Characteristics of Poor Recordability of Intraoperative Neurophysiological Monitoring during Metastatic Spinal Tumor Surgery: A Multicenter Study

Naoki Segi[1], Hiroaki Nakashima[1], Masahiro Funaba[2], Jun Hashimoto[3], Shigenori Kawabata[3], Masahito Takahashi[4], Go Yoshida[5], Hiroki Ushirozako[5], Kenta Kurosu[5], Hideki Shigematsu[6], Tsunenori Takatani[7], Shinji Morito[8], Kei Yamada[8], Hiroshi Iwasaki[9], Yasushi Fujiwara[10], Akimasa Yasuda[11], Muneharu Ando[12], Shinichirou Taniguchi[12], Kanichiro Wada[13], Nobuaki Tadokoro[14], Kazuyoshi Kobayashi[15], Naoya Yamamoto[16], Kazuyoshi Nakanishi[17], Tsukasa Kanchiku[18], Katsushi Takeshita[19], Yukihiro Matsuyama[5] and Shiro Imagama[1]

1) Department of Orthopaedic Surgery, Nagoya University Graduate School of Medicine, Nagoya, Japan
2) Department of Orthopedic Surgery, Yamaguchi University Graduate School of Medicine, Yamaguchi, Japan
3) Department of Orthopaedic and Spinal Surgery, Tokyo Medical and Dental University, Tokyo, Japan
4) Department of Orthopaedic Surgery, Kyorin University, Tokyo, Japan
5) Department of Orthopaedic Surgery, Hamamatsu University School of Medicine, Hamamatsu, Japan
6) Department of Orthopedic Surgery, Nara Medical University, Nara, Japan
7) Division of Central Clinical Laboratory, Nara Medical University, Nara, Japan
8) Department of Orthopedic Surgery, Kurume University School of Medicine, Kurume, Japan
9) Department of Orthopedic Surgery, Wakayama Medical University, Wakayama, Japan
10) Department of Orthopedic Surgery, Hiroshima City Asa Citizens Hospital, Hiroshima, Japan
11) Department of Orthopedic Surgery, National Hospital Organization Saitama Hospital, Saitama, Japan
12) Department of Orthopedic Surgery, Kansai Medical University, Osaka, Japan
13) Department of Orthopaedic Surgery, Hirosaki University Graduate School of Medicine, Hirosaki, Japan
14) Department of Orthopaedic Surgery, Kochi University, Kochi, Japan
15) Department of Orthopaedic Surgery, Japan Red Cross Aichi Medical Center Nagoya Daini Hospital, Aichi, Japan
16) Department of Orthopaedic Surgery, Tokyo Women's Medical University Medical Center East, Tokyo, Japan
17) Department of Orthopaedic Surgery, Nihon University School of Medicine, Tokyo, Japan
18) Department of Orthopedic Surgery, Yamaguchi Rosai Hospital, Yamaguchi, Japan
19) Department of Orthopedic Surgery, Jichi Medical University, Tochigi, Japan

Abstract:

Introduction: The objective of this study is to investigate the poor recordability characteristics of intraoperative neurophysiological monitoring (IONM) for metastatic spinal tumors, focusing on tumor status or preoperative muscle weakness.

Methods: A total of 132 patients (age 65.3±11.8 years; 82 men) with or without preoperative lower extremity muscle weakness were included in this study. The patients' background characteristics, the presence and degree of pre- and postoperative muscle weakness, and the IONM outcome, including the availability of transcranial motor evoked potential (Tc-MEP) recording and the occurrence of Tc-MEP alarms, were investigated. The data between the groups with and without preoperative muscle weakness were compared. Logistic regression analysis was performed to identify the risk factors for unrecordable Tc-MEP.

Results: Sixty-seven patients with muscle weakness had significantly more unrecordable Tc-MEP (19% vs. 5%, p=0.009) than the 65 patients without muscle weakness. The highest percentage of recordable Tc-MEP in the group with muscle weakness was noted in the plantar muscle (72%). Multivariate analysis identified manual muscle test (MMT) score of ≤3 (odds ratio [OR] 4.529) and ventral spinal cord compression by metastatic tumor (OR 3.924) as independent significant factors for unrecordable Tc-MEP.

Corresponding author: Hiroaki Nakashima, nakashima.hiroaki.s8@f.mail.nagoya-u.ac.jp
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Conclusions: IONM for metastatic spinal cord tumors with muscle weakness had a high rate of unrecordable Tc-MEP. Additionally, Tc-MEP may not be detectable in cases of ventral spinal cord compression by a tumor; therefore, preoperative imaging should be thoroughly evaluated.

Keywords:
intraoperative neurophysiological monitoring, transcranial motor evoked potential, somatosensory evoked potential, multimodal monitoring, metastatic spinal tumor, epidural spinal cord compression, palliative surgery

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Introduction

The spine is a common site for cancer metastases, and approximately 20% of patients with cancer will develop spinal metastases[1]. Recent advances in oncologic therapies, including chemotherapy, molecular-targeted biologics, and immunotherapy, have prolonged the survival of these patients. However, as these advancements have extended the life expectancy of patients with cancer, an increasing number of patients develop spinal metastases[2]. Spinal metastases often cause severe pain and neurological deficits that can severely affect the activities of daily living and worsen the quality of life[2-4]. Spinal metastases differ from other bone metastases given they can cause severe paralysis, with surgery as the treatment of choice in cases without effective alternatives.

As with other spine surgeries, surgery for metastatic spinal tumors seeks to prevent neurological damage from surgery and not worsen preexisting muscle weakness. Intraoperative neurophysiological monitoring (IONM) should be used to achieve these outcomes. Transcranial motor evoked potential (Tc-MEP), the most widely used IONM, is a highly sensitive method for monitoring the risk of motor deficits[5-7].

Unfortunately, patients with metastatic spinal tumors requiring surgery often present with rapidly progressive paralysis and severely damaged spinal cords. Many patients exhibit preoperative muscle weakness, manual muscle test (MMT) scores ≤3, and thoracic spinal lesions, making Tc-MEP waveforms much more difficult to detect in real-world clinical practice[8]. Consequently, the manner in which the type, nature, and location of a tumor affect Tc-MEP remains poorly understood. Therefore, this study investigated the characteristics and risk factors associated with an unrecordable IONM for metastatic spinal tumors. The study data were obtained from a prospective multicenter database.

Materials and Methods

Patients

A prospective database is used in this retrospective multicenter study. The intraoperative neurophysiological monitoring working group, with which the authors are members of, conducted a prospective nationwide multicenter survey that involved 9,572 patients (mean age, 61.4±19.9 years; 4,985 men [52%]) who underwent spine surgery using IONM at 16 spine centers between April 2017 and March 2022. In this database, 156 cases included metastatic spinal tumors in the surgical target disease. Three cases of intramedullary metastases, two cases of biopsy, and one case of debridement that was performed due to a surgical site infection were excluded. Moreover, nine cases with only upper limb paralysis and nine cases for which raw IONM data were not available were excluded. Thus, the analysis included a total of 132 patients (mean age, 65.3±11.8 years; 82 men [62%]) with or without preoperative lower extremity muscle weakness (Fig. 1). All study participants provided informed consent, and the institutional review board approved the study protocol at the coordinating institution and at each spine center.

Anesthesia management, intraoperative neurophysiological monitoring, and surgical intervention techniques

The interventions were performed as described previously[9,10]. Total intravenous anesthesia was maintained using pump-controlled intravenous infusions of remifentanil (1 mg/kg/h) and propofol (100-150 mg/kg/min with target-controlled infusion) based on the bispectral index (BIS) (>40 and <60) of each patient during IONM.

Needle-type or disk-type electrodes were used to record Tc-MEP waveforms from the deltoid, biceps, triceps, abductor pollicis brevis, abductor digiti minimi, adductor longus, quadriceps, hamstrings, tibialis anterior, gastrocnemius, and abductor hallucis muscle groups. Corkscrew-type stimulating or silver-silver chloride electrodes were bilaterally and symmetrically placed 5 cm lateral and 2 cm anterior to Cz (international 10-20 electrode placement system). Fewer than 20 transcranial stimuli were delivered in trains of 5-10 stimuli with a stimulation intensity of 100-200 mA, an interstimulus interval of 2 ms, a filter of 2-3 kHz, and a recording time of 100 ms.

The Tc-MEP waveform recorded before the invasive surgical investigation was the baseline waveform in the present study. The baseline waveform was considered unrecordable if no evaluable baseline waveform was detected. An alarm point was defined as any amplitude drop of ≥70% from baseline[5]. In response to the Tc-MEP alarm, the spine surgeons performed rescue interventions, such as additional decompression, warm saline irrigation of the spinal cord, and intravenous steroid injection, to promote the Tc-MEP ampli-

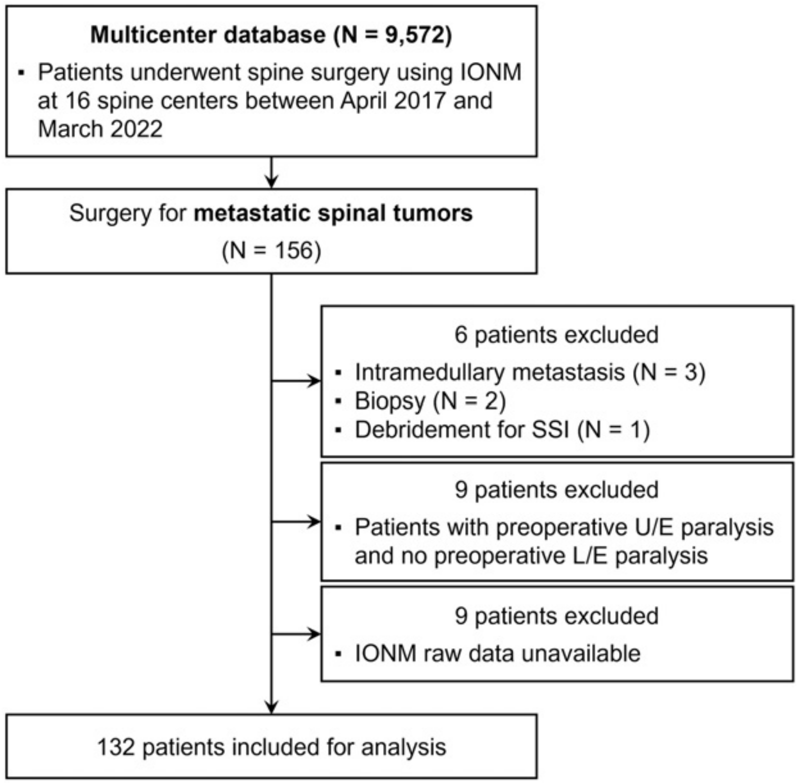

Figure 1. Patient selection flowchart.
U/E, upper extremities; L/E, lower extremities

tude recovery. If the amplitudes did not show sufficient recovery, the surgeons decided whether or not to continue the surgical procedure, considering the entire set of circumstances and the condition of the patient[9].

For multimodal IONM, somatosensory evoked potentials (SEPs) were also recorded in some cases, and the stimulation electrodes for SEP were bilateral posterior tibial nerves.

Variables

The patients' background characteristics, the presence and degree of pre- and postoperative muscle weakness, and the IONM outcome, including the availability of Tc-MEP or SEP recording and the occurrence of Tc-MEP alarms, were investigated. The level of the lesion was determined through a comprehensive judgment of the level diagnosis from the patient's neurological deficits, including sensory impairment, and through imaging diagnosis using magnetic resonance imaging (MRI). In this series, the level of the lesion corresponded to the level of the spinal cord most compressed on MRI. Therefore, the epidural spinal cord compression (ESCC) scale[11,12] at this level was also investigated. According to a four-point scale, the ESCC scale was rated as follows: grade 0, bone involvement only; 1, epidural impingement; 2, spinal cord compression but with visible cerebrospinal fluid (CSF); and 3, spinal cord compression but with no CSF. In addition, the direction of the spinal cord compression by the metastatic tumor was classified as ventral, lateral, dorsal, or other.

MMT was used to assess lower extremity muscle weakness, and the worst MMT score was recorded. The MMT was treated as unknown if muscle weakness was present but the degree of weakness was not recorded. Histories of preoperative chemotherapy or radiation therapy (RT) consistent with the lesion level were determined. The data of the groups with and without preoperative muscle weakness were compared. Additionally, the data of the groups with recordable Tc-MEP and unrecordable Tc-MEP were compared. A logistic regression model was used to investigate the independent risk factors of unrecordable Tc-MEP.

Statistical analysis

Data are presented as means±standard deviations for continuous variables and as numbers and percentages for categorical data. R version 4.2.2 (http://www.R-project.org) was used to perform statistical analyses for the Wilcoxon rank sum and Fisher's exact test. A $p<0.05$ indicates significant difference. Items obtaining a p-value of <0.1 in the univariate analysis and items of clinical importance, such as age, sex, thoracic lesion, preoperative MMT score of ≤3, ESCC scale of 3, ventral spinal cord compression by the metastatic tumor, and prior RT, were included in a logistic regression model. Moreover, the odds ratios (ORs) and 95% confidence intervals were calculated to identify the independent predictors.

Results

The lung (19%) was the most common primary site, fol-

Table 1. Patient Characteristics.

	N=132
Age, year	65.3±11.8
Sex, male	82 (62%)
Primary site	
Lung	25 (19%)
Prostate	22 (17%)
Renal	19 (14%)
Digestive	15 (11%)
Breast	11 (8%)
Hematological	10 (8%)
Thyroid	10 (8%)
Unknown origin	5 (4%)
Other	15 (11%)
Lesion segment	
Thoracic	90 (68%)
Cervical	24 (18%)
Lumbar	16 (12%)
Other	2 (2%)
ESCC scale	
0	4 (3%)
1	22 (17%)
2	41 (31%)
3	65 (49%)
Preoperative muscle weakness	67 (51%)
Preoperative worst MMT score	
0	6 (5%)
1	4 (3%)
2	11 (8%)
3	19 (14%)
4	23 (17%)
5	65 (49%)
Unknown	4 (3%)
Operation procedure	
Posterior fusion/fixation	112 (85%)
Decompression	9 (7%)
Anterior	2 (2%)
Other	9 (7%)
Operation time, min	221.8±116.9
Blood loss, mL	384.9±593.4

MMT, manual muscle test; ESCC, epidural spinal cord compression

lowed by the prostate (17%), kidney (14%), digestive organs (11%). The thoracic spine (68%) was the most common metastatic segment, followed by the cervical (18%) and lumbar (12%) spines. The majority of patients showed some degree of spinal cord compression, with 31% and 49% of patients exhibiting ESCC scales of 2 and 3, respectively. Posterior fusion/fixation (with or without decompression) was the most common procedure (85%) (Table 1).

Preoperative lower extremity muscle weakness was present in 67 patients (51%), with 40 patients obtaining an MMT score of 0-3, 23 patients having an MMT score of 4, and 4 patients having an unknown score (Table 1). Moreover, the 67 patients with muscle weakness (67.2 years, 61% men) had significantly more unrecordable Tc-MEP (19% vs. 5%, p=0.009) and unrecordable SEP (28% vs. 7%, p=0.016) compared with the 65 patients without muscle weakness (63.4 years, 63% men) (Table 2). Three cases of new postoperative muscle weakness were found, i.e., two patients with a true positive alarm and one with a false negative alarm. The highest percentage of recordable Tc-MEP in the group with muscle weakness was noted in the plantar muscle (abductor hallucis or flexor hallucis brevis; 72%) (Table 3).

Table 4 compares the data between the groups with unrecordable and recordable Tc-MEP. Although no significant difference was observed in the distribution of primary sites, all patients in the unrecordable group had thoracic lesions, and the degree of preoperative muscle weakness was significantly worse. The unrecordable group had higher ESCC scale, with significantly more patients in the same group having an ESCC scale of 3 (75% vs. 46%, p=0.028). Ventral compression was the most common direction of spinal cord compression due to a metastatic tumor in both groups, with the unrecordable group having relatively more cases of ventral compression (75% vs. 59%, p=0.23). Tc-MEP and SEP could not be recorded in five patients. Thus, 42% of the unrecordable group could not be monitored with these two modalities.

The analysis using a logistic regression model identified an MMT score of ≤3 (OR 4.529, p=0.012) and ventral compression of the spinal cord (OR 3.924, p=0.041) as independent significant risk factors of unrecordable Tc-MEP. Additionally, having an ESCC scale of 3 was associated with an unrecordable Tc-MEP (OR 3.529, p=0.055) (Table 5).

A case of unrecordable Tc-MEP

A female patient in her 60s undergoing breast cancer management developed progressive muscle weakness in both lower extremities. She was diagnosed with a metastatic tumor and spinal cord compression, specifically an ESCC scale of 2 with ventral compressions in the 2nd-3rd thoracic spine (Fig. 2A-C). Palliative surgery was indicated; thus, the patient underwent posterior spinal fusion and decompression (Fig. 2D). Although preoperative lower extremity muscle strength was maintained with an MMT score of 4 in all muscles of both lower extremities, Tc-MEP was unrecordable in all lower extremities (Fig. 2E). Postoperatively, the muscle strength in both lower extremities improved gradually and did not worsen. As a result, the patient could walk and was discharged.

Discussion

This study investigated the characteristics and risk factors of unrecordability of IONM during surgery for metastatic spinal tumors. Patients with preoperative lower extremity muscle weakness had a high rate of unrecordable Tc-MEP (19%), and patients in the severe muscle weakness group (MMT score ≤3) reached an unrecordability rate of 25%. The analysis using a logistic regression model identified an

Table 2. Comparison of Data among Patients Stratified by the Presence of Preoperative Muscle Weakness.

	Preoperative muscle weakness *N*=67	No preoperative muscle weakness *N*=65	p-value
Age, year	67.2±12.0	63.4±11.2	**0.028**
Sex, male	41 (61%)	41 (63%)	0.82
Lesion segment			0.82
Thoracic	48 (72%)	42 (65%)	
Cervical	10 (15%)	14 (22%)	
Lumbar	8 (12%)	8 (12%)	
Other	1 (2%)	1 (2%)	
ESCC scale			**<0.001**
0	0 (0%)	4 (6%)	
1	9 (13%)	13 (20%)	
2	13 (19%)	28 (43%)	
3	45 (67%)	20 (31%)	
Direction of tumor invasion			0.51
Ventral	37 (55%)	44 (68%)	
Lateral	14 (21%)	11 (17%)	
Dorsal	6 (9%)	3 (5%)	
Other	10 (15%)	7 (11%)	
Chemotherapy	27 (40%)	33 (51%)	0.23
Radiation therapy	11 (16%)	22 (34%)	**0.021**
Unrecordable Tc-MEP	13 (19%)	3 (5%)	**0.009**
Unrecordable SEP	11 (28%)	3 (7%)	**0.016**
No SEP	27	24	
Both unrecordable	5 (13%)	0 (0%)	**0.026**
No SEP	27	24	
Postoperative worsening muscle weakness	1 (2%)	2 (3%)	0.62
Tc-MEP outcome			0.12
True positive	0 (0%)	2 (3%)	
False negative	1 (2%)	0 (0%)	
False positive	5 (10%)	2 (3%)	
True negative	45 (88%)	58 (94%)	
Unable to determine	13	3	

ESCC, epidural spinal cord compression; Tc-MEP, transcranial motor evoked potential; SEP, somatosensory evoked potential

Table 3. Tc-MEP Recordability Rate per Monitoring Muscle.

	Preoperative muscle weakness *N*=67	No preoperative muscle weakness *N*=65
Recordable muscle		
Quad	63% (35/56)	93% (49/53)
Ham	53% (9/17)	92% (11/12)
TA	71% (39/55)	98% (56/57)
Gc	68% (21/31)	91% (30/33)
AH or FHB	72% (47/65)	94% (60/64)

Quad, quadriceps; Ham, hamstring; TA, tibialis anterior; Gc, gastrocnemius; AH, abductor hallucis; FHB, flexor hallucis brevis

MMT score of ≤3 and ventral spinal cord compression by a metastatic tumor as independent significant factors of unrecordable Tc-MEP.

It was found that IONM for metastatic spinal tumors has a considerably high rate of failure to record Tc-MEP. Besides metastatic spinal tumors, the risk factors for the unrecordability of Tc-MEP included a heavy body weight or high body mass index, the presence of thoracic level lesions, an MMT score of ≤3, and high-risk spine surgeries (surgeries for spinal deformity, ossification of posterior longitudinal ligament, and extramedullary or intramedullary spinal cord tumor)[8]. In this study cohort, 19% of the patients were unrecordable. This is an extremely high rate compared with that of previous studies. For example, one study reported

Table 4. Comparison of Data among Patients Stratified by the Availability of Tc-MEP Recordings.

	Tc-MEP unrecordable *N*=16	Tc-MEP recordable *N*=116	p-value
Age, year	66.0±8.8	65.3±12.1	0.98
Sex, male	10 (63%)	72 (62%)	0.97
Primary site			0.74
Lung	4 (25%)	21 (18%)	
Prostate	4 (25%)	18 (16%)	
Renal	1 (6.3%)	18 (16%)	
Digestive	3 (19%)	12 (10%)	
Breast	1 (6.3%)	10 (8.6%)	
Hematological	2 (13%)	8 (6.9%)	
Thyroid	0 (0%)	10 (8.6%)	
Unknown origin	0 (0%)	5 (4.3%)	
Other	1 (6.3%)	14 (12%)	
Lesion segment			**0.035**
Thoracic	16 (100%)	74 (64%)	
Cervical	0 (0%)	24 (21%)	
Lumbar	0 (0%)	16 (14%)	
Other	0 (0%)	2 (1.7%)	
Preoperative worst MMT score			**<0.001**
0	5 (31%)	1 (0.9%)	
1	2 (13%)	2 (1.7%)	
2	2 (13%)	9 (7.8%)	
3	1 (6.3%)	18 (16%)	
4	3 (19%)	20 (17%)	
5	3 (19%)	62 (53%)	
Unknown	0 (0%)	4 (3.4%)	
Worst MMT score ≤3	10 (63%)	30 (26%)	**0.007**
ESCC			0.10
0	0 (0%)	4 (3.4%)	
1	0 (0%)	22 (19%)	
2	4 (25%)	37 (32%)	
3	12 (75%)	53 (46%)	
ESCC scale 3	12 (75%)	53 (46%)	**0.028**
Direction of compression			0.79
Ventral	12 (75%)	69 (59%)	
Lateral	2 (13%)	23 (20%)	
Dorsal	1 (6.3%)	8 (6.9%)	
Other	1 (6.3%)	16 (14%)	
Ventral compression	12 (75%)	69 (59%)	0.23
Chemotherapy	7 (44%)	53 (46%)	0.88
Radiation therapy	1 (6.3%)	32 (28%)	0.072
Unrecordable SEP	5 (42%)	9 (13%)	**0.029**
No SEP	4	47	
Both unrecordable	5 (42%)	0 (0%)	**<0.001**
No SEP	4	47	
Postoperative worsening muscle weakness	0 (0%)	3 (2.6%)	>0.99
Tc-MEP outcome			–
True positive	–	2 (1.7%)	
False negative	–	1 (0.9%)	
False positive	–	7 (6.0%)	
True negative	–	106 (91%)	
Unable to determine	16	–	

MMT, manual muscle test; ESCC, epidural spinal cord compression; Tc-MEP, transcranial motor evoked potential; SEP, somatosensory evoked potential

Table 5. Multivariate Analysis of the Tc-MEP Unrecordable Risk Factors.

	OR	95% CI	p-value
Worst MMT score ≤3	4.529	1.432–15.479	**0.012**
ESCC scale 3	3.529	1.026–14.321	0.055
Ventral compression	3.924	1.141–16.466	**0.041**

MMT, manual muscle test; ESCC, epidural spinal cord compression

unrecordable Tc-MEP in 73 out of 3,625 patients (2%)[8] and another in 32 out of 949 high-risk cases (3%)[13]. The high unrecorded rate is attributed to the fact that the present investigation is a prospective study, and, as real-world data, Tc-MEP may not derive from metastatic spinal tumors at a very high rate.

Severe muscle weakness (MMT score ≤3) and ventral spinal cord compression due to a metastatic tumor seen on MRI were the independent risk factors of unrecordable Tc-MEP for metastatic spinal tumors. Furthermore, an ESCC scale of 3 (p=0.055) may also be a risk factor, given the relatively small statistical power of this study. Preoperative muscle weakness is known as a risk factor for unrecordable Tc-MEP[8]. However, unrecordable Tc-MEP occurred in 16% of patients with muscle weakness with an MMT score of 4. Given that the MRI findings were identified as another risk factor, the imaging findings may explain the discrepancy between the degree of muscle weakness and electrophysiological findings. In addition, the basic understanding of the disease process of neurological dysfunction caused by tumor-induced spinal cord compression is still limited[14]. Hence, attention must be paid to MRI findings in addition to preoperative muscle weakness to understand the IONM findings in metastatic spinal tumor surgery.

Ventral spinal cord compression due to a metastatic tumor was found to be a risk factor for an unrecordable Tc-MEP. Metastatic lesions often mainly involve the pedicles and vertebral body, enter the spinal canal laterally or ventrally, and compress the spinal cord. The main motor tract (lateral corticospinal tract) is lateral to the spinal cord[15]. However, ventral compression could affect the anterior spinal artery, which then affects the motor tract due to impaired spinal cord blood flow[16]. These pathological conditions may impair motor tract transmission with or without clinical muscle weakness, which may have led to a considerably higher rate of unrecordable Tc-MEP. Furthermore, the unrecordability rate of SEP was also high; however, since 50% of cases had both unrecordable Tc-MEP and SEP, it is possible that the remaining 50% of cases could be monitored with SEP and that multimodal IONM with SEP may be effective for metastatic spinal tumors.

In addition, chemotherapy and RT appear to exert minimal influence on Tc-MEP recordability. Although chemotherapy is a major tool for treating cancers, some drugs, such as cisplatin, paclitaxel, and vincristine, carry a known risk of chemotherapy-induced peripheral neuropathy (CIPN). Axonal degeneration was previously observed in CIPN sciatic nerve lesions developed in an animal study[17]. Usually, CIPN presents as painful or painless sensory axonal polyneuropathy[18]. Thus, CIPN appears to minimally affect Tc-MEP. Radiotherapy damages both vascular and glial structures when it is administered to the spinal cord[19]. Fortunately, such damage is almost always reversible if it occurs early in treatment[19]. Thus, RT to the spine would have only a small influence on Tc-MEP. Given that the group with unrecordable Tc-MEP underwent chemotherapy and RT at similar rates, the impact of these treatments on unrecordable Tc-MEP appears small.

Conversely, Tc-MEP recording was possible in some cases despite a motor deficit, while the unrecorded signal was a false negative in other cases. Tc-MEP presents extremely high sensitivity, and the incidence of false negatives is low[5-7]. However, Tc-MEP waveforms were not always available from all muscles examined in patients with metastatic spinal tumors. When the waveform recordings were incomplete, alarms could only be determined based on the recorded baseline waveforms, which is a potential methodological limitation. Efforts should be made to expand the role of intraoperative monitoring, hopefully avoiding further neurological complications. Such efforts are particularly important in patients with spinal metastases and muscle weakness undergoing emergency surgery. This high-risk population for intraoperative monitoring had the highest rate of Tc-MEP recordability of plantar muscles like abductor hallucis, as previously reported[13]. However, clinicians should attempt to include as many muscle groups as possible when monitoring to improve the accuracy of this assessment.

The other possible measures in cases wherein Tc-MEP or SEP is not recordable include multimodal monitoring using other techniques, such as transcranial stimulation spinal cord evoked potentials and spinal cord stimulation spinal cord evoked potentials[20], which involve epidurally inserting electrodes in the operative field. However, the surgery for metastatic spinal tumors, with the majority being hypervascular[21], often results in massive bleeding. Not only does the safe placement of electrodes in the epidural prolong the operative time, but their placement may also invade the epidural space, thereby contributing to bleeding. Therefore, generalizing these monitoring procedures in metastatic spinal tumor surgery might not always be advisable.

The present study had several limitations. First, the number of patients was relatively small. Second, the data on chemotherapy regimens or RT doses before surgery as well as data on the time from onset of paralysis to surgery were unavailable. Lastly, analyses related to recovery of paralysis could not be performed because patient outcome information was unavailable. Despite these limitations, the present study is the largest prospective multicenter analysis of Tc-MEP for metastatic spinal tumors and is the first study to demonstrate that ventral compression of the spinal cord and decreased MMT scores are the major causes of the high number of unrecordable Tc-MEP among patients with metastatic spinal

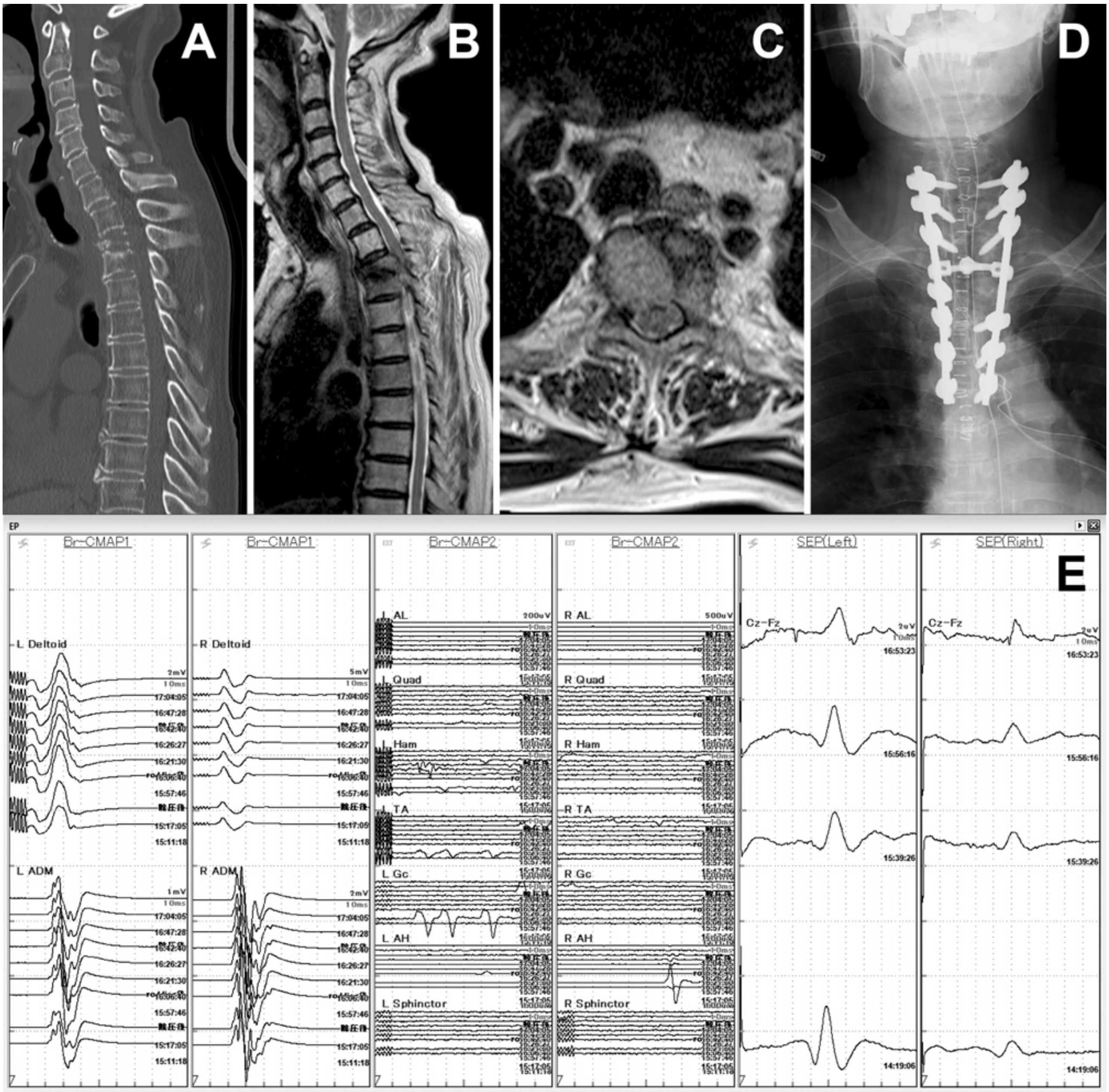

Figure 2. Unrecordable Tc-MEP cases.
A woman in her 60s with breast cancer thoracic metastasis (A, CT sagittal image; B, MRI T2-weighted sagittal image; C, MRI T2-weighted trans image) and muscle weakness with an MMT score of 4 for both lower extremities underwent posterior decompression and fusion (D). Tc-MEP recording was impossible in any lower extremity muscle (E). However, there was no deterioration in the muscle strength of both lower extremities postoperatively, and the muscle strength improved afterward.
CT, computed tomography; MRI, magnetic resonance imaging; MMT, manual muscle test; Tc-MEP, transcranial motor evoked potential; ADM, abductor digiti minimi; AL, adductor longus; Quad, quadriceps; Ham, hamstrings; TA, tibialis anterior; Gc, gastrocnemius; AH, abductor hallucis

tumors.

Conclusions

This study, which investigated the IONM outcomes during the surgery for metastatic spinal tumors, found that patients with preoperative lower extremity muscle weakness had a 19% rate of obtaining unrecordable Tc-MEP. Multivariate analysis identified an MMT score of ≤3 and ventral spinal cord compression by a metastatic tumor as independent significant risk factors for unrecordable Tc-MEP. Attention should be paid to the imaging findings in addition to preoperative muscle weakness to evaluate the IONM results in metastatic spinal cord tumor surgery.

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Ethical Approval: The institutional review board approved the study protocol at the coordinating institute (IRB No.354-3) and at each spine center.

Informed Consent: All participants in this study provided informed consent for data publication.

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