} -EP sm _{P,VM,PL} -EP EMG _{P,VM,PL} n _{PN} ,Saphn _C -EP	All motor and sensory potential pathological available	Threshold stimulation identified screws L2&3 left with recessus perforation	L2 and L3 radiculopathy left
f, 66 years	T11–T12	Progressive Instability and myelopathy after T12-fracture and vertebroplastia	Decompression and corrective fusion from dorsal	5.8 h	cm _{TA,AH} -EP n _{TNC} -EP EMG _{TA,AH}	All motor and sensory EP pathological available	Intercurrent continuous reduction of cm/nc-EP	cerebro-vascular attack
f, 53 years	C0–T1	Development tumor with Arnold-Chiari malformation	Dekompression C1–C2 from dorsal	4.5 h	cm _{BR,ADM} -EP n _{MNC} -EP EMG _{BR,ADM}	Normal potentials	Cont. alteration of ncEP MN both side	Ataxia upper extremities

(0.8% as shown in Table 4) observed in only eight cases are justifiable as so called “unnecessary disturbances” of the surgical procedure by the neurophysiologist. Based upon our experience over the past 5 years, in close collaboration with the spine surgeons and anaesthetists, this low level of false positives does not represent an issue.

As the aim of the present study was the determination of overall specificity and sensitivity of MIOM, the detailed analysis of the patient population as related to the individual diagnoses and regions of the spine is the subject of separate papers.

In conclusion, the 5 years' experience with 1,017 monitored cases, and the high sensitivity and specificity reported, justify the statement that MIOM performed by

experienced neurologists/neurophysiologists may or even should become an integral part of all spine surgical procedures where potential complications are to be expected. In this respect, single monitoring procedures such as nc-EP or continuous EMG are definitely not sufficient to account for the complex function of the spinal cord and nerve roots.

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References

1. Boyd SG, Rothwell JC, Cowan JM, Webb PJ, Morley T, Asselman P, Marsden CD (1986) A method of monitoring function in corticospinal pathways during scoliosis surgery with a note on motor conduction velocities. *J Neurol Neurosurg Psychiatry* 49(3):251–257
2. Croft TJ, Brodkey JS, Nulsen FE (1972) Reversible spinal cord trauma: a model for electrical monitoring of spinal cord function. *J Neurosurg* 36(4):402–406
3. Cronin AJ (2002) Spinal cord monitoring. *Curr Opin Orthop* 13:188–192
4. Deletis V, Sala F (2004) Intraoperative neurophysiological monitoring during spine surgery: an update. *Curr Opin Orthop* 15:154–158
5. Deutsch H, Arginteanu M, Manhart K, Perin N, Camins M, Moore F, Steinberger AA, Weisz DJ (2000) Somatosensory evoked potential monitoring in anterior thoracic vertebrectomy. *J Neurosurg* 92(2 Suppl):155–161
6. Gunnarsson T, Krassioukov AV, Sarjeant R, Fehlings MG (2004) Real-time continuous intraoperative electromyographic and somatosensory evoked potential recordings in spinal surgery: correlation of clinical and electrophysiologic findings in a prospective, consecutive series of 213 cases. *Spine* 29(6):677–684
7. Iwasaki H, Tamaki T, Yoshida M, Ando M, Yamada H, Tsutsui S, Takami M (2003) Efficacy and limitations of current methods of intraoperative spinal cord monitoring. *J Orthop Sci* 8(5):635–642
8. Kothbauer K, Deletis V, Epstein F (1998) Motor evoked potential monitoring for intramedullary spinal cord tumor surgery: correlation of clinical and neurophysiological data in a series of 100 consecutive procedures, http://www.aans.org/journals/online_j/may98/4-5-1
9. Kurokawa T (1972) Spinal cord action potentials evoked by epidural stimulation of cord—a record of human an animal record. *Jpn J Elektraenceph Elektromyogra* 64–66
10. Luk KD, Hu Y, Wong YW, Cheung KM (2001) Evaluation of various evoked potential techniques for spinal cord monitoring during scoliosis surgery. *Spine* 26(16):1772–1777
11. Nash CL, Brodkey JS, Croft TJ (1972) A model for electrical monitoring of spinal cord function in scoliosis patients undergoing correction. *J Bone Joint Surg Am* 15A:197–198
12. Nuwer MR, Dawson EG, Carlson LG, Kanim LE, Sherman JE (1995) Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. *Electroencephalogr Clin Neurophysiol* 96(1):6–11
13. Owen JH (1999) The application of intraoperative monitoring during surgery for spinal deformity. *Spine* 24(24):2649–2662
14. Patton HD, Amassian VE (1954) Single and multiple-unit analysis of cortical stage of pyramidal tract activation. *J Neurophysiol* 17(4):345–363
15. Sala F, Krzan MJ, Deletis V (2002) Intraoperative neurophysiological monitoring in pediatric neurosurgery: why, when, how? *Childs Nerv Syst* 18(6–7):264–287
16. Sutter M, Eggspühler A, Muller A, Dvorak J (2007) Multimodal intraoperative monitoring: an overview of proposed methodology based on 1017 patients. *Eur Spine J* (Suppl)
17. Tamaki T, Yamashita T, Kobayashi H (1972) Spinal cord monitoring. *Jpn J Elektraenceph Elektromyogra* 196
18. Vauzelle C, Stagnara P, Jouvinroux P (1973) Functional monitoring of spinal cord activity during spinal surgery. *Clin Orthop Relat Res* 93:173–178
19. Winkler T, Sharma H, Stalberg E (1998) Spinal cord bioelectric activity, edema and cell injury following a focal trauma to the rat spinal cord. In: Stalberg E, Sharma H, Olsson Y (eds) *An experimental study using pharmacological and morphological approaches. Spinal cord monitoring*. Springer, Wien, pp 283–363
20. Zentner J (1991) Motor evoked potential monitoring during neurosurgical operations on the spinal cord. *Neurosurg Rev* 14(1):29–36