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ORIGINAL ARTICLE

Characteristics of multi-channel Br(E)-MsEP waveforms for the lower extremity muscles in thoracic spine surgery: comparison based on preoperative motor status

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Abstract

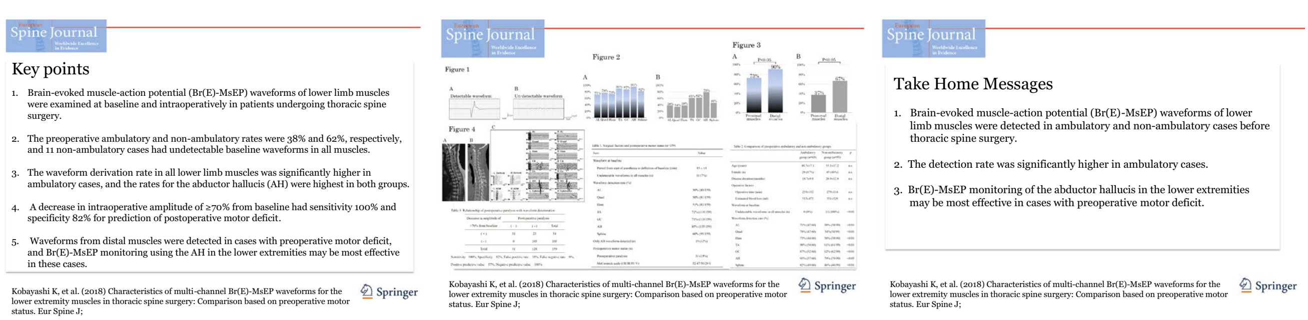
Purpose To evaluate the characteristics of brain-evoked muscle action potential [Br(E)-MsEP] waveforms of lower limb muscles in thoracic spine surgery.

Methods The subjects were 159 patients who underwent thoracic spine surgery with intraoperative Br(E)-MsEP monitoring from January 2009 to December 2015, using a total of 2226 muscles in the extremities. The waveform derivation rate for each lower extremity muscle was examined at baseline and intraoperatively. Data were interpreted based on the preoperative motor status.

Results The preoperative ambulatory and non-ambulatory rates were 38% (60/159, McCormick grades I and II) and 62% (99/159, grades III–V), respectively. Eleven cases (all non-ambulatory) had undetectable baseline waveforms in all muscles, and in 19 cases (12%) a baseline waveform could only be derived from the abductor hallucis (AH). The waveform derivation rate in all lower limb muscles was significantly higher in ambulatory cases ($p < 0.05$), and the rates for the AH were the highest in both groups ($p < 0.05$). Postoperative paralysis occurred in 31 cases (19%). A decrease in intraoperative amplitude of ≥ 70% from baseline occurred in 54 cases and had sensitivity of 100% and specificity of 82% for prediction of postoperative motor deficit.

Conclusions This is the first study of Br(E)-MsEP waveforms for each lower limb muscle based on preoperative ambulatory status. Detection of waveforms from distal muscles was still possible in a case with preoperative motor deficit, and the AH had an especially high derivation rate, even in cases with preoperative muscle weakness. Collectively, the results support use of Br(E)-MsEP monitoring using the AH in the lower extremities.

Graphical abstract



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Keywords Br(E)-MsEP · Lower limb muscle · Thoracic surgery · Waveform change · Abductor hallucis

Introduction

The rate of neurological complications is 1.0% in overall spinal surgery [1]. However, in high-risk spinal surgeries such as those for spinal deformity, spinal cord tumors, or ossification of the posterior longitudinal ligament (OPLL), neurological complications are among the most frequent perioperative complications, occurring at a rate of 13 to 31% [2–6]. Furthermore, neurological complications after spinal surgery are associated with increased rates of morbidity and mortality, and higher healthcare costs.

Brain-evoked muscle action potential [Br(E)-MsEP] monitoring has become widely used in spinal surgery [7–10] for prevention of neurological deterioration and increased accuracy in detection of spinal cord injury [11–14]. Among modalities such as somatosensory-evoked potentials (SEP), cord-evoked potentials after stimulation of the brain (D-wave), and free-running electromyography (EMG), Br(E)-MsEP monitoring has become the standard method due to its high sensitivity and importance in preserving motor function [15, 16].

Multi-channel Br(E)-MsEP monitoring has been shown to have improved efficacy [17], with sensitivities of 73%, 100% and 100% for prediction of postoperative motor deficit based on waveform deterioration using 4, 8, and 16 channels, respectively. In addition, the coverage rates (intraoperative detection of muscles related to postoperative motor deficit) were 38%, 60%, and 100% for 4, 8, and 16 channels, respectively. Therefore, a multi-channel approach is desirable for real-time detection of intraoperative spinal cord injury, and recognition of the characteristics for each detected muscle is important.

There have been no previous reports on Br(E)-MsEP waveform characteristics that have focused on each lower limb muscle and have been based on preoperative motor status. The purpose of this study is to evaluate the Br(E)-MsEP waveform characteristics of each lower limb muscle in thoracic spine surgery.

Materials and methods

Subjects

The subjects were 159 patients who underwent thoracic spine surgery using intraoperative Br(E)-MsEP monitoring from January 2009 to December 2015 at our hospital. A total of 2226 muscles in the lower extremities were included in the study. The patients had a mean age of 51.6 years (range 10–87), and 83 were female and 76 were male. Diseases included spinal intradural extramedullary tumor ($n = 58$), OPLL ($n = 57$), spinal intramedullary tumor ($n = 22$), vertebral tumor ($n = 9$), thoracic spinal cord herniation ($n = 4$), and others ($n = 9$). The average disease duration was 20.1 months (range 3–37). The waveform derivation rate for each lower muscle was examined retrospectively at baseline and in the intraoperative period based on the preoperative motor status. This study was approved by our Institutional Review Board (IRB No. 354-3), and each patient provided informed consent before enrollment.

Neurological assessment

A preoperative neurological clinical grade was assigned using the modified McCormick scale (I = normal gait; II = mild gait disturbance not requiring support; III = gait with support; IV = assistance required; and V = wheelchair needed) [18]. McCormick grades I and II were defined as ambulatory with no support required for walking, indicating independent gait ability, and grades III, IV and V were defined as non-ambulatory. Grades were assigned on the basis of documented neurological examinations. Functional assessments were conducted pre- and postoperatively. A decrease in the postoperative manual muscle test (MMT) score of ≥ 1 compared with the preoperative MMT was defined as postoperative paralysis.

Anesthetic management and general conditions during surgery

A minimal benzodiazepine dose was used as preanesthetic medication to avoid possible suppression of waveform latency and amplitude. Propofol (3–4 mg/kg), fentanyl (2 mg/kg), and vecuronium (0.12–0.16 mg/kg) were administered for induction, and anesthesia was maintained with propofol (50–100 μg/kg/min), fentanyl (1–2.5 μg/kg/h), and vecuronium (0.01–0.04 mg/kg/h). Concomitant hypotensive anesthesia was given as appropriate with continuous PGE1 and a short-acting β1 blocker (landiolol). Patients were maintained in a normothermic state, and the temperature was raised in the event of possible intraoperative spinal damage. End-tidal CO_2 was maintained in the reference range throughout surgery. For intraoperative body temperature monitoring, a catheter with a vesical temperature sensor was used. Hemodynamic data were electronically recorded with invasive arterial BP monitoring. Systolic blood pressure (SBP) variation was measured during surgery, and SBP was also determined at the time of waveform deterioration.

Stimulation and recording methods

A MS120B system (Nihon Kohden, Tokyo, Japan) was used to perform transcranial stimulation. The stimulation parameters were 5 stimuli in a row at 2-ms intervals, a constant biphasic current of 200 mA for 500 µs, a 50–1000 Hz filter, and a 100-ms epoch time with ≤ 20 recorded signal responses. The stimulated point was 2 cm anterior and 6 cm lateral from the Cz location over the cerebral cortex motor area. Using the Neuromaster MEE-1232 ver. 05.10 (Nihon Kohden, Japan), which is expandable to 32 channels, muscle action potentials were recorded from the upper and lower extremities via a pair of needle electrodes 3–5 Br(E)-MsEPs apart. The bilateral deltoid, abductor digit minimi, adductor longus (AL), quadriceps femoris (Quad), hamstrings (Ham), tibialis anterior (TA), gastrocnemius (GC), abductor hallucis (AH), and anal sphincter (Sphinc) were used as target muscles. The AL, Quad, and Ham were defined as proximal muscles, and the TA, GC, and AH were defined as distal muscles. Br(E)-MsEP data from these muscles were used for analysis. Multimodal monitoring was used in all cases, with a particular combination of D-wave potentials and SEPs. Free-running EMGs from all the above muscles were also monitored throughout the operation.

Monitoring and alert parameters

The Br(E)-MsEP at baseline was recorded immediately after documented surgical exposure of the spine, as the control waveform. During surgery, surgeons were informed of an acute decrease in amplitude of the Br(E)-MsEP response of ≥ 70% from baseline [19]. The control waveform was defined as a detected amplitude ≥ 3.6 µV in the left or right muscle at the start of surgery [20] (Fig. 1). The derivation rate was defined as the number of muscles detected/number of muscles prepared for monitoring. If a waveform changed during surgery, SBP was raised or hypotensive anesthesia was reversed (anesthetic-related factors); or surgery was interrupted, the position of an inserted screw was confirmed, or release of correction was performed (technical factors). After these approaches, the patient was warmed, irrigation was performed with warm saline, and steroids were used. If the waveform did not recover, a wake-up test was performed, and surgery was terminated if there was no improvement.

Examined items

The items examined for the relationship of postoperative paralysis with waveform deterioration were sensitivity and specificity, false positive rate, false negative rate, positive predictive value, and negative predictive value. The positive predictive value is the probability that subjects with a positive screening test truly have the disease, and is defined as (number of true positives)/(number of true positives + number of false positives).

Statistical analysis

Analysis was performed using SPSS ver. 22 for Windows (IBM, Chicago, IL). Differences between two groups were analyzed by Mann–Whitney *U* test or Student's *t* test. $p < 0.05$ was considered to be significant in all analyses.

Results

Among all patients, 22, 38, 53, 38, and 8 were classified preoperatively into McCormick grades I, II, II, IV, and V, respectively. Thus, the preoperative ambulatory and non-ambulatory rates were 38% (60/159) and 62% (99/159), respectively. Baseline (control) waveforms were detected at an average of 85 (63–109) min after the start of anesthesia. The mean operative time was 267 ± 141 min, and the mean estimated blood loss (EBL) was 342 ± 508 mL. Eleven cases had undetectable baseline waveforms in all muscles. The waveform derivation rate for each lower limb muscle at baseline is shown in Table 2. There were 19 cases (12%) in which a waveform could only be derived from the AH at baseline. Postoperative paralysis occurred in 31 cases (19%), and postoperatively, 32, 47, 50, 29, and 1 patients were classified into McCormick grades I, II, II, IV, and V, respectively (Table 1).

A comparison of preoperative ambulatory and non-ambulatory cases is shown in Table 2. Demographic data, diagnosis, disease duration, and operative factors did not differ significantly between the two groups. All cases with undetectable waveforms were in the non-ambulatory group, and the waveform detection rate in all lower limb muscles was significantly higher in the ambulatory group ($p < 0.05$). The baseline waveform detection rates in the ambulatory and

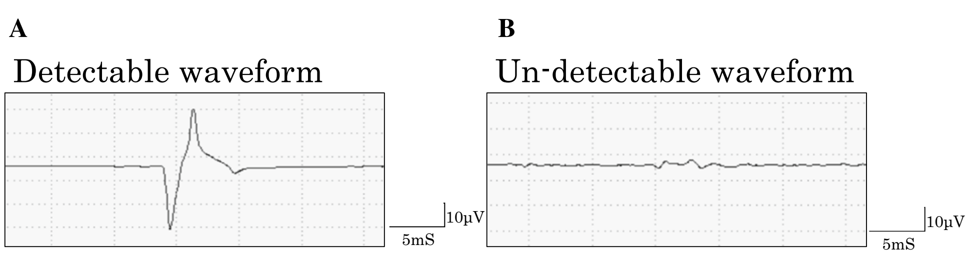

Fig. 1 **a** Detectable waveform. **b** Undetectable waveform

Table 1 Surgical factors and postoperative motor status ($n = 159$)

Item	Value
Waveform at baseline	
Period from start of anesthesia to definition of baseline (min)	85 ± 14
Undetectable waveforms in all muscles (*n*)	11 (7%)
Waveform detection rate (%)	
AL	50% (80/159)
Quad	50% (81/159)
Ham	51% (82/159)
TA	72% (114/159)
GC	71% (113/159)
AH	85% (135/159)
Sphinc	60% (95/159)
Only AH waveform detected (*n*)	19 (12%)
Postoperative motor status (*n*)	
Postoperative paralysis	31 (19%)
McCormick scale (I/II/III/IV/V)	32/47/50/29/1

Table 2 Comparison of preoperative ambulatory and non-ambulatory groups

	Ambulatory group ($n = 60$)	Non-ambulatory group ($n = 99$)	*p*
Age (years)	48.7 ± 17.1	53.1 ± 17.2	n.s.
Female (*n*)	28 (47%)	45 (46%)	n.s.
Disease duration (months)	18.7 ± 9.8	20.9 ± 12.8	n.s.
Operative factors			
Operative time (min)	259 ± 152	279 ± 134	n.s.
Estimated blood loss (mL)	313 ± 475	351 ± 528	n.s.
Waveform at baseline			
Undetectable waveforms in all muscles (*n*)	0 (0%)	11 (100%)	< 0.01
Waveform detection rate (%)			
AL	71% (42/60)	38% (38/99)	< 0.01
Quad	78% (47/60)	34%(34/99)	< 0.01
Ham	73% (44/60)	38% (38/99)	< 0.01
TA	90% (54/60)	61% (61/99)	< 0.01
GC	87% (52/60)	62% (62/99)	< 0.01
AH	95% (57/60)	79% (79/99)	< 0.05
Sphinc	82% (49/60)	46% (46/99)	< 0.01

non-ambulatory groups are shown in Fig. 2. The AH had the highest rate in both groups. There was a significant difference in the rates for proximal (AL, Quad, Ham) and distal (TA, GC, AH) muscles in both groups ($p < 0.05$, Fig. 3).

The relationship of postoperative paralysis with waveform deterioration is shown in Table 3. A decrease in intraoperative amplitude of ≥ 70% from baseline occurred in 54 cases and had sensitivity 100%, specificity 82%, false positive rate (FPR) 18%, false negative rate (FNR) 0%, positive predictive value (PPV) 57%, and negative predictive value (NPV) 100% for prediction of postoperative motor deficit (Table 3).

As an illustrative case, we describe a 44-year-old male with thoracic canal stenosis due to thoracic OPLL (Fig. 4a, b). Preoperatively, he had myelopathy and was non-ambulatory (modified McCormick grade IV). The patient underwent posterior decompression and dekyphotic corrective fusion with instrumentation from T1 to T12 with decompression. In intraoperative Br(E)-MsEP monitoring (Fig. 4c), baseline waveforms were acceptable for the bilateral TA and AH muscles. Intraoperatively, the right TA waveform deteriorated, and finally only left TA and bilateral AH waveforms were obtained. Postoperatively, motor status improved 3 months after surgery and the patient was able to walk (McCormick grade II).

Discussion

A thoracic lesion can cause preoperative motor deficits, and in our series these deficits occurred at a high rate of 62% (99/159). Surgical procedures for thoracic lesions, including resection of intra- and extramedullary tumors, correction of deformities, and decompression and corrective procedures due to stenosis in cases of OPLL, are technically demanding and carry a high risk of postoperative motor deficit [2, 20–24]. Thus, spinal cord monitoring is essential in thoracic spine surgery to confirm the functional integrity of the entire spinal cord. Sometimes, there is a possibility of poor derivation of waveforms at the start of surgery due to a high rate of preoperative motor deficit. For a non-ambulatory patient with poor evoked responses at the preoperative baseline, this is not necessarily pertinent to the success of intraoperative monitoring. However, our findings could help in prevention of neurological deterioration and increase the accuracy of detection of spinal cord injury. Therefore, utilization of spinal cord monitoring for safer surgery requires an improved waveform derivation rate at the start of surgery.

Multi-channel detection has high sensitivity for prediction of postoperative paralysis using intraoperative waveform deterioration and permits real-time detection [17]. However, many facilities are not equipped to perform multi-channel monitoring. Thus, in using detection from a limited number of muscles, there is a need to select specific muscles that can give a reliable waveform. We believe that selection of the muscle for deriving a waveform should include consideration of the disease, surgical lesion, surgical procedure, and preoperative motor status. In addition, information on the waveform characteristics (e.g., derivation rate, sensitivity, and specificity) of Br(E)-MsEPs for each lower limb muscle and the relationship to postoperative motor deficit are important. Kothbauer et al. [21] reported that the TA and flexor

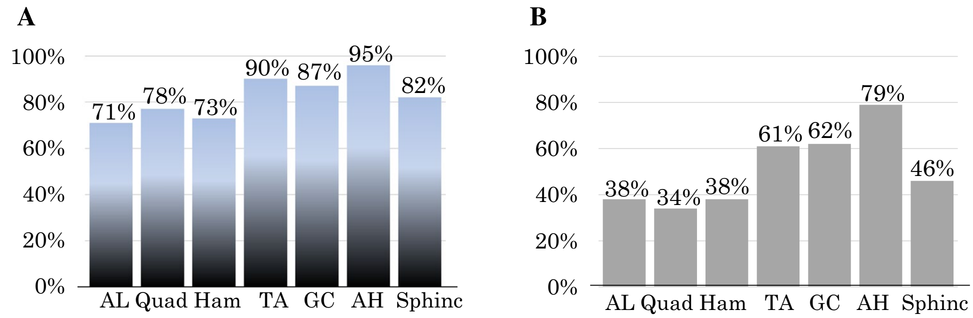

Fig. 2 Baseline waveform derivation rate for each lower limb muscle in the **a** ambulatory and **b** non-ambulatory groups

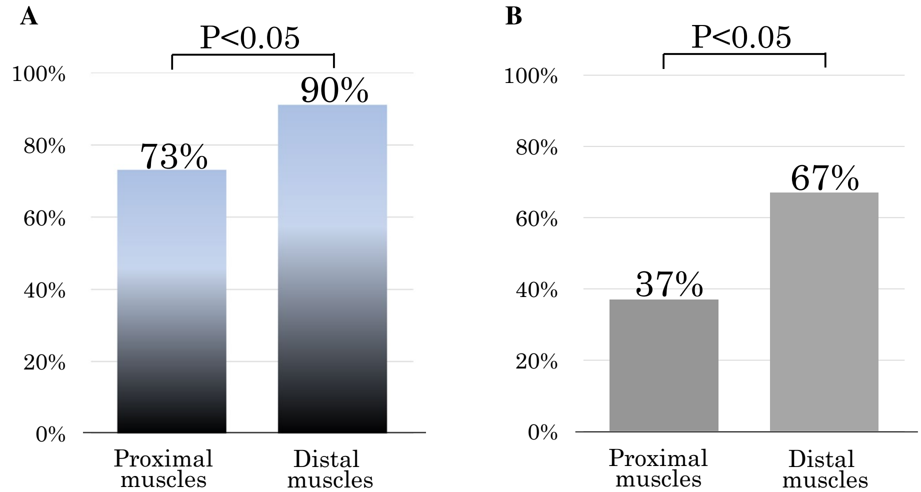

Fig. 3 Baseline waveform derivation rates in proximal muscles (AL, Quad, Ham) and distal muscles (TA, GC, AH) in the **a** ambulatory and **b** non-ambulatory groups

Table 3 Relationship of postoperative paralysis with waveform deterioration

Decrease in amplitude of ≥ 70% from baseline	Postoperative paralysis		
	(+)	(−)	Total
(+)	31	23	54
(−)	0	105	105
Total	31	128	159

Sensitivity = 100%, specificity = 82%, false positive rate = 18%, false negative rate = 0%, positive predictive value = 57%, negative predictive value = 100%

hallucis brebis (FHB) muscles are suitable for derivation of Br(E)-MsEP waveforms. Deletis et al. [25] found that the TA and AH muscles have efficacy for wave detection, and that the AH is optimal because of its dominant dorsal-and-lateral column innervation, while the TA is an alternative to the AH. In contrast, in a preliminary study, Jankowska et al. [26] found that the waveform amplitude was the highest in the flexor muscle group of the foot upon stimulation of the corticospinal tract and showed that the highest amplitude of the excitatory postsynaptic potential (EPSP) was found in the alpha-motoneuron pools for the lower extremity muscles (small and long flexors of the foot) after dorsal-and-lateral column stimulation. Furthermore, regarding the neurophysiological mechanism, monosynaptic EPSPs of cortical origin were seen in all motoneuron species investigated, including distal as well as proximal hindlimb muscles. The proportion of motoneurons in which EPSPs were evoked and the amplitudes of the EPSPs indicated a more extensive cortical projection to motor nuclei for distal than for proximal muscles, as previously found for forelimb motoneurons [26]. In our series, we used multi-channel detection and obtained results consistent with these reports.

For examination of postoperative motor deficit and intraoperative waveform change, it is important that the muscle showing waveform deterioration is consistent with the actual weakened muscle. For this purpose, detection of many muscles is effective for evaluation, and it is not desirable to monitor a waveform intraoperatively that is poorly derived at baseline, especially when using equipment with a small number of channels. Therefore, it is desirable to derive a waveform from a monitorable muscle. Deletis et al. [25] reported that increasing the number of monitored muscles does not always give a major advantage, and that due to the overlap of myotomal innervation, it is unlikely that muscle Br(E)-MsEP monitoring can provide adequate information

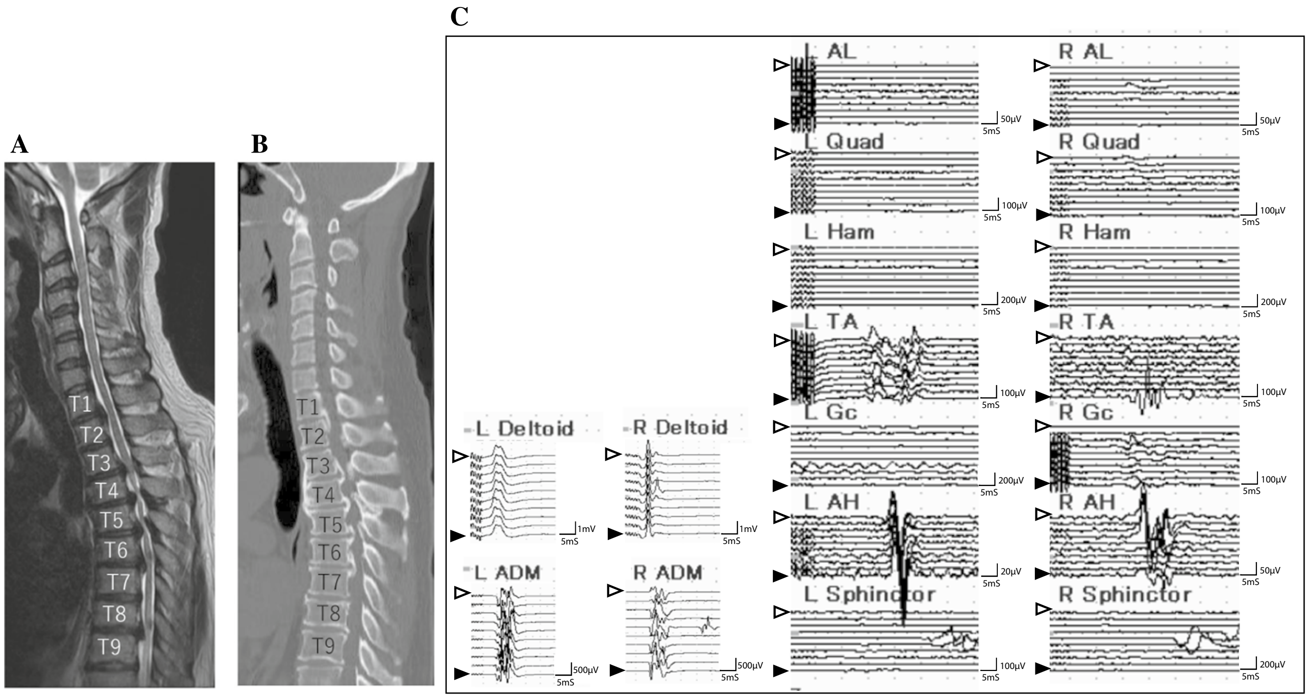

Fig. 4 The case of a 44-year-old male with OPLL. **a** Preoperative T2-weighted MRI. **b** Preoperative CT. **c** Baseline Br(E)-MsEP waveforms were obtained for the bilateral TA and AH, but not for other muscles (arrowhead). In the surgical procedure, posterior decompression and dekyphotic corrective fusion with instrumentation from T1 to T12 with decompression was performed. Postoperatively, left TA and bilateral AH waveforms were maintained, whereas the right TA waveform showed deterioration (open arrowhead)

during surgery on a root lesion. For example, in use of 8-channel equipment, 2 channels are derived from the upper limbs and at least 4 should be derived from distal muscles, since waveforms of distal muscles should be monitored as much as possible. This implies that in cases with a high risk of postoperative motor deficit, monitoring and detection of waveforms from distal muscles are particularly important.

There are several limitations in this study. First, the number of cases was limited, and the cases included intramedullary tumor, intradural extramedullary tumor, and OPLL, which are all likely to be associated with postoperative motor deficit and are treated with different surgical procedures. Second, the series focused on thoracic lesions, but did include a conus lesion. Fujiwara et al. [27] showed that corticospinal tracts and spinal cord segments coexist in a conus lesion, and that segmental and corticospinal tract disorders should be considered separately, but are hard to evaluate with a Br(E)-MsEP waveform. Third, our findings were not examined from the neurophysiological perspective, and there is a need to conduct a further study for elucidation of the underlying mechanism. Fourth, in our study, surgeons were informed during surgery of an acute decrease in amplitude of the Br(E)-MsEP response of ≥ 70% from baseline. Previous studies have used a criterion of a 50–80% decrease in amplitude [13–15, 19, 28–31], and some have used complete loss of response [32] or morphological change [3, 33]. Many studies have used a decrease of ≥ 50% [30, 31], and a further study of this criterion is desirable. However, a key feature of our study is that the devices were expandable to 32 recorded channels, which made it possible to detect many lower limb muscles in most cases. Thus, in our series, calculations with G*Power software (v. 3.1.9, Heinrich-Heine-University, Dusseldorf, Germany) showed that the statistical power for all groups was 84.7%. A calculated statistical power of > 80% is generally optimal for a significant result.

This is the first study of Br(E)-MsEP waveforms focused on each lower limb muscle and based on preoperative ambulatory status. The derivation rate was significantly higher in distal muscles than in proximal muscles, and detection of waveforms from distal muscles was still likely in a case with preoperative motor deficit, even though the derivation rate in these cases was generally low. The AH had a high derivation rate, even in cases with preoperative muscle weakness. Sensitivity of waveform deterioration to postoperative motor deficit also tended to be higher in distal muscles, which suggests that these muscles are reliable and should be targets in monitoring. Collectively, these results support our standard electrode montages for monitoring the AH in the lower extremities. We note that this study focused on Br(E)-MsEP waveform monitoring for lower limb muscles in thoracic spine surgery, and we plan to investigate the amplitude of Br(E)-MsEP waveforms for cervical or conus lesions in a further study.

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Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

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