Intraoperative Neuromonitoring in Patients with Intradural Extramedullary Spinal Cord Tumor: A Single-Center Case Series

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■ BACKGROUND: **Intradural extramedullary spinal cord tumors (ID-EMSCT) make up 40% of all spinal neoplasms. Resection of these tumors is mostly conducted using intraoperative neuromonitoring (IONM). However, the literature shows heterogenous data on its added value for ID-EMSCT. The aim of this study is to define sensitivity and specificity of IONM in ID-EMSCT resection and to study possible correlations between preoperative, intraoperative, and postoperative variables and neurologic outcomes after ID-EMSCT resection.**

■ METHODS: **Data of patients undergoing ID-EMSCT surgeries with IONM from January 2012 until July 2019 were examined. Using neurologic status 6 weeks and 1 year postoperatively, sensitivity and specificity for IONM were calculated. IONM test results and neurologic outcomes were paired to preoperative, intraoperative, and postoperative parameters.**

■ RESULTS: **Data of 78 patients were analyzed. 6 weeks postoperatively, 14.10% of patients had worse neurologic status, decreasing to 9.84% 1 year postoperatively. Multimodal IONM showed a sensitivity of 0.73 (95% confidence interval [CI], 0.39–0.94) and a specificity of 0.78 (95% CI, 0.66–0.87) after 6 weeks, and a sensitivity of 1.00 (95% CI, 0.54–1.00) and a specificity of 0.71 (95% CI, 0.57–0.82) after 1 year.**

■ CONCLUSIONS: **IONM yielded high to perfect sensitivity and high specificity. However, IONM signals did not always determine the extent of resection, and false-positive results did not always result in incomplete tumor resections, because of surgeons overruling IONM. Therefore, IONM cannot fully replace clinical judgment and other perioperative information.**

INTRODUCTION

Primary spinal cord tumors make up as much as 10% of all central nervous system neoplasms.[1] Of these tumors, 5% are intramedullary spinal cord tumors (IMSCTs), and 95% are extramedullary spinal cord tumors (EMSCTs). EMSCTs can be divided into extradural (55% of spinal neoplasms) and intradural (ID) extramedullary (40% of spinal neoplasms).[2] In the United States, the incidence of primary spinal cord tumors is 0.74 cases per 100,000 person-years, of which 69% are nonmalignant.[3] Both types of EMSCT can present with a wide variety of symptoms in patients. Lesions generally cause back pain and radicular pain as a result of compression of the spinal cord and/or radices.[4,5] Patients with primary spinal tumors often experience a long diagnostic delay, with the median time to diagnosis being 12.3 months.[1,6] Therapies vary from radiation therapy to surgical resection to prevent neurologic deterioration.

In 1887, Sir Victor Horsley performed the first operation to remove a spinal ID tumor that had caused cord compression.[7]

Key words
- Extramedullary tumor
- IONM
- Neurologic function
- Neuromonitoring
- Neurosurgery
- Spinal cord tumor

Abbreviations and Acronyms
EMSCT: Extramedullary spinal cord tumor
FN: False negative
FP: False positive
ID: Intradural
IMSCT: Intramedullary spinal cord tumor
IONM: Intraoperative neuromonitoring
MEP: Motor evoked potentials
mIONM: Multimodal intraoperative neuromonitoring
mMCS: modified McCormick Scale
MRI: Magnetic resonance imaging
SEP: Somatosensory evoked potentials
TN: True negative
TP: True positive

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However, this type of surgery can cause neurologic complications as a result of damage of functional tissues.[8] To reduce the risk of those complications, intraoperative neuromonitoring (IONM) was introduced by Tamaki and Yamane in 1975.[9] Since then, surgery and neuromonitoring have continuously been improved and different monitoring modalities are used.[10-12] IONM is now widely used, but the literature on its added value shows heterogenous results. Most research focuses on cohorts of various kinds of spinal tumors instead of solely ID-EMSCT. Two studies in 2014[13] and 2018[14] presented research on sensitivity and specificity of IONM with subgroup analyses for ID extramedullary tumors, but they had small sample sizes of 25 and 21 cases, respectively. Recently Ishida et al.[15] considered diagnostic and therapeutic values of intraoperative electrophysiologic neuromonitoring during resection of ID extramedullary spinal tumors, but with only 6 months follow-up time, and no information on the influence of IONM signals on the extent of resection. On the contrary, Safaee et al.[16] did not study sensitivity and specificity but did find that using IONM compared with not using it for spinal nerve sheath tumors did not result in fewer postoperative complications. However, according to that study, the use of IONM did result in a higher rate of gross total resections.

In our previous study,[17] we reported on our IMSCT resection series, in which the use of IONM showed high but not perfect sensitivity and specificity. Because of the different nature of EMSCTs and IMSCTs, we believe that there is also a need to define sensitivity and specificity of IONM in ID-EMSCT resection.

Furthermore, it may be useful to relate IONM test results to the extent of resection in this type of surgery. IONM results can be true negative (TN), false positive (FP), false negative (FN), or true positive (TP) as defined in Table 1.

Because reduction in signal can be quantified from 0% to 100%, it is at the surgeon's discretion to choose a cutoff point from where they may or may not stop resection, with 50% signal reduction being the most common used warning criterion in practice for most neuromonitoring modalities.[18]

Because spinal cord surgery may have better long-term outcomes than shortly after the procedure because of neuronal plasticity and rehabilitation, both the short-term and long-term neurologic status should be taken into account when evaluating efficiency of IONM.

The primary outcome of this study is sensitivity and specificity for IONM in ID-EMSCT resection. Secondary outcomes are correlations between preoperative, intraoperative, and postoperative variables and neurologic outcomes, after ID-EMSCT resection.

METHODS

This study was approved by our hospital's ethical committee (MEC-2019-0462).

Because data were collected retrospectively and no extra patient interventions were performed for the purpose of this study, informed consent from participants was not required.

Inclusion and Exclusion Criteria

Clinical and neurophysiologic records of patients undergoing spinal surgery with the use of IONM from January 2012 until July 2019 in our hospital were examined. All patients undergoing surgery for ID-EMSCT resection with IONM were included. Lesions were considered ID extramedullary if they were freely moveable on the surface of the spinal cord, with no ingrowth. All patients were subject to multimodality neuromonitoring with recording of somatosensory evoked potentials (SEP) and motor evoked potentials (MEP) during surgery. In some cases, additional neuromonitoring including direct nerve stimulation and/or D-waves and/or bulbocavernosus reflex was used. There was no age restriction. Patients undergoing a second resection on locations in which a tumor was previously resected were also included. Patients were excluded if the preoperative and/or postoperative neurologic outcomes were not documented.

Table 1. Intraoperative Neuromonitoring Outcomes

Outcome	Intraoperative Neuromonitoring Amplitude Decrease	Neurologic Outcome
True negative (TN)	Not significant	Same or better
False positive (FP)	Significant (>50%)	Same or better
False negative (FN)	Not significant	Worse
True positive (TP)	Significant (>50%)	Worse

Data Collection

Using our hospital's records, the following data were retrieved: patient's baseline characteristics, duration of the surgery, blood loss, hospital stay duration, type of tumor (as reported by pathologic analysis), location and extent of the tumor, extent of resection, neuromonitoring modalities, changes of neurophysiologic signals and preoperative and postoperative neurologic status using a modified McCormick Scale (mMCS) (Table 2). Preoperative neurologic scoring was based on the neurosurgeon's or neurologist's neurologic assessment during preoperative intake. Postoperative outcome was based on the neurosurgeon's report of the patient's neurologic examination during the first postoperative outpatient visit, scheduled 6–7 weeks after hospital discharge, and the neurologic examination during the outpatient visit after 1 year.

The extent of tumor resection was based on the surgeon's judgment and/or extracted from the surgery report. An objective overview of persistent postoperative residual tumor and possible tumor regrowth was made by analyzing magnetic resonance

Table 2. Modified McCormick Scale

Grade	
I	Intact neurologically, normal ambulation, minimal dysesthesia
II	Mild motor or sensory deficit, functional independence
III	Moderate deficit, limitation of function, independent with external aid
IV	Severe motor or sensory deficit, limited function, dependent
V	Paraplegia or quadriplegia, even with flickering movement

Table 3. Sensitivity and Specificity and Subgroup Analysis per Disease

	Sensitivity (95% CI)	Specificity (95% CI)
6 weeks		
MEP	0.64 (0.31–0.89)	0.82 (0.70–0.90)
SEP	0.45 (0.17–0.77)	0.91 (0.82–0.97)
mIONM	0.73 (0.39–0.94)	0.78 (0.66–0.87)
1 year		
MEP	1.00 (0.54–1.00)	0.77 (0.64–0.88)
SEP	0.67 (0.22–0.96)	0.87 (0.76–0.95)
mIONM	1.00 (0.54–1.00)	0.71 (0.57–0.82)
Subgroup analysis for mIONM 6 weeks		
Schwannoma (n = 33)	0.75 (0.19–0.99)	0.79 (0.60–0.92)
Meningioma (n = 17)	0.67 (0.09–0.99)	0.71 (0.42–0.92)
Others (n = 28)	0.75 (0.19–0.99)	0.79 (0.58–0.93)
Subgroup analysis for mIONM 1 year		
Schwannoma (n = 27)	1.00 (0.29–1.00)	0.75 (0.53–0.90)
Meningioma (n = 11)	1.00 (0.03–1.00)	0.50 (0.19–0.81)
Others (n = 23)	1.00 (0.16–1.00)	0.76 (0.53–0.92)

CI, confidence interval; MEP, motor evoked potentials; SEP, somatosensory evoked potentials; mIONM, multimodal intraoperative neuromonitoring.

imaging (MRI) reports made as soon as possible after surgery and 1 year after surgery. Description of a postoperative residual tumor by the radiologist was used to verify the extent of resection as judged by the neurosurgeon.

All data were anonymized after retrieval and before analysis.

Perioperative Interventions

All procedures were performed by a small, experienced team of neurosurgeons (n = 3), neurologists (n = 2), neurophysiologic technicians (n = 3), and neurologists specialized in clinical neurophysiology (n = 4). Anesthesia was standardized according to local protocols, with most procedures being attended by 2 dedicated neuroanesthesiologists. Total intravenous anesthesia was the modality of first choice and the use of volatile and other anesthetic agents that could influence electrophysiologic signals was avoided by the anesthesiologist. During surgery, several corrective measures were applied when a significant (>50%) decrease in IONM signal(s) was registered. Hypotension, if present, was corrected. The surgeon also irrigated the surgical site with warm saline and temporarily stopped resection. When signals did not improve despite these interventions, the surgeon decided whether or not to continue resection, to prevent iatrogenic damage. Where there was no clearly identifiable attachment plane between the tumor and the spinal cord, the surgeon stopped. When signal decreases randomly occurred and were not obviously caused by manipulation of the spinal cord, resection was usually continued.

Statistical Analysis

We calculated the number of TP, TN, FP, and FN results from IONM as defined in Table 1. An amplitude decrease was considered significant if the initial signal was reduced to 50% or lower at the end of the surgery. A worse neurologic outcome was defined as a higher-grade mMCS score (Table 2).

The primary outcome measures were the sensitivity and specificity of significant amplitude decreases of MEP, SEP, and multimodal IONM (mIONM) for predicting new postoperative neurologic deficits. mIONM was regarded as a combination of MEP and SEP. Secondary outcome was the correlation of extent of resection and new postoperative neurologic deficits.

Calculations of sensitivity and specificity were made using Cochrane Review Manager 5.3 version 5.3.5.[19] All other statistical analyses were made using SPSS version 25 (IBM Corp., Armonk, New York, USA).[20] All P values were calculated using either a Fisher exact test whenever possible or alternatively using a χ^2 test. For calculating rank-order correlation between variables, the Spearman coefficient was used. A P value <0.05 was considered as statistically significant.

RESULTS

A total of 82 patients underwent ID-EMSCT surgery between January 2012 and June 2019. Three patients were excluded because of incomplete IONM data and 1 patient because of loss to clinical follow-up, resulting in 78 patients meeting inclusion criteria. Of these patients, 67 (85.90%) had the same or better mMCS score after 6–weeks compared with their mMCS score before surgery, whereas 11 (14.10%) had a higher mMCS score, which means a worsening of their neurologic state compared with the preoperative evaluation. Sixty-one patients (78.21%) had data available on their neurologic status after 1 year, showing that 55 patients (90.16%) did not have a new deficit, whereas 6 (9.84%) did have worse neurologic status compared with preoperatively. MEP signals were usable in 76 cases (97.44%) and SEP signals were usable in all 78 cases. Direct nerve stimulation and bulbocavernosus reflex were used during 29 (37.18%) and 38 (48.72%) of 78 surgeries, respectively, mainly when an approach on the lumbar level was used. D-wave monitoring was used for only 5 of 78 cases (6.41%), with a thoracal or cervical level approach.

Sensitivity and specificity of MEP, SEP, and mIONM considering neurologic status after 6 weeks showed high sensitivity and even higher specificity. These results are shown in Table 3.

Considering neurologic status after 1 year, both MEP and mIONM increased to show a perfect sensitivity of 1.00. For all modalities sensitivity increased, with a slight decrease of specificity (Table 3). A subgroup analysis of specificity and sensitivity of mIONM for schwannomas, meningiomas, and other diseases yielded no major differences compared with the total group (Table 3).

Patients' baseline characteristics did not seem to have any significant correlation with neurologic outcomes, as shown in Table 4. In Table 5, perioperative and postoperative data are

Table 4. Overview Baseline Characteristics Classified for Neurologic Outcome

	No New Deficit (n = 67), n (%)	New Deficit at 6 weeks (n = 11), n (%)	*P* Value
Male sex	29 (43.3)	5 (45.5)	1.000
Female sex	37 (56.1)	6 (54.5)	1.000
Smoking	7 (10.4)	1 (9.1)	1.000
Antiplatelet medicine use	3 (4.5)	2 (18.2)	0.143
Diabetes mellitus	3 (4.5)	1 (9.1)	0.463
Radiating pain	48 (71.6)	7 (63.6)	0.723
Motor deficit	35 (52.2)	7 (63.6)	0.533
Sensible deficit	25 (37.3)	3 (27.3)	0.737
Incontinence	17 (25.4)	2 (18.2)	1.000
Age			
≤18 years	4 (6)	0 (0)	0.583
19–33 years	7 (10.4)	2 (18.2)	
34–48 years	14 (20.9)	3 (27.3)	
49–63 years	27 (40.3)	2 (18.2)	
64–78 years	13 (19.4)	3 (27.3)	
≥79 years	2 (3)	1 (9.1)	
Pain before surgery			
≤0 months	12 (22.2)	1 (12.5)	0.734122
1–3 months	4 (7.4)	0 (0)	
4–6 months	4 (7.4)	2 (25)	
7–9 months	10 (18.5)	2 (25)	
10–12 months	4 (7.4)	0 (0)	
13–18 months	5 (9.3)	1 (12.5)	
19–24 months	5 (9.3)	0 (0)	
25–48 months	7 (13)	1 (12.5)	
49–96 months	3 (5.6)	1 (12.5)	
Level			
Craniocervical	2 (3)	0 (0)	0.756
Cervical	17 (25.4)	4 (36.4)	
Cervicothoracal	5 (7.5)	0 (0)	
Thoracal	12 (17.9)	2 (18.2)	
Thoracolumbar	4 (6)	2 (18.2)	
Lumbar	23 (34.3)	3 (27.3)	
Lumbosacral	2 (3.00)	0 (0)	
Sacral	2 (3)	0 (0)	
Lesion extent			
1–2 vertebrae	52 (77.6)	5 (45.5)	0.060
≥2 vertebrae	15 (22.4)	6 (54.5)	
Preoperative Modified McCormick Scale score			
I	18 (26.9)	5 (45.5)	0.477
II	41 (61.2)	6 (54.5)	
III	5 (7.5)	0 (0)	
IV	3 (4.5)	0 (0)	

shown. Shorter surgery duration was significantly associated with a positive neurologic outcome. There was also a positive correlation between surgery duration and hospital length of stay, which was statistically significant ($r_s = 0.416$; $P < 0.001$).

In Table 6, mIONM outcome (FN, FP, TN, or TP) and type of disease are paired with extent of resection during surgery as judged by the surgeon. In Tables 7 and 8, mIONM outcome is paired with tumor remnants at the site of surgery as shown on the postoperative MRI tumor and tumor recurrence as shown on MRI after 1 year. Both patients with an FN IONM outcome had recurrence of tumor growth after 1 year. For all 3 other outcomes (FP, TN, and TP), the rate of tumor recurrence was significantly lower (range, 0%–14.30%).

The extent of resection as judged by the neurosurgeon during surgery showed no statistically significant correlation with recurrent tumor growth at the lesion site.

However, as expected, partial resection as judged by the surgeon showed a significant ($P < 0.001$) correlation with tumor remnants on MRI. Where the surgeon judged the extent of resection to be total ($n = 41$), 36 patients (85.37%) were tumor free on imaging. Of patients with resections judged subtotal by the neurosurgeon ($n = 17$), 5 (29.41%) were tumor free on radiologic imaging.

DISCUSSION

In this study, we found that IONM for ID-EMSCT yielded a high sensitivity and specificity for predicting postoperative neurologic outcomes at 6 weeks. The sensitivity was even higher after 1 year, because of several patients' neurologic status improving over time, with a perfect sensitivity for MEP and mIONM. Patients' baseline characteristics, except for lesion extent, did not seem to have any significant correlation with neurologic outcomes. New neurologic deficits were associated with longer duration of surgery.

Primary outcome, sensitivity, and specificity of IONM for our series of EMSCT at 6 weeks postoperatively was different from the sensitivity and specificity of IONM for IMSCT as established by Rijs et al.[17]: for all 3 modalities, sensitivity was lower but specificity was higher compared with the results in the study concerning IMSCT. A possible explanation could be that extramedullary tumors are generally easier to resect without major manipulation of the spinal cord compared with intramedullary tumors.

Table 5. Overview of Perioperative and Postoperative Data Classified for Neurologic Outcome

	No New Deficit (n = 67), n (%)	New Deficit (n = 11), n (%)	*P* Value
Pathologic diagnosis			
Carcinoid	1 (1.5)	0 (0)	—
Ependymoma	4 (6)	1 (9.1)	
Hemangioblastoma	0 (0)	1 (9.1)	
Lipoma	2 (3)	0 (0)	
Meningioma	14 (20.9)	3 (27.3)	
Malignant peripheral nerve sheath tumor	3 (4.5)	0 (0)	
Neurofibroma	13 (19.4)	1 (9.1)	
Paraganglioma	1 (1.5)	0 (0)	
Schwannoma	29 (43.3)	4 (36.4)	
Schwannoma and ependymoma	0 (0)	1 (9.1)	
Extent of resection			
Subtotal	17 (25.4)	6 (54.5)	0.073
Total	50 (74.6)	5 (45.5)	
Surgery duration (hours:minutes)			
≤4:00	14 (21.9)	0 (0)	0.016
4:01—6:00	25 (39.1)	1 (9.1)	
6:01—8:00	17 (26.6)	7 (63.6)	
<8 days	8 (12.5)	3 (27.3)	
Hospital stay duration			
2—9 days	53 (79.1)	4 (36.4)	<0.001
10—20 days	10 (14.9)	7 (63.6)	
≥21 days	4 (6)	0 (0)	

Table 6. Test Outcome and Disease Linked to Extent of Resection (N = 78)

	Nontotal Resection, n (%)	Total Resection, n (%)	*P* Value
Multimodal intraoperative neuromonitoring outcome			
False negative	1 (33.3)	2 (66.7)	0.170
False positive	3 (20)	12 (80)	
True negative	14 (26.9)	38 (73.1)	
True positive	5 (62.5)	3 (37.5)	
Pathological diagnosis			
Carcinoid	0 (0)	1 (100)	0.017
Ependymoma	3 (60)	2 (40)	
Hemangioblastoma	0 (0)	1 (100)	
Lipoma	2 (100)	0 (0)	
Meningioma	2 (11.8)	15 (88.2)	
Malignant peripheral nerve sheath tumor	2 (66.7)	1 (33.3)	
Neurofibroma	7 (50)	7 (50)	
Paraganglioma	0 (0)	1 (100)	
Schwannoma	6 (18.2)	27 (81.8)	
Schwannoma and ependymoma	1 (100)	0 (0)	
Total	23 (29.5)	55 (70.5)	

Sensitivity and specificity were also lower compared with the outcomes reported by Ishida et al.[15] In that study, a similar retrospective review was conducted of 103 patients. This difference could be caused by many different factors, such as the surgeon's level of experience, experience with IONM, or tumor type. Another big difference is the follow-up time, with Ishida et al. having only 6 months follow-up compared with our 6 weeks and 1 year follow-up time.

Using neurologic status after 1 year, sensitivity increased, and specificity slightly decreased. Here, MEP and mIONM showed a sensitivity of 1.00, indicating that all patients with a significant IONM amplitude decrease during surgery showed persisting neurologic deficit.

This increased sensitivity may be caused by neurologic outcomes improving over time as a result of rehabilitation and recovery. Another factor could be that 17 patients were lost to follow-up because of death or being reoperated on within 1 year after surgery, which might have caused an artificial change in sensitivity.

Surprisingly, in patients with FP IONM results, there was no significant negative effect on the extent of resection. Of patients with an FP result, 80.00% still received a total tumor resection, compared with TN, TP, and FN findings, which all had lower percentages of total resection.

Table 7. Tumor Remnants on Magnetic Resonance Imaging (N = 58) (*P* = 0.221)

	No Tumor Remnants, n (%)	Tumor Remnants on Magnetic Resonance Imaging, n (%)
Multimodal intraoperative neuromonitoring outcome		
False negative	1 (50)	1 (50)
False positive	12 (85.7)	2 (14.3)
True negative	24 (68.6)	11 (31.4)
True positive	3 (42.9)	4 (57.1)
Total	40 (69)	18 (31)

Table 8. Tumor Recurrence on Magnetic Resonance Imaging After 1 Year (N = 58) ($P < 0.001$)

	No Recurrence on MRI, n (%)	Recurrence on MRI, n (%)
Multimodal intraoperative neuromonitoring outcome		
False negative	0 (0)	2 (100)
False positive	13 (92.9)	1 (7.1)
True negative	35 (100)	0 (0)
True positive	6 (85.7)	1 (14.3)
Total	54 (93.1)	4 (6.9)

MRI, magnetic resonance imaging.

This finding raises the question of how much MEP and SEP signals influence the surgeon's decision whether to continue resection or not. An important factor could be the surgeon's experience in resecting this type of tumor, together with signals of other neuromonitoring modalities such as D-waves. At our own institution, the surgeon primarily relies on clinical expertise while operating on extramedullary tumors. IONM in ID-EMSCT is mostly used as a back-up if in doubt and to increase awareness of unpredicted damage. Stable IONM signals might reassure the surgeon that no iatrogenic damage is done. Signal decreases can cue the surgeon to temporarily stop resecting, to proceed with resection but with more caution, or to choose a different resection plane, in which signals often improve again, such as seen in Figure 1. The resection strategy can also depend on factors such as the aggressivity of the tumor. Sometimes, no spinal cord manipulation is undertaken, but nevertheless a decrease of IONM signals still occurs. This situation gives an indication of possible changes in the anesthesia regimen or the patient's general condition. An example of this is seen in Figure 2, where a signal drop is shown which occured due to patient positioning. When this occurrence is suspected, mostly because all the IONM signals show a reduction of amplitude instead of 1 isolated signal, the neurosurgeon and anesthesiologist can take action to rectify the (anesthesiologic) cause to prevent neurologic damage. This is an extra benefit of using IONM, even when no spinal cord manipulation is expected. Alternatively, significant decreases in electrophysiologic signals can occur without any good explanation, when no manipulation of the spinal cord takes place nor changes regarding anesthesia occur, and thus the neurosurgeon decides to continue resection. Considering this situation, one might ask what the importance of IONM is during resection of ID extramedullary tumors. It might be regarded as an aid to the surgeon instead of a primary decision-making tool.

Whether IONM should be a primary decision-making tool or not for ID-EMSCT resection could be determined by a randomized

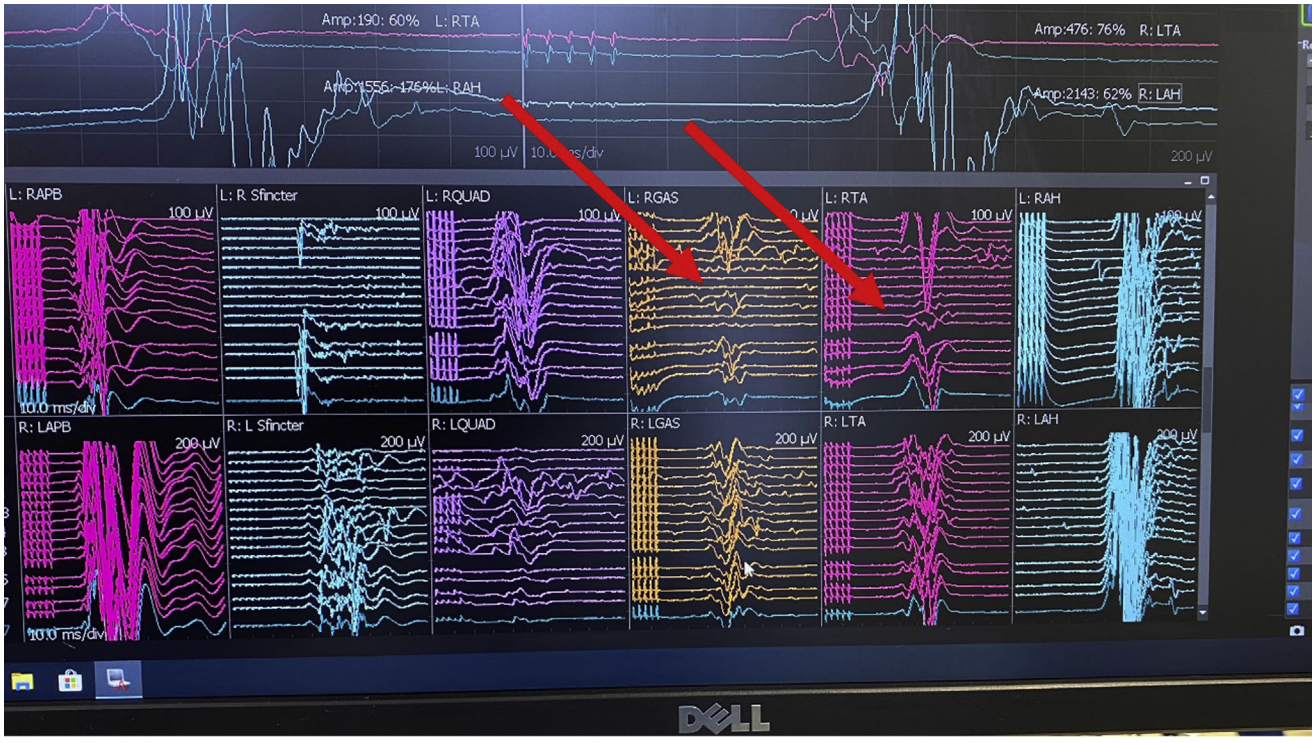

Figure 1. Intraoperative neuromonitoring showing temporary decrease of the signals of the right gastrocnemius and right tibialis anterior (*red arrows*) and later recovery.

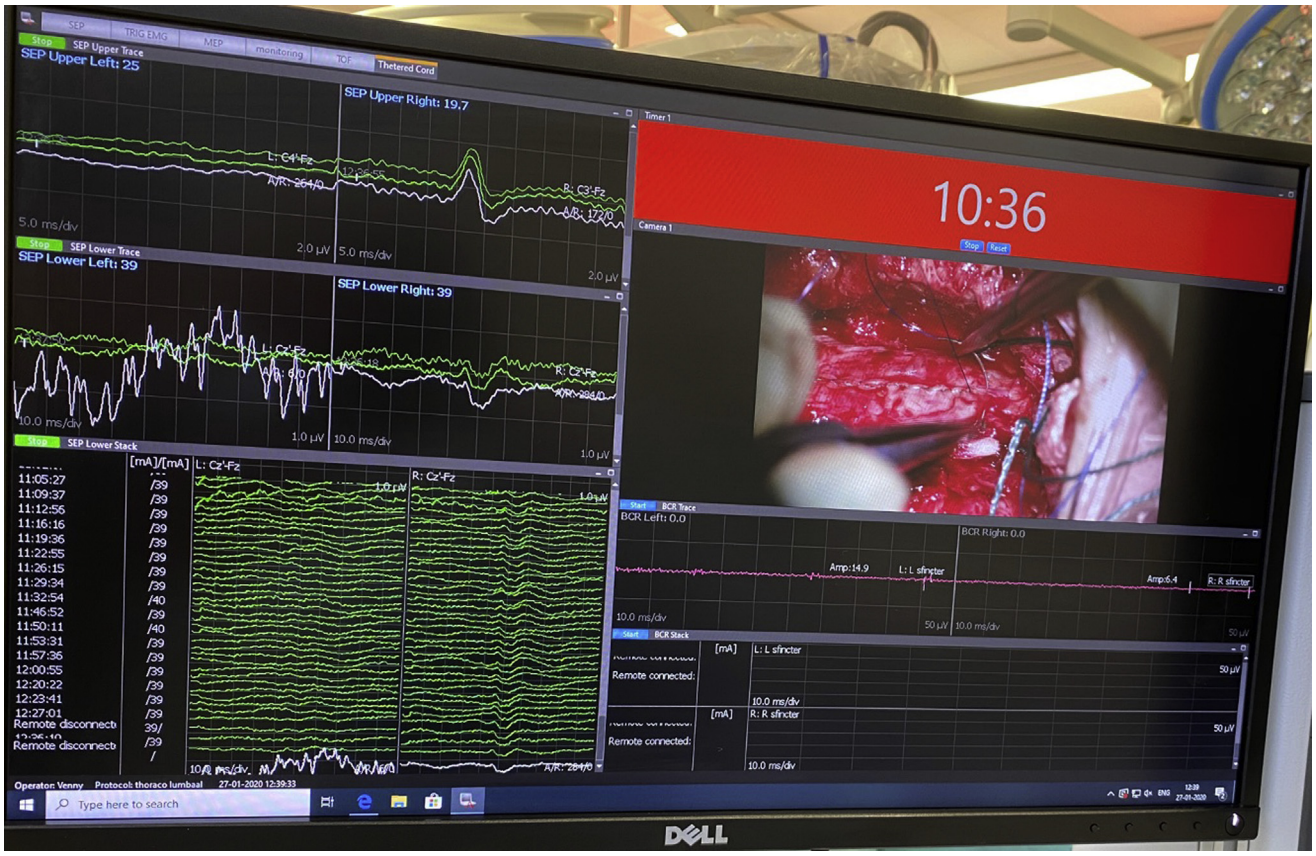

Figure 2. Intraoperative neuromonitoring showing decreased somatosensory evoked potentials signals of the left upper extremity, while lumbar surgery is performed, indicating a problem with patient positioning.

controlled study comparing outcomes after resections using IONM versus not using IONM strictly for decision making. However, not using IONM for this kind of surgery is generally deemed unethical and placing a monitoring result higher than clinical expertise might be dangerous as well. Hence, future conduct of such a study is not likely. An alternative to a randomized controlled trial is a prospective cohort study, which should give more reliable epidemiologic data compared with a retrospective study.

The possible legal aspects of the use of IONM for resection of an extramedullary spinal tumor also deserve a comment. Although our results do not support bypassing the use of IONM altogether, they do support that the expert opinion of the neurosurgeon can safely overrule the objective finding of the IONM. Still, the responsible neurosurgeon determines the extent of resection and not the IONM device. However, overruling a deterioration of the IONM signals and continuing the resection can be compared with ignoring and/or turning of an alarm, which should never be undertaken without good reasons and increasing alertness afterward.

Another factor to be considered in the interpretation of these results is how the amplitude criteria were applied. Because, in this study, the definitive criterion for a positive IONM result was an amplitude decrease $\geq$50% at the end of surgery, intraoperative amplitude decreases, which resolved before closure, were not considered significant. In 1 example, a patient had a persisting amplitude decrease in 1 MEP lead, which was resolved at the end of the surgery. This patient nevertheless had a new neurologic deficit. According to the warning criteria in this study, this was an FN result, possibly showing a weakness in using strict criteria for determining positive or adverse IONM test results. In similar cases, clinicians may prefer their own clinical judgment instead of a strict cutoff value.

Recurrence of tumor growth after 1 year showed different associations with mIONM outcomes. The statistical finding of all FN results being correlated to new tumor growth might be a result of the limited number of patients (6.90%) with recurrent tumor growth. Postoperative MRI analysis indicated that intraoperative judgment of the extent of resection by the neurosurgeon did not always correspond to the radiologic tumor remnants, indicating the need of direct postoperative imaging.

The analysis of perioperative and postoperative variables showed that patients with a new neurologic deficit had significantly longer duration of surgery. This finding might be compatible with the known association between longer duration

of surgery and worse postoperative outcomes.[21-23] Longer duration of surgery was also correlated with longer hospital stay.

Tumor lesion extension as determined perioperatively was associated with new neurologic deficits. Therefore, this parameter should be considered in preoperative risk—benefit evaluations and communications. Radiologic imaging can determine lesion length preoperatively, and for patients with longer lesions, worse postoperative outcomes might be expected.

This study has some limitations. First, this is a retrospective study, which implies some study bias. This bias is expected to be small because of the minimal differences in how these surgeries are set up and conducted at our institution, together with standardized methods of data collection. The number of staff surgeons, neuromonitoring technicians, and neurologists was small, and strict anesthesia protocols were used. All surgery using IONM, which is routinely used for all spinal resections, was performed by the same dedicated team. Next, the amount of loss to follow-up may have introduced selection bias. Especially considering 1-year postoperative imaging, 25.64% of all patients' data are missing. This loss is explainable because at our institution a postoperative MRI is not performed routinely at the 1-year mark. It is conducted only if the patient's clinical status calls for it.

Because it was a single-center cohort with a small group of surgeons with extensive experience with spinal cord surgery and the use of IONM, results are primarily applicable to similar academic institutions. Because of how rare this type of tumor is, only a few surgeries were performed every year and thus only a small group of patients was included. Our database provides no data on patient satisfaction, which is a topic worth further research.

CONCLUSIONS

IONM for ID-EMSCT yielded a high sensitivity and specificity for predicting postoperative neurologic outcomes, and the extent of tumor resection showed a significant correlation with long-term neurologic outcomes.

IONM can be considered as an important aid for decision making during ID-EMSCT resection, but the decisions on tumor resection are still taken by the surgeon. Therefore, IONM cannot fully replace clinical judgment and other perioperative information.

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