European Spine Journal (2019) 28:599–610
https://doi.org/10.1007/s00586-018-5861-0

ORIGINAL ARTICLE

The impact and value of uni- and multimodal intraoperative neurophysiological monitoring (IONM) on neurological complications during spine surgery: a prospective study of 2728 patients

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Received: 23 August 2018 / Revised: 7 December 2018 / Accepted: 12 December 2018 / Published online: 17 December 2018

Abstract

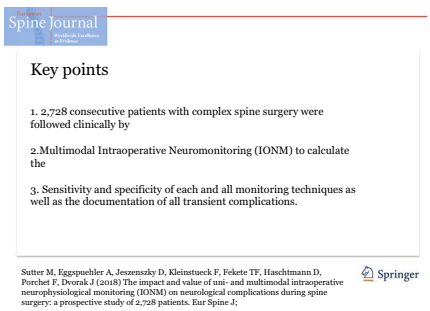
Purpose We compared the value of different uni- and multimodal intraoperative neurophysiological monitoring (IONM) methods on the detection of neurological complications during spine surgery.

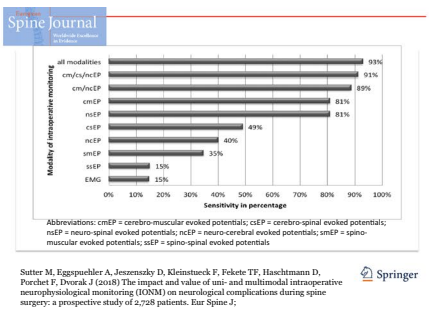
Methods IONM data derived from sensory spinal and cortical evoked potentials combined with continuous electromyography monitoring, motor evoked potentials and spinal recording were evaluated in relation to subsequent post-operative neurological changes. Patients were categorised based on their true-positive or true-negative post-operative neurological status.

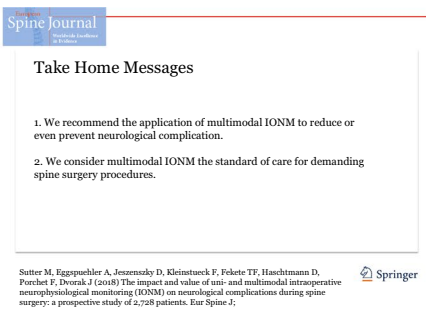
Results In 2728 consecutive patients we had 909 (33.3%) IONM alerts. We had 8 false negatives (0.3%) with post-operative radicular deficit that completely recovered within 3 months, except for one. There was no false negative for spinal cord injury. 107 were true positives, and 23 were false positives. Multimodal IONM sensitivity and specificity were 93.0% and 99.1%, respectively. The frequency of neurological complications including minor deficits was 4.2% ($n=115$), of which 0.37% ($n=10$) were permanent. Analysis of the single IONM modalities varied between 13 and 81% to detect neurological complications compared with 93% when using all modalities.

Conclusion Multimodal IONM is more effective and accurate in assessing spinal cord and nerve root function during spine surgeries to reduce both neurological complications and false-negative findings compared to unimodal monitoring. We recommend multimodal IONM in all complex spine surgeries.

Graphical abstract These slides can be retrieved from Electronic Supplementary Material.







Keywords Spine surgery · Intraoperative neuromonitoring · Sensitivity · Specificity · Complications

Introduction

Intraoperative neurophysiological monitoring (IONM) of the central and peripheral nervous system during spine surgery indicates the online functional integrity of the spinal

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-018-5861-0) contains supplementary material, which is available to authorized users.

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cord and nerve roots, which helps to guide the operative technique and reduce associated neurological complications [1]. Unimodal monitoring methods involving somatosensory or motor evoked potentials (SSEP/MEP) have been used, yet with limitations [2]. A novel proposal was presented [3] for a standardised multimodal IONM of the descending and ascending spinal cord and nerve root pathways.

The application of IONM is routine in several spine centres, yet its specificity and sensitivity as well as the clinical experience and outcome measurements associated with its use during spine surgery are not well documented [4–7]. A retrospective study confirmed the efficacy of multimodal intraoperative monitoring (MIOM) using SSEP, descending neurogenic evoked potentials, neurogenic MEP and electromyography in 12,375 spine interventions [8]. Further analysis of this cohort revealed 45 (0.36%) false-negative (FN) cases with the highest incidence (0.170%) resulting from monitoring nerve root function with continuous EMG [9]. The technique used to monitor spinal cord function was more efficacious (0.032% FNs), and there were no FNs with transcranial electrical MEP (tceMEP) monitoring.

IONM proves useful in the preservation of neurological function where an alteration in surgical approach is required to optimise the outcome of more complex spine surgery [10]. Furthermore, there is strong evidence that IONM is sensitive and specific for detecting intraoperative neurological injury [11]. There is a need to develop prospectively validated evidence-based protocols to deal with intraoperative changes in IONM [11] and establish a standard of care (SOC) [12]. An analysis of 3436 paediatric spinal deformity surgeries revealed that IONM accurately indicated the permanent neurological status in 99.6% of all cases; the total number of transient and permanent neurological injuries was 0.17% [13]. Zuccaro et al. [14] performed a quantitative analysis of 806 patients surgically treated for scoliosis; true-positive alerts for tceMEP were observed in 60 (7.4%) and only 7 (0.9%) alerts for SEP. The authors suggest that IONM be considered the SOC during high-risk paediatric spinal deformity surgery.

A recent comparison of uni- and multimodal IONM of motor function was made in a multicentre surgeon survey study [15]. The best combination for monitoring motor tract function was MEP with muscle and spinal D-waves, which had the lowest false-positive (6.1%) and FN (0.2%) rates [16, 17].

As part of an ongoing prospective study [3] using standardised multimodal IONM procedures in our clinic, the aims were to define the predictive value of different unique and combined monitoring modalities in assessing all neural function and determine the impact of different modalities on the frequency of motor and sensory deficits, neuropathic pain as well as bladder and anal sphincter complications reported during complex spine surgeries.

Materials and methods

The protocol and patient population during the initial part of this ongoing study have been previously described [3, 16]. The same protocol was used to include additional patients for the second part of this prospective study spanning January 2006 to June 2011. IONM monitoring details have also been described previously [3]; the placement of stimulating and recording electrodes and extension cables was carried out during the induction of anaesthesia. IONM prolonged the pre-surgical procedure by an average of 5–15 min, depending on whether a spinal electrode required insertion by lumbar puncture for monitoring the spinal cord at the onset of surgery.

From a total of 14,177 patients who underwent spine surgery at our institution between March 2000 and June 2011, 2728 (19.2%) patients were monitored using IONM techniques and included in this study. Patients were selected after both surgeon and neurologist considered the underlying pathology and potential risk of confronting neural structures due to the foreseen operation. We did not have a pre-defined list of indications for monitoring, and all decisions were made upon considering each case individually with our team's expertise; the final decision was then made by the spine surgeon. All patients underwent pre-operative examination by the surgical spine team, which included additional neurological and electrophysiological tests. We used the neurophysiological baseline testing as a starting reference point, and this had no influence on surgical procedure. Post-surgery, patients were examined by the neurologist and/or spine surgeon to assess the presence of any new neurological deficits or document the immediate post-operative neurological status.

The patient population comprised 1641 females and 1087 males with an average age of 55 years (range 0.6–93 years). All surgical interventions were performed by experienced, consultant spine surgeons. The main diagnoses were (in decreasing order of frequency): lumbar spinal stenosis with or without instability; cervical or thoracic spinal stenosis; deformities such as scoliosis and kyphosis; and tumours of the spinal cord, spine and sacrum (Table 1).

Anaesthesia protocol

Complete intravenous anaesthesia was accomplished using propofol or ketamine in combination with short-acting opioids as previously described [3]. Muscle relaxants were only used for intubation. The same protocol was used for all patients in order to avoid substances that would significantly alter or abolish evoked potentials [18].

Table 1 Frequency of clinical diagnoses in all 2728 monitored cases during 12 years

Diagnosis	Frequency	Percentage
Lumbar spinal stenosis with or without instability	1106	40.5
Cervical/thoracic spinal stenosis	656	24.0
Deformities	720	26.4
Tumours	246	9.0
Total	2728	100.0

Including 1017 patients derived from the 2000–2005 database published in (blinded for review) Sutter et al. [16]

Method and principles of IONM

All monitoring was performed by two experienced neurologists with 10 years of clinical experience in neurophysiology at the study onset. Neural structures to be stimulated and recording sites were chosen in accordance with any anticipated neurological complication caused by the surgical site/procedure. Monitoring was always done on both sides with simultaneous recording on the right and left sides of the proximal and distal sites of risk in order to distinguish systemic changes (e.g. anaesthesia, perfusion or temperature) from direct surgery-related changes.

Spino-spinal evoked potentials (ssEP) with spinal cord stimulation and spinal cord recording (also known as spinal cord evoked potentials, SCEP) were used in our clinic for the most challenging surgical cases involving intramedullary tumours and severe spine deformities with pre-operatively existing relevant spinal cord deficits. As SCEP represents dorsal tract rather than corticospinal tract motor information, we recorded SCEP only in cases where we wanted to have direct input control of cerebro-spinal evoked potentials (csEP) with D-wave recording proximal to the surgical site. In these complex cases, we also recorded neuro-spinal evoked potentials (nsEP) (peripheral nerve stimulation with ascending spinal dorsal tract recording caudal (control) and rostral (diagnostic trace) of the surgical site) as well as spino-muscular evoked potentials (smEP) with proximal (diagnostic) spinal cord stimulation, and cerebro-muscular evoked potentials (cmEP) with distal (control) stimulation (i.e. tceMEP with muscle recording).

For all surgeries completed from January 2004 that involved the placement of pedicle screws, threshold values were routinely determined; if values fell below 5 mA, the surgeon checked the screw position. Based on initial data [3], MEP and EMG monitoring were routinely made for the evaluation of C5 nerve root function (deltoid muscle) and during surgical procedures at the thoraco-lumbar junction for T11–L2 (rectus abdominis and transversus abdominis muscles) and L2–L3 nerve root (pectineus muscle). Any relevant change in single monitoring parameters indicating potential neurological injury was defined as a monitoring alert [3].

For true-positive (TP) and true-negative (TN) cases, IONM correctly identified the presence and absence of a neurological complication, respectively. For false-positive (FP) cases, IONM incorrectly predicted the presence of a neurological complication, while for a FN, IONM was unable to identify a neurological complication.

Neurological complication ("injury") definition

A neurological complication was defined as any new neurological symptom and/or sign or worsening of a pre-existing

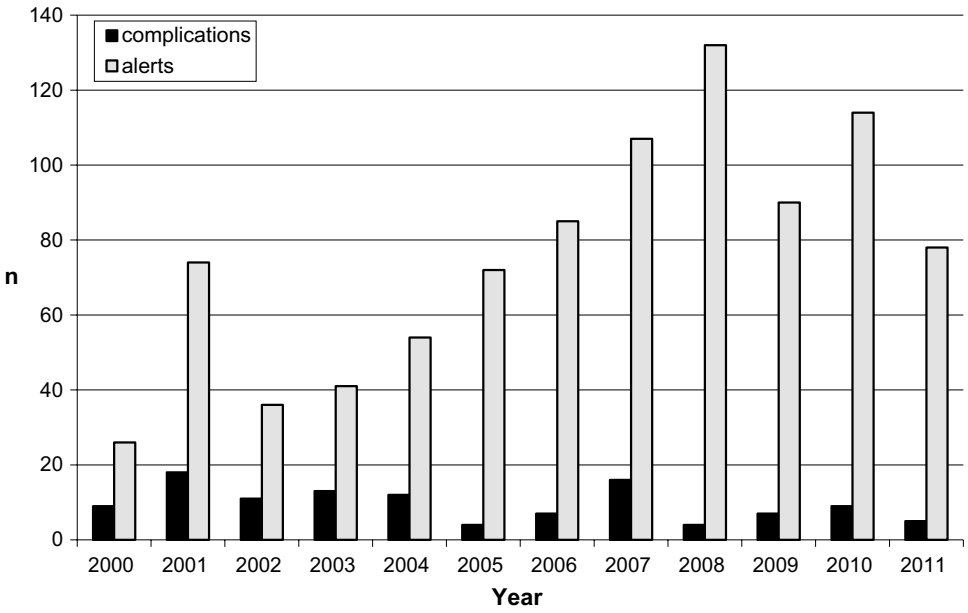
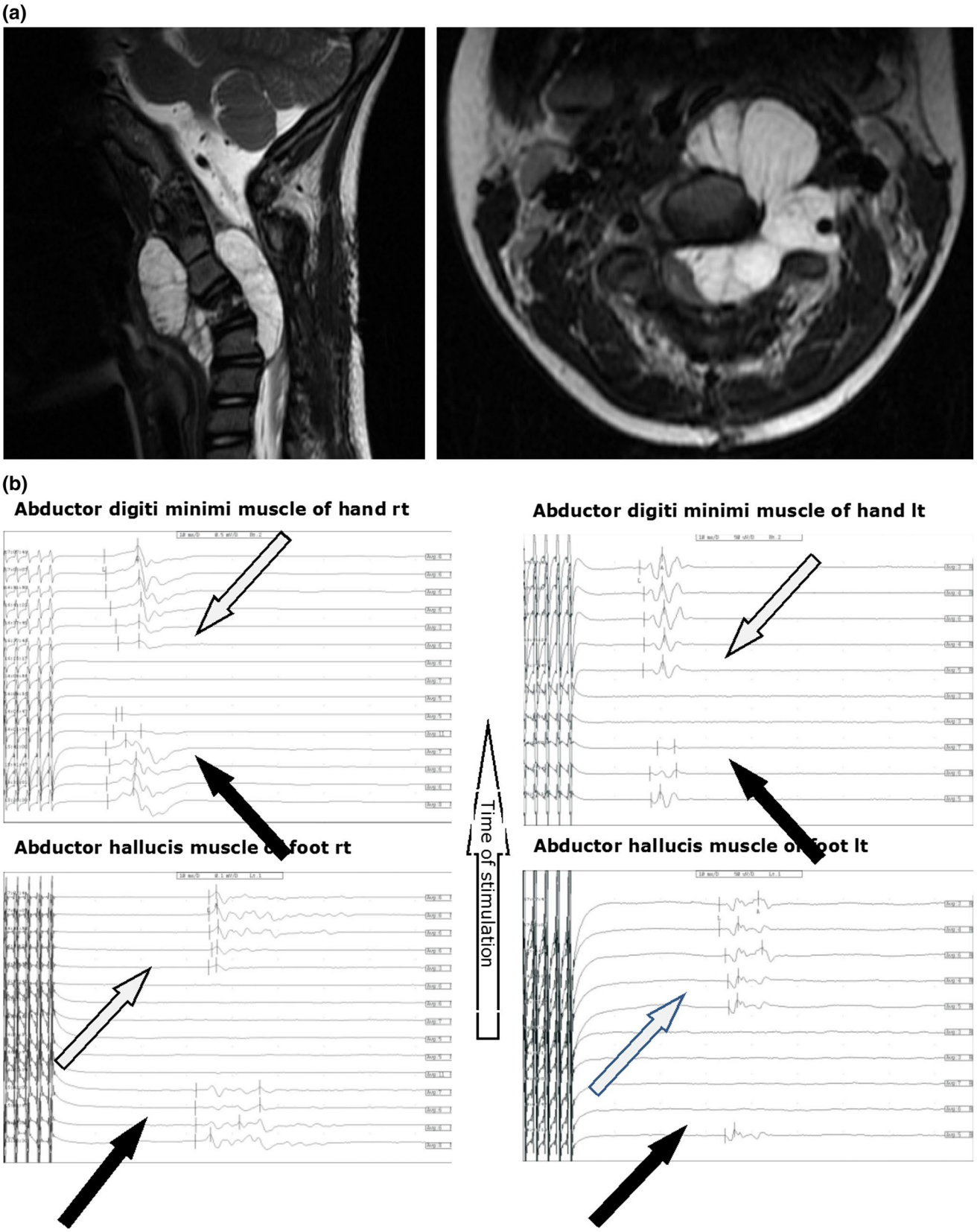


Fig. 1 Monitoring alerts ($n = 909$) and post-operative neurological complications ($n = 115$) per year out of 2728 monitored cases over the 12-year period


(a)
(b)
Abductor digiti minimi muscle of hand rt
Abductor digiti minimi muscle of hand lt
Abductor hallucis muscle of foot rt
Abductor hallucis muscle of foot lt
Time of stimulation

◂**Fig. 2** **a** Sagittal and axial MRI (T2) of the cervical spine showing a C2–4 chordoma causing incomplete tetraparesis. In a first step, dorsal stabilisation of C1–5 was performed with the aid of IONM, where normal evoked potentials were recorded. Ventral access was subsequently performed for the tumour removal step. **b** Neuromonitoring output graphs show the complete loss of cerebro-muscular evoked potentials (cmEP) of the abductor digiti minimi (upper left and right) and abductor hallucis muscles (lower left and right) as indicated by the black arrows, which occurred within 5 min after the ventral opening was made. We decided to carry out an emergency revision of the dorsal surgical site; arterial bleeding was found compressing the spinal cord and could be stopped. Grey arrows indicate the return of cmEP within a few minutes after the bleeding was stopped. Ventral removal of the entire tumour could be successfully completed 4 days later, which was followed by proton irradiation therapy. The child survived without neurological deficits and is now 17 years old and relapse-free

symptom and/or sign, which occurred immediately after the operation and was either of a transient or permanent nature. The final clinical evaluation was made by the neurologist. Neurological injuries were classified as: mild (i.e. mild motor or sensory deficit still allowing functional independence); moderate (i.e. limitation of function allowing independence only with external aid); and severe (i.e. limited function with complete dependence).

Results

The average time for IONM was 5 h and 5 min per patient, which included an average of 45 min for calibrating baseline data and 15 min for electrode removal. An average of 15 min was also required for case preparation and data analysis. The shortest monitoring time was 60 min for a simple decompression and dorsal stabilisation at the L2/3 level; 20 h and 30 min (longest duration) was required for monitoring the total resection of a chordoma spreading from C3 to the clivus followed by 360° stabilisation of the occiput to C5.

On average, 18 different monitoring tests (sum of different stimulation and recording sites) were applied per patient with a minimum of 1, maximum of 70 and a mean of 12 different tests carried out for the study cohort [3].

Monitoring alerts and neurological complications ("injuries")

The surgeon was alerted based on the negative alteration of IONM results and, after discussion with the responsible neurologist, adapted the surgical procedure for most of the 909 (33.3%) of the 2728 interventions (Fig. 1). In principle, we discussed all relevant signal changes (i.e. 50% or greater reduction in amplitude; 20% or greater increase in latency of diagnostic traces compared with proximal input control) as well as prolonged EMG discharges. For pedicle screw surgery, each pedicle with a threshold value of less than or equal to 5 mA from stimulation drill, pedicle finder or final pedicle stimulation feedback was counted as a single alert. Figures 2 and 3 demonstrate the value of IONM and its impact on surgical procedure in two specific cases of a 7-year-old boy with a known C2–4 chordoma causing incomplete tetraparesis and a 39-year-old female with isthmic dysplastic spondylolisthesis L5/S1 grade II–III after Meyerding, respectively.

A total of 115 (4.2%) neurological complications were observed within the immediate post-operative period; the majority were described as minor and transient events. Only 10 patients (0.37%) presented with a permanent neurological deficit (Table 2). None of the patients sustained a severe neurological complication such as incomplete or complete paraplegia.

IONM specificity, sensitivity, and positive and negative predictive values

We documented 2590 TNs (95.0%), 8 FNs (0.3%), 107 TPs (3.9%) and 23 FPs (0.84%) after comparing pre- to post-operative clinical neurological status for all patients. Of the FN cases, the neuromonitoring procedure did not predict the occurrence of a neurological deficit in 1 patient who suffered permanent (radicular) deficits and in 7 who recovered within less than 3 months (Table 3).

Although the 107 TP cases included some serious pathologies such as tumours, deformities and myelopathies, post-operative neurological deterioration was considered minor and mostly involved monosegmental motor and/or sensory radicular deficits/pain.

Multimodal IONM sensitivity in our 2728 examinations including all 8 FN cases was 93%; when only the single FN case with permanent radicular deficit was included in the calculation, sensitivity increased to 99.2%. Specificity, including all 23 FPs, was 99.1%. Positive and negative predictive values were 82.3% and 99.7%, respectively.

Impact of multimodal and unimodal techniques on the occurrence of neurological complications

Analysis of the various unimodal monitoring methods revealed that continuous EMG alone alerted 15% of all intraoperative TP neurological complications, SSEP with cortical potentials (neuro-cortical EP [ncEP]) alone 40% and tceMEP with multiple muscle recording (cmEP) alone 81%; the combination of ncEP and cmEP methods detected 89% of the complications and additional methods involving spinal recording and stimulation, up to 93% (Table 4 and Fig. 4). Our cohort has shown little (and late) diagnostic impact of spino-spinal evoked potentials (ssEP) in identifying surgery-related spinal cord dysfunction and injuries. In addition, we

show higher impact of ncEP (cortical SEP) compared with ssEP in identifying dorsal tract injury.

Discussion

The main reasons for implementing neuromonitoring methods during complex spine surgery are to allow the surgeon to work in an optimal manner and reduce neurological complications as well as improve surgical outcome when structural adaptations are required. IONM also helps the surgeon gather experience on the limits of mechanical irritations from surgical manipulations which could lead to neurological damage. In our clinic, multimodal IONM has a sensitivity of 93% and specificity of 99% with a 0.3% incidence of FN. Based on IONM alerts, our surgeons were able to adapt close to a third of all surgeries, and compared to unimodal options, multimodal IONM increases the detection of neurological complications, most of which were considered minor and transient.

Fehlings et al. [11] presented a theoretical model for prospectively comparing different spine pathologies treated surgically in a controlled manner, with and without IONM, to assess the impact on complication rate. However, based on our neuromonitoring knowledge [3, 16] and consensus recommendations for MIOM during spine surgery advocated by an experienced expert group [19], the proposed approach appears ethically infeasible. A recent systematic literature

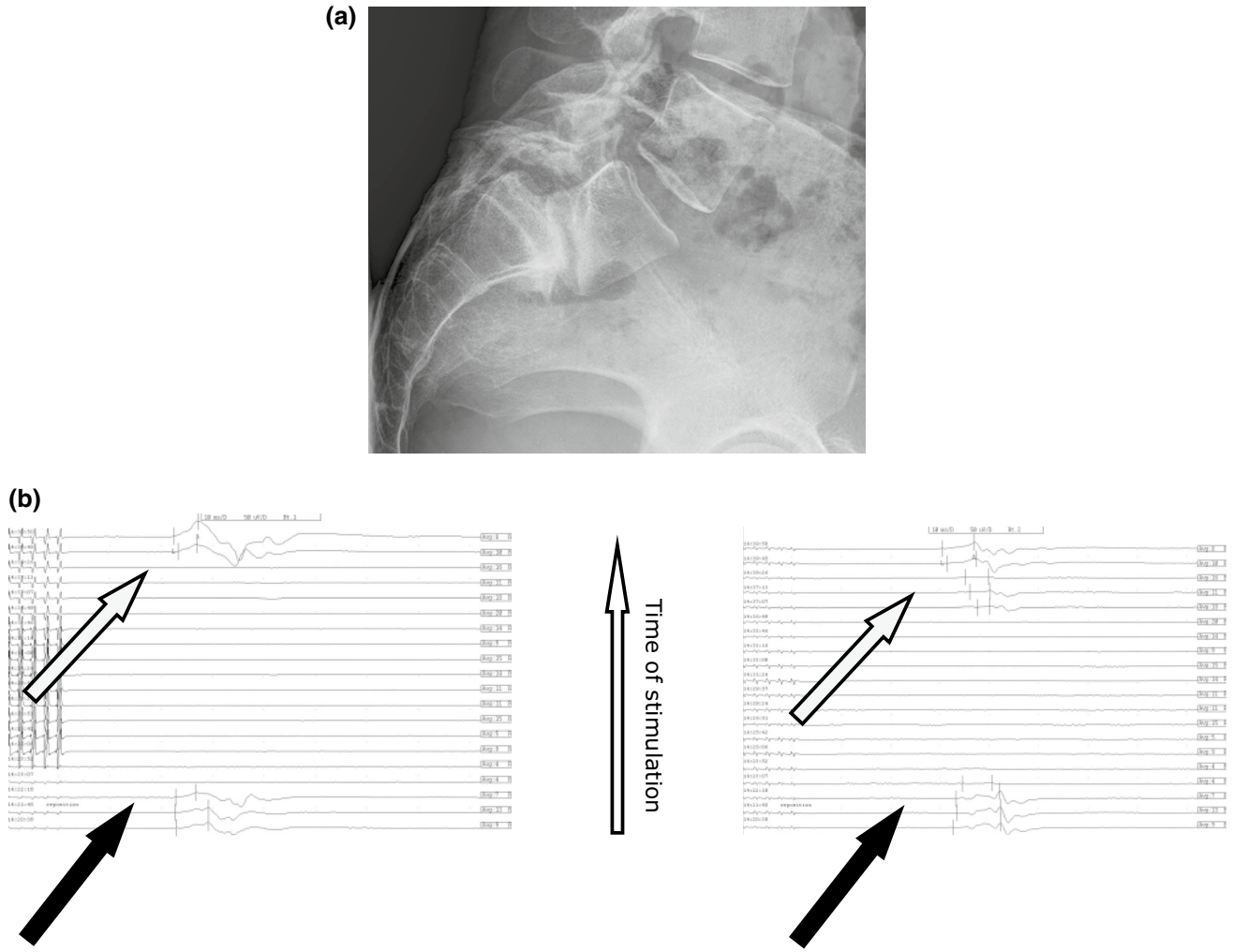


Fig. 3 **a** Lateral radiograph of the lumbar spine showing isthmic dysplastic spondylolisthesis L5/S1 grade II–III after Meyerding. The patient underwent reduction and instrumented L5/S1 fusion. **b** IONM revealed a loss of motor evoked potentials (MEP) to the tibialis anterior muscle (left) and abductor hallucis right muscle (right) during repositioning as indicated by the black arrows. Subsequently, the reduction was released and an extended decompression for the nerve roots L5 and S1 on the right was performed, which resulted in MEP recovery (grey arrows). A second reduction attempt was performed thereafter, and MEP remained stable. No new post-operative neurological deficits were recorded

Table 2 Detailed description of the ten patients with permanent neurological deficits

Patient	Region	Pathology	Surgery	OP time	IOM modalities	IOM baseline	IOM changes	Neurological deterioration	Time course
f, 14y	L4–S1	Ptosis L5/S1	Dorso-ventro-dorsal decompression, partial correction and fusion	9 h	$cm_{TA,AH}EP$ $s_{edT10}m_{TA,AH}EP$ $cs_{edT10}EP$ $n_{PN,TN}sEP$ $n_{PN,TN}cEP$	All potentials normal	Loss of $cm_{Tal}EP$ and $n_{PNl}cEP$ with reposition	Radiculopathy L5 lt (M2/5)	Partial recovery L5 (M3/5) within 1.5y
m, 42y	L5–S1	Spondylolytic spondylolisthesis 2°	Dorso-ventral decompression and fusion: injury of common iliac vein and lumbar plexus	7 h	$cm_{TA,AH}EP$ $s_{edL3}m_{TA,AH}EP$ $n_{PN}sEP$	All potentials normal	Loss of cm/ncEP left leg	Radiculopathy L5 and S1 lt (M3/5)	Full recovery of neurological deficits left leg within 2 mo; persistent retrograde ejaculation
f, 56y	L4–L5	Pseudarthrosis L4/5; previous discectomy and translaminar fusion L4–S1	Revision surgery with dorsal decompression and fusion	3.8 h	$cm_{VM,TA,AH}EP$ $sm_{VM,TA,AH}EP$ ped.screw stimulation $n_{PN}cEP$	Pathological cm/ncEP	Alteration of $cm_{TA,AHr}EP$ and $n_{PNr}cEP$ during pedicular screwing L5rt, threshold value 2 mA.	Radiculopathy L5 rt (M3/5)	Full recovery of motor deficits within 3mo; persistent neuropathic pain
m, 11y	T3–L5	Deformity, arthrogryposis multiplex congenita	Intended dorsal correction stopped after pedicular screwing	2,5 h	$cm_{VM,TA}EP$ $sm_{VM,TA}EP$ (ped.screws) $EMG_{VM,TA}$, $n_{PN}cEP$	Small amplitudes, otherwise normal EP	Rapid loss of all EP with intractable bleeding	Disseminated intravascular coagulation, cardiac arrest	Unsuccessful reanimation
f, 61y	L4–S1	Ptosis L5/S1 with secondary fracture and dislocation after in situ fixation 47y earlier	Dorsal decompression, correction and fusion	12.8 h	$cm_{P,VM,TA,AH}EP$ $sm_{P,VM,TA,AH}EP$ Ped.scr.threshold values $EMG_{P,VM,TA,AH}$ $n_{PN,TN}cEP$	All potentials normal	None	Radiculopathy L5 and S1 lt (M2/5)	No recovery
F, 74y	L2–L3	Recurrent ependymoma conus-cauda after primary operation 6y earlier	Subtotal tumour resection	5.8 h	$cm_{P,VM,TA,AH,SA}EP$ $sm_{P,VM,TA,AH,SA}EP$ $EMG_{P,VM,TA,AH,SA}$ $cs_{L1}EP$ $rmEP_{VM,TA,AH,SA}$ $n_{PudN,TNPN,SAphN}sEP$ $n_{PudN,TNPN,SAphN}cEP$, BAR	Slightly pathological EP's below L5 on both sides	After tumour resection, alteration of c/sm_{SA} EP left, $n_{PudN}s/cEP$, loss BARs: resection therefore incomplete (2 mm)	Radiculopathy S1–S5 left sensory deficit, urinary and bowel continence preserved	No recovery
f, 58y	T2	Cavernous hemangioma with chronic osteomyelitis	En bloc dorsal tumour vertebrectomy	5.8 h	$cm_{ADM,TA}EP$ $cs_{edT4}EP$ $sm_{TA}EP$ $EMG_{ADM,TA}$ $n_{UN,TN}cEP$ $n_{TN}sEP$	All potentials normal	Loss of $cm_{TA}/csEP$ with caudal columnotomy	Anterior spinal artery syndrome	

Table 2 (continued)

Patient	Region	Pathology	Surgery	OP time	IOM modalities	IOM baseline	IOM changes	Neurological deterioration	Time course
f, 76y	L3 to right lumbar plexus	Non-Hodgkin lymphoma	Complete tumour resection	5 h	$cm_{P,VM,TA,AH}EP$ $sm_{P,VM,TA,AH}EP$ $rm_{P,VM,TA,AH}EP$ in situ stim $EMG_{P,VM,TA,AH}$ $n_{PN}cEP$	Pathological EP rt	Alteration of cm/$sm_{VM,TA}EP$ with mobilisation and complete resection	Radiculopathy L3rt (M1/5), L4rt (M3/5)	
m, 51y	T2	Ependymoma	Complete tumour resection	6 h	$cm_{BR,ADM,AH}EP$, $cs_{edT5}EP$, $n_{TN,UN}cEP$, $n_{TN}sT5EP$, EMG $_{BR,ADM,AH}$	nc > cm > csEP legs rt > lt impaired	With tumour resection, additional alteration of cm > csEP leg rt > lt	Incomplete paraparesis	
f, 46y	C0–C2	Post-traumatic deformity with instability, coiled giant aneurysmal vertebral artery right	Ventro-dorsal decompression and fusion intended; OP stopped during anterior approach	2.5 h	$cm_{D,ADM,TA}EP$, EMG $_{D,ADM,TA}$, $n_{TN,UN}cEP$, EEG	All potentials normal	During anterior approach, sudden loss of cm/ncEP rt	Hemiplegia right due to embolic occlusion internal carotid artery left	

cmEP cerebro-muscular evoked potentials, *csEP* cerebro-spinal evoked potentials, *nsEP* neuro-spinal evoked potentials, *ncEP* neuro-cerebral evoked potentials, *smEP* spino-muscular evoked potentials, *ssEP* spino-spinal evoked potentials, *BAR* bulbo-anal reflex

review and meta-analysis, including mainly case–control/comparative cohort studies, highlights the trend of fewer neurological events in IONM patients [20]; only 6 studies met the inclusion criteria whereby selection bias and statistical heterogeneity were apparent. The authors state that the role of IONM remains unclear and that it is imperative to conduct randomised controlled trials to clarify the impact of IONM on spine surgery complications as well as the indications for its application [20]; this is in line with Fehlings et al. [11].

Our clinic routinely implemented MIOM from 2000 after several years of developmental work as well as influence from the groups of Tamaki [21, 22] and Deletis [2, 23, 24]. It was our strategy to use board-certified neurologists with additional specialisation in neurophysiology. These specialists actively contribute to the development of IONM by providing data for internal quality control of the surgical procedures as well as scientific evidence to promote these procedures as the SOC, a concept initially proposed by Dormans [12].

Our original IONM analysis achieved a sensitivity of 89% and specificity of 99% [16]. Our broad definition of neurological complication or injury accounted for the comparatively large number of TP as well as FN findings in the earlier study and a lower degree of sensitivity. After 12 years of monitoring, IONM sensitivity increased to 99% when considering only 1 clinically relevant FN with permanent radicular deficit: This 62-year-old female with complete L5 spondyloptosis and severe pain since a surgical procedure 47 years ago underwent surgical repositioning and fusion; she was extremely satisfied with post-operative pain and function, but developed a permanent foot drop albeit well tolerated. We believe the L5 nerve root lesion was a late onset of nerve root ischaemia, which explains why no signal changes were detected despite selectively assessing L4, L5 and S1 nerve roots [25].

Our study neurologists acquired 14,577 h in total of hands-on IONM experience, which has allowed for a greater understanding of the surgical procedures and underlying pathologies. The experience gained in the post-operative follow-ups and knowledge of the neurophysiological results obtained during monitoring has also allowed for the development of a mutual confidence between surgeon and neurologist when monitoring alerts arise. Based on our entire cohort, we can state with a clear conscience that no single severe neurological complication was missed, despite some extremely serious pathologies including chordoma of the craniocervical junction, severe deformities and intramedullary tumours. This can be attributed not only to the skill and experience of our surgeons, but also to the improvement of the surgical procedures by continuous functional surveillance of the nervous system using IONM.

Table 3 Detailed description of all false-negative IONM events with post-operative neurological deterioration ($n = 8$)

Patient	Region	Pathology	Surgery	OP time	IOM modalities	IOM baseline	IOM changes	Neurological deterioration	Duration	Recovery
f, 61y	L4–S1	Ptosis L5/S1 with secondary fracture and dislocation after in situ fixation 47y earlier	Dorsal decompression, correction and fusion	12.8 h	$cm_{P,VM,TA,AH}EP$ $sm_{P,VM,TA,AH}EP$ Ped.scr.threshold values $EMG_{P,VM,TA,AH}$ $n_{PN,TN}cEP$	All potentials normal	None	Radiculopathy L5 and S1 lt (M2/5)	Persistent; normal ADL with foot drop brace	None
f, 40y	T10–L5	Adult scoliosis	Dorsal correction and fusion	5 h	$cm_{ADM,P,VM,PL}EP$ $sm_{P,VM,PL}EP$ Ped.scr.threshold values $EMG_{ADM,P,VM,PL}$ $n_{PN,UN}cEP$, EEG	All potentials normal	None	Sensory deficit L3 lt	4 weeks	Complete
f, 18	T5–L3	Idiopathic scoliosis	Dorsal correction and fusion	5 h	$cm_{ADM,P,VM,TA}EP$ $sm_{P,VM,TA}EP$ Ped.scr.threshold values $EMG_{ADM,P,VM,TA}$ $n_{PN,UN}cEP$ EEG	All potentials normal	Threshold value ped.scr.T6r: 6 mA: medial pedicle wall perforated, screw not inserted	Sensory deficit L1 lt	3 months	Complete
f, 70y	C5–C7	Spondylotic cervical myelopathy	Dorsal decompression	3.3 h	$cs_{T1}EP$ $cm_{ADM,,AH}EP$ $n_{MN}cEP$ $EMG_{ADM,AH}$	All potentials available, but pathologic	None	Radiculopathy C5 lt	1 week	Complete
m, 39y	T9–L2	Achondroplasia; multisegmental stenosis and kyphosis	Dorsal laminectomy T9–L1, osteotomy, correction and fusion	11.8 h	$cs_{T7,L1}EP$ $cm_{VM,TA}EP$ $s_{L1}s_{T7}EP$ $n_{TN}cEP$ $ns_{T7}EP$ $sm_{VM,TA}EP$ $EMG_{VM,TA}$	All potentials available, but pathologic	None	Radiculopathy L2, L3 lt	3 months	Complete
f, 51y	L5–S1	Pseudarthrosis (5th OP)	Dorsal decompression and fusion	2.3 h	$cm_{TA,AH}EP$ $n_{TN}cEP$	All potentials available, but pathologic	None	Weakness foot extension	3 months	Complete
f, 62y	L1	Mammary carcinoma, metastasis, fracture	Dorsal vertebrectomy, fusion and vertebroplasty	5 h	$cm_{Pect.,VM,TA}EP$ $EMG_{P,VM,TA}$ $n_{PN}cEP$	All potentials available, but pathologic	None	Sensory deficit L2	1 week	Complete
m, 72y	L2–L5	Degenerative stenosis and instability	Dorsal decompression and fusion	4.5 h	$cm_{VM,TA,AH}EP$ $s_{L2}m_{VM,TA,AH}EP$ $n_{PN}cEP$ $EMG_{VM,TA,AH}$	cmEP right not available, other potentials severely pathologic	None	Urinary and bowel incontinence	3 months	Complete

cmEP cerebro-muscular evoked potentials, *csEP* cerebro-spinal evoked potentials, *nsEP* neuro-spinal evoked potentials, *ncEP* neuro-cerebral evoked potentials, *smEP* spino-muscular evoked potentials, *ssEP* spino-spinal evoked potentials

Table 4 Value of uni- and multimodal IONM techniques in detecting neurological complications ranked from lowest to highest sensitivity (bold and italicised values)

	Intraoperative monitoring techniques									
	EMG	ssEP	smEP	ncEP	csEP	nsEP	cmEP	cm/ncEP	cm/cs/ncEP	All
True positive	15	3	9	44	24	10	93	102	105	107
True negative	2506	46	1397	2604	353	270	2582	2593	2593	2590
False positive	6	0	2	9	2	2	18	20	20	23
False negative	87	6	17	66	25	22	22	13	10	8
Number of applied tests	2614	55	1425	2723	404	304	2715	2728	2728	2728
Sensitivity (%)	***14.7***	***15.0***	***34.6***	***40.0***	***49.0***	***80.9***	***80.9***	***88.7***	***91.3***	***93.0***
Specificity (%)	99.8	100.0	99.9	99.7	99.4	99.3	99.3	99.2	99.2	99.1
Positive predictive value (%)	71.4	100.0	81.8	83.0	92.3	97.9	83.8	83.6	84.0	82.3
Negative predictive value (%)	28.6	73.0	98.8	97.6	93.4	92.5	99.2	99.5	99.6	99.7

EMG electromyography, *ssEP* spino-spinal evoked potentials, *smEP* spino-muscular evoked potentials, *ncEP* neuro-cerebral evoked potentials, *csEP* cerebro-spinal evoked potentials, *nsEP* neuro-spinal evoked potentials, *cmEP* cerebro-muscular evoked potentials

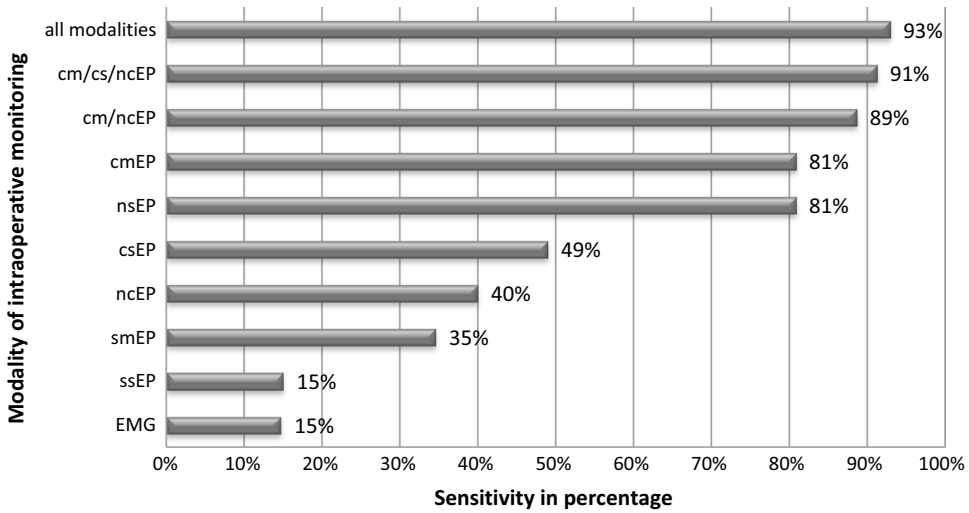


Fig. 4 Sensitivity of uni- and multimodal intraoperative monitoring methods in detecting neurological complications from the lowest (EMG) to highest sensitivity (all modalities). *cmEP* cerebro-muscular evoked potentials, *csEP* cerebro-spinal evoked potentials, *nsEP* neuro-spinal evoked potentials, *ncEP* neuro-cerebral evoked potentials, *smEP* spino-muscular evoked potentials, *ssEP* spino-spinal evoked potentials

We agree with the conclusion from a large analysis of pooled data combined with a literature review that the use of IONM should be considered a SOC during complex spine surgery [10]. Our sensitivity, specificity and predictive values clearly indicate that monitoring using unimodal recording has low sensitivity and could be a reason for FN in complex spine procedures. Triggered EMG may be useful in the placement of pedicle screws only.

To date, only one comprehensive study has focused on analysing common high-risk spine surgical manoeuvres for impending TP neurological alerts using IONM [25]. Of 3139 patients with severe pathologies, 62 TP alerts were detected without any FN. Monitoring alerts occurred more often with the following techniques: thoracic screw placement (16.1%); osteotomy (35.5%); deformity correction (30.6%); and spinal decompression (17.8%). Based on their work, Wang et al. [26] recommend the necessity of a team comprising experienced IONM experts with detailed knowledge of the surgical procedures and skilled members of surgery and anaesthesiology. The anaesthesiologist has a crucial role in reducing FP alerts by, in particular, adapting the medication and controlling blood pressure. They also advocate the role of an intraoperative adapted response to IONM alerts upon which the surgeon must pay close attention, in order to address these alerts with utmost expertise and timeliness for the benefit of the patient. We fully endorse this concept based on our observations.

We analysed the value and sensitivity of single- and multimodal monitoring in order to highlight the message that spine surgeons need to be aware of and know what to expect from the different techniques and the specialists operating the system. We determined the overall accuracy of diagnostic impact of IONM in spine surgery, which does not refer to the number of IONM procedures required to prevent

surgery-related injuries in a specific diagnostic and/or surgical procedure group. Our results show IONM as helpful in identifying and thus preventing intraoperative spinal cord and nerve root injuries independent of a designated patient group or surgical procedure. Any decision on which cases should or must be monitored requires the consideration of ethical and economic issues that are beyond the scope of this work, but must be based on accurate diagnostic power.

In conclusion, we recommend the application of multimodal IONM to reduce or even prevent neurological complication for demanding spine surgery procedures.

Acknowledgements The authors wish to thank the Dr. Lote Medicus fund for financial support in the development of IONM at the Schulthess Clinic as well as Dave O'Riordan for manuscript preparation and Melissa Wilhelmi, Ph.D., and Anne Mannion, Ph.D., for their critical review of the manuscript.

Compliance with ethical standards

Conflict of interest All support for this research was provided by Schulthess Clinic. On behalf of all authors, the corresponding author states that there is no conflict of interest. All authors also state that they have full control of all primary data and agree to allow the journal to review their data if requested.

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