



Wave changes in intraoperative transcranial motor-evoked potentials during posterior decompression and dekyphotic corrective fusion with instrumentation for thoracic ossification of the posterior longitudinal ligament

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Abstract

Background A prospective clinical study of amplitudes of intraoperative transcranial motor-evoked potentials (TcMEPs) was performed in patients undergoing surgery for the posterior longitudinal ligament of thoracic spine (T-OPLL).

Objective To investigate intraoperative TcMEPs during posterior decompression and dekyphotic corrective fusion with instrumentation for T-OPLL.

Methods The subjects were 33 patients with an average age of 48 years at surgery who underwent posterior decompression and fusion with instrumentation under intraoperative TcMEP monitoring. Age, gender, BMI, modified McCormick scale, prone and supine position test (PST), operative time, estimated blood loss, and Japanese Orthopaedic Association (JOA) score were recorded. Rates of successful appearance of TcMEPs, factors related to successful appearance, intraoperative amplitude changes, procedures related to amplitude deterioration, recovery of amplitude, procedures related to recovery, and postoperative paralysis were also investigated.

Results The rate of appearance was highest from the abductor hallucis (AH) (83.3%) compared with other muscles. There were 24 cases with amplitude deterioration: during exposure in 6, screwing in 2, and decompression in 16. No deterioration occurred during rod placement. There were 13 (39%) with postoperative motor deficits. Significantly lower rates of amplitude appearance occurred in cases with BMI, positive PST, modified McCormick scale IV, and preoperative JOA score.

Conclusions AH muscles were particularly useful for functional assessment of corticospinal conduction. High BMI, positive PST, modified McCormick scale IV, and low preoperative JOA score were associated with low rates of amplitude appearance. Amplitude deteriorations occurred throughout surgery, except during rod placement, and speedy rigid rod placement is important.

Keywords Wave change · Intraoperative transcranial motor-evoked potentials · Ossification of the posterior longitudinal ligament · Postoperative motor deficit

Introduction

Thoracic myelopathy due to ossification of the posterior longitudinal ligament (T-OPLL) generally requires surgical intervention because of its progressive nature and poor

response to conservative therapy. However, surgical outcomes are unsatisfactory [1–3]. We perform indirect spinal cord decompression with primary, wide laminoplasty decompression and dekyphosis with instrumentation via a posterior approach for cases of beak and flat-type OPLL accompanied by ossification of the ligamentum flavum and facet destruction [4].

Neurologic deterioration is a concern after surgery for thoracic OPLL, particularly in cases with a sharply protruded segmental form of ossification [5–7]. Neural complications are the most severe risks in surgery for T-OPLL, and

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intraoperative spinal cord monitoring is important to reduce these complications [8–10]. Transcranial motor-evoked potential (TcMEP) monitoring is increasingly used and is particularly effective for the corticospinal tract because it is easy to perform and has high sensitivity and specificity. There are several steps during surgery for T-OPLL (exposure, screw insertion, decompression, rod placement, and dekyphosis) that have the potential to decrease the amplitude of the TcMEP waveform [4] and to result in neurological deficit. The objective of this study was to investigate TcMEP wave changes and postoperative neurological deficits in thoracic posterior fusion surgery for T-OPLL.

Materials and methods

From 2010 to 2016, 33 consecutive patients with T-OPLL underwent indirect spinal cord decompression with primary decompression and dekyphosis with instrumentation via a posterior approach under intraoperative neurophysiological TcMEP monitoring at our hospital. Data from these cases were reviewed in this study. We followed the patients for a minimum of 1 year and an average of 3 years 10 months (12–96 months).

Anesthetic management

Benzodiazepine was used minimally, if at all, as a preanesthetic medication because it suppresses waveform latency and amplitude. Propofol (3–4 mg/kg), fentanyl (2 mg/kg), and vecuronium (Fuji Pharma Co., Ltd, Tokyo, Japan; 0.12–0.16 mg/kg) were administered for induction, and anesthesia was maintained using propofol (50–100 µg/kg/min) and fentanyl (1–2.5 µg/kg/hr). Concomitant hypotensive anesthesia was given (blood pressure 90–100 mmHg), as appropriate, by continuously administering PGE1 and a short-acting β1-blocker (landiolol). Patients were maintained in a normothermic state, and should intraoperative spinal damage occurs, the temperature was raised. End-tidal CO₂ was maintained in the reference range throughout surgery.

Surgical treatment

Surgical treatment of OPLL with posterior decompression and dekyphotic corrective fusion with instrumentation was performed as described elsewhere [4, 11, 12]. The basic decompression area was the level at which the spinal cord was compressed. The fusion area included 3 vertebrae above and below the OPLL lesion with a segmental screw. After gentle insertion of pedicle screws, a temporary titanium alloy or cobalt–chromium alloy rod (≥ 6 mm in diameter; currently the most rigid rod available) was placed on one side. Laminectomy was then performed using an air drill. In the

placement of rigid bilateral rods, dekyphosis was achieved with the cantilever technique under intraoperative TcMEP monitoring to achieve greater decompression of the spinal cord. The degree of decompression was checked by ultrasonography, and additional dekyphosis was performed with a compression maneuver and in situ rod bending if needed. TcMEP monitoring was checked frequently during surgery. A full segmental pedicle screw construct is usually advantageous for this procedure. All patients underwent initial posterior decompression and dekyphotic corrective fusion with instrumentation, followed by a rehabilitation program for standing and gait exercise. Rehabilitation was continued for patients in whom symptoms improved after surgery. A second surgery for resection of beak-type T-OPLL was performed if there was no improvement by 3 weeks after surgery or there was aggravation of symptoms. Recently, we have also performed this surgery using resection at an anterior site of the spinal cord from a posterior approach (RASPA) [12, 13].

Stimulating and recording methods

Transcranial stimulation was performed with a MS120B system (Nihon Kohden, Tokyo, Japan), using 5 consecutive stimuli 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 point of stimulation was 2 cm anterior and 3 cm lateral from the Cz (International 10–20 System) over the cerebral cortex motor area (left: anode, right: cathode). Muscle action potentials from the upper and lower extremities were recorded via two needle electrodes that were 3–5 cm apart, using Neuromaster MEE-1000 ver. 04.12 (Nihon Kohden, Japan), which can be expanded to 32 channels as many of the following muscles as possible were chosen for monitoring, depending on the spinal level at which surgery was performed: deltoid and hypothenar from the upper extremities, and bilateral sphincters (SP), adductor longus (AL), quadriceps femoris (Quad), hamstrings (Ham), tibialis anterior (TA), gastrocnemius (GS), and abductor hallucis (AH) from the lower extremities. Only MEP data from lower extremity muscles were used for analysis.

Monitoring and alert parameters

TcMEP baseline values were recorded immediately after surgical exposure of the spine. Signals were recorded after each step of exposure: insertion of pedicle screws, insertion of a temporary titanium alloy or cobalt–chromium alloy rod on one side, laminectomy, placement of rigid bilateral rods, and dekyphosis. TcMEP monitoring was performed at least every 10 min, in addition to after each step. A final TcMEP test was performed after wound closure. Data for

TcMEP peak-to-peak amplitude measurements are in μV . A decreased amplitude of the TcMEP waveform of $\geq 70\%$, based on use of this criterion in a nationwide, prospective multicenter study in Japan and in other studies [14], was defined as amplitude deterioration. Recovery of amplitude was defined as recovery to the control waveform.

Operative time and estimated blood loss (EBL) were examined. Age, gender, BMI, and Japanese Orthopaedic Association (JOA) score (maximum 11 points) [15] were recorded. Postoperative recovery rate was determined by Hirabayashi's method as follows: recovery rate = (postoperative JOA score – preoperative JOA score) \times 100 / (full score – preoperative JOA score). The modified McCormick scale was used to define global functional impairment [16]: 1 = neurologically intact; 2 = mild motor or sensory deficit, but functional independence; 3 = moderate deficit and limitation of function; 4 = severe motor or sensory deficit, dependent; and 5 = paraplegia or quadriplegia. Aggravation of symptoms due to a spinal alignment change while in bed was based on evaluation of symptoms such as numbness or spasticity when in a persistent prone or supine position in bed. Most cases have aggravation of these symptoms within 60 s. We refer to this test as a prone and supine position test (PST), and in this test cases with aggravation of symptoms are defined as positive [11, 12]. A postoperative motor deficit was defined as a 1-point or greater decrease in the manual muscle test on the most immediate check after return to the recovery room, compared with the preoperative motor status. Operative time and estimated blood loss (EBL) were examined. Rates of successful appearance in the lower extremities, intraoperative amplitude change, factors related to successful appearance, procedure during amplitude deterioration, recovery of amplitude, procedure during recovery, and postoperative paralysis were also investigated. The study followed the guidelines of the IRB of our institute, and informed consent was obtained from all subjects.

Statistical analysis

Statistical analysis was performed by unpaired *t* test and Chi-square test. Differences among 3 groups were analyzed using the Kruskal–Wallis test in SPSS for Windows ver. 22 (SPSS Inc, IBM, Armonk, NY, USA). $P < .05$ was considered significant in all analyses.

Results

The characteristics of the 33 patients are shown in Table 1. The patients included 21 men, and 12 women and had an average age at surgery of 48 years (17–79 years) and an average body mass index (BMI) of 33.5 kg/m^2 (22–50 kg/m^2). The mean preoperative JOA score was 3.8, and 16/33

Table 1 Demographic and clinical data of patients

Item	Value
Gender	
Men/women	21/12
Age at surgery (years)	47.8 \pm 13.7
Body mass index (kg/m^2)	33.5 \pm 7.3
Preoperative JOA score	3.8 \pm 2.8
Preoperative modified McCormick scale I/II/III/IV	0/1/17/15
Positive finding in a preoperative PST (<i>n</i>)	16
Location of OPLL: upper (T1–5)/middle (T5–9)/lower (T9–12)	7/25/1
Operative time	407.0 \pm 148.5
Estimated blood loss	1141.6 \pm 755.8
Average of number of OPLL	1.6 \pm 1.0
Type of OPLL: continuous/segmental/mixed/beak	0/0/11/22
Postoperative JOA score (1 year)	7.5 \pm 2.7
Recovery rate (1 year)	52.0 \pm 33.5

Data are shown as mean \pm standard deviation

JOA Japanese Orthopaedic Association, PST prone and supine position test

patients had a positive PST. The levels of OPLL were mostly in the middle thoracic region ($n = 25$, 56.8%), followed by the upper region ($n = 7$, 15.9%). The mean operative time was 407 min (range 240–823 min), and EBL was 1141 ml (251–1900 ml). The JOA score and recovery rate in all cases at 1 year after surgery were 7.5 and 52%, respectively, and these values gradually increased up to 1 year after surgery, except for one case with postoperative cerebral infarction. Postoperatively, there were two cases with infection and one with a cerebral deficit. Fourteen muscles in each patient (462 muscles in 33 patients) in the lower extremities were examined for monitoring, and 221 muscles (47.7%) were detected at baseline, giving an appearance rate of 47.8%. Among these muscles, the AH appearance rate of 83.3% was the highest (Table 2). There were 24 cases with intraoperative amplitude deterioration, during exposure ($n = 6$), screw insertion ($n = 2$), and decompression ($n = 16$). No case had amplitude deterioration during rod placement (Table 2). Recovery of amplitude occurred in 20 cases (21 procedures), during temporary rod placement ($n = 5$), decompression ($n = 5$), and bilateral rod placement ($n = 10$), and not during a procedure ($n = 1$) (Table 2). Thirteen cases (39%) had postoperative motor deficits, including 5 with amplitude deterioration and recovery, 5 with amplitude deterioration but no recovery, and 3 with flat waveforms during surgery (Table 3). The amplitude appearance rate was significantly lower in patients with BMI $< 40 \text{ kg/m}^2$ (25.9% vs. 54.9%, $P < .05$), positive PST (31.3% vs. 63.4%, $P < .005$), modified McCormick scale IV (26.7%, $P < .005$), and preoperative JOA score < 4 (36.1% vs. 63.8%, $P < .005$), but did not

Table 2 Intraoperative TcMEP monitoring findings

Item	Value
Rates of successful derivation (%)	47.8 ± 33.2
AL	28.8 ± 45.1
Quad	30.3 ± 46.7
Ham	40.9 ± 47.5
TA	65.2 ± 44.2
GS	47.0 ± 48.3
AH	83.3 ± 36.8
SP	34.8 ± 47.6
Amplitude change, number of cases (number of procedures)	22 (24)
Change during procedure	
Exposure	6
Screwing	2
Temporary rod placement	0
Decompression	16
Bilateral rod placement (with dekyphosis)	0
Recovery of amplitude, number of cases (number of procedures)	20 (21)
Recovery during procedure	
Exposure	0
Screwing	0
Temporary rod placement	5
Decompression	5
Bilateral rod placement (with dekyphosis)	10
No procedure	1

Table 3 Relationship between postoperative motor deficits and intraoperative TcMEP

Item	Postoperative motor deficit	No postoperative motor deficit
Number of cases	13 (39%)	20 (61%)
Amplitude deterioration and recovery	5	12
Amplitude recovery to baseline	0	4
Amplitude deterioration and no recovery	5	0
Flat waveform during surgery	3	0
No change during surgery	0	4

differ significantly between males and females (Table 4). Two illustrative cases are described below.

Case 1 Beak-type OPLL at the T4/5 region and progressive myelopathy (Fig. 1a, b). At the start of surgery, right AL, TA, GC, and bilateral AH waves were detected as controls (Fig. 1c). Surgery for posterior correction and fusion at T1–11 was performed under regular TcMEP monitoring. The TcMEP amplitude decreased from baseline during exposure (Fig. 2a, b), recovered following temporary rod placement (Fig. 2c), decreased again during decompression

(Fig. 3a), and ultimately recovered after bilateral rod placement (Fig. 3b, c). The patient had no additional neurological deficit and could walk without a cane at 3 months after surgery.

Case 2 Beak-type OPLL at the 8/9 regions and progressive myelopathy (Fig. 4a, b). At the start of surgery, only a right AH wave was detected as a control (Fig. 4c). Surgery for posterior correction and fusion at T6–11 was performed under regular TcMEP monitoring (Fig. 5a). The TcMEP amplitude decreased from baseline during exposure (Fig. 5b), recovered following temporary rod placement (Fig. 5c), decreased again during decompression (Fig. 5d), and ultimately did not recover after bilateral rod placement (Fig. 6a). The patient had additional neurological deficit, but his lower extremity motor weakness recovered after RASPA (Fig. 6b) [12, 13].

Discussion

Symptomatic OPLL occurs more often in cervical vertebrae than in thoracic vertebrae. However, the risk of postoperative neurological deficits of T-OPLL is higher than for cervical OPLL [17, 18], and in this study, there was a high rate of postoperative neurological deficits (39%). This may reflect the higher risk of these deficits for T-OPLL. A recent prospective study from the Japanese Multicenter Research Organization for Ossification of the Spinal Ligament reported a rate of 32.2% for postoperative neurological deficits (37/115 cases) [19]. Therefore, spinal cord monitoring during surgery for T-OPLL is important, but has not been previously studied in detail. In this study, acceptable baseline TcMEP responses were obtained from only 221 of 462 (47.8%) muscles used for monitoring in the lower extremities. This may be because most of the patients had motor and sensory deficits and severe myelopathy, based on the mean preoperative JOA score of 3.8. The AH appearance rate was 83% in patients with T-OPLL with severe myelopathy. AH muscles have been used for functional assessment of corticospinal conduction because waveform appearance is simple using the standard belly–tendon method [20, 21]. The dominant nerves of AH muscles are L5–S1, and this may also be a reason for the high AH wave appearance rate because sacral regions tend to be spared during incomplete spinal cord injury [22]. Our findings show that AH muscles in spinal cord monitoring during surgery for T-OPLL with severe myelopathy are extremely important indicators of intraoperative neurological conditions (Figs. 1, 2).

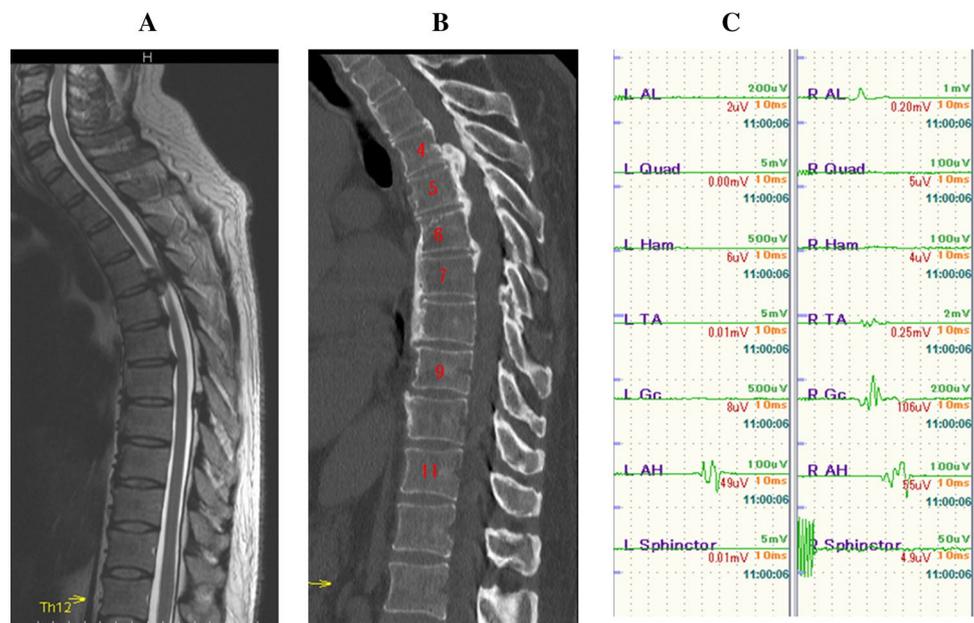
A decrease from a baseline TcMEP amplitude of ≥ 70% occurred in 24 cases (66.7%). Of these cases, five without amplitude recovery had postoperative motor deficits. To examine the relationship between postoperative motor deficits and intraoperative TcMEP, cases with amplitude

Table 4 Factors related to waveform derivation in intraoperative neurophysiological monitoring

	Rate of derivation (%)	Significance (P)
Sex		
Male (n = 21)	46.6 ± 31.6	NS
Female (n = 12)	50.0 ± 37.3	
Body mass index (kg/m ²)		
< 40 (n = 25)	54.9 ± 34.1	< .05
≥ 40 (n = 8)	25.9 ± 18.7	
Prone and supine position test		
(+)	31.3 ± 27.1	< .005
(-)	63.4 ± 31.4	
Modified McCormick scale		
I (n = 0)		< .005
II (n = 1)	100	
III (n = 17)	63.4 ± 31.4	
IV (n = 15)	26.7 ± 22.0	
Japanese Orthopaedic Association score		
< 4 (n = 19)	36.1 ± 29.4	< .05
≥ 4 (n = 14)	63.8 ± 32.4	

Data are shown as mean ± standard deviation
 NS not significant

Fig. 1 Case 1. **a, b** The patient was a 41-year-old man with beak-type OPLL at the T4/5 region and progressive myelopathy. **c** Right AL, TA, GC, and bilateral AH waves were detected at the start of surgery



deterioration and recovery were divided into those with and without a postoperative motor deficit (Table 3). This deficit was defined as a decrease of 1 point or more in the first manual muscle test after return to the recovery room, compared with the preoperative motor status. We evaluated postoperative motor status because spinal cord damage may remain after recovery of a deteriorated amplitude to the baseline waveform, and this damage may lead to a transient motor deficit (Table 3). Factors related to lower rates

of amplitude appearance included high BMI, positive PST, modified McCormick scale IV, and lower preoperative JOA score (Table 4). The last three of these factors indicate severe myelopathy, and patients with severe myelopathy have motor deficits, which reduce the amplitude appearance rate. To our knowledge, this is the first study to find an association of BMI with the rate of amplitude appearance. High BMI may simply reflect inadequate recording and a lower wave

Fig. 2 **a, b** TcMEP amplitude decreased from baseline during exposure. **c** Amplitude recovered following temporary rod placement

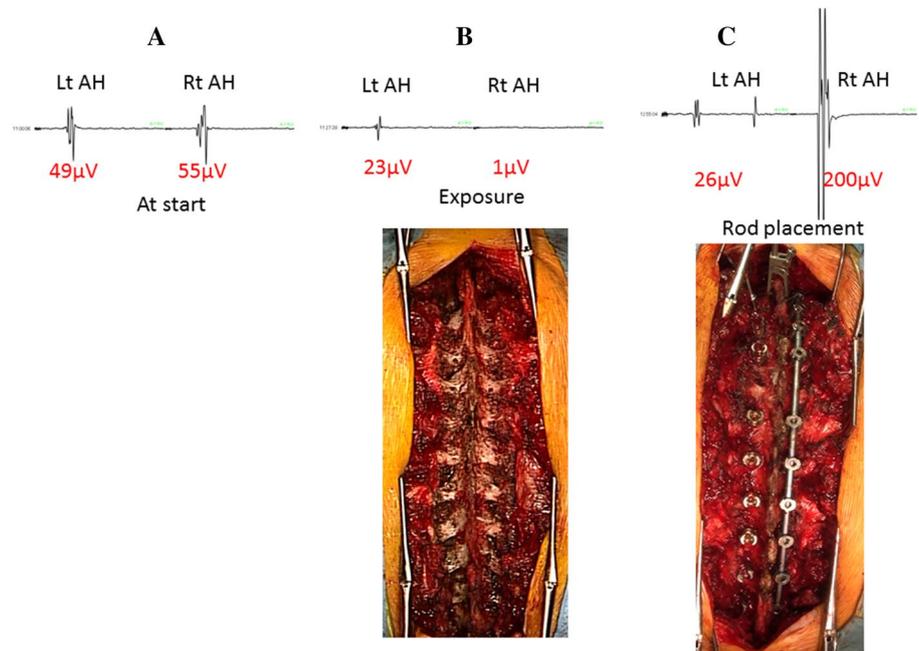
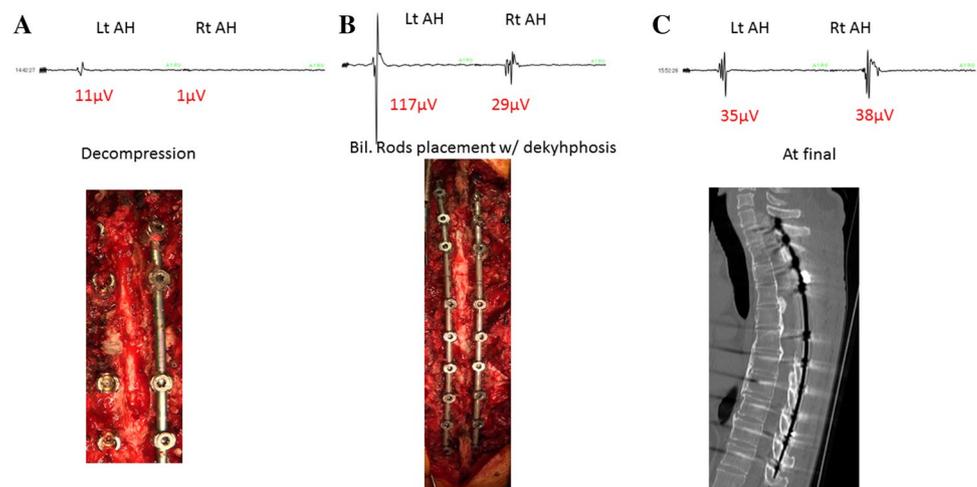


Fig. 3 **a** Amplitude decreased again during decompression. **b, c** Amplitude recovered after bilateral rod placement



amplitude in patients with increased body mass due to technical difficulties related to body size.

Amplitude deterioration occurred at the time of exposure, as well as during removal of the spinous process and decompression. Matsuyama et al. [5] found that thoracic kyphosis can progress easily due to positioning of the patient during surgery or in laminectomy [5]. This may lead to postoperative neurological deterioration because of the vulnerable spinal cord due to severe compression. A subtle alteration in spinal cord alignment during exposure procedures may also increase spinal cord compression, leading to deterioration of symptoms. Amplitude recovery occurred in five cases in rod placement on one side and in ten cases in bilateral rod placement, and rapid rod placement was important for

spinal cord recovery. Segmental gentle screw insertion and rigid rod (such as a cobalt–chromium alloy rod ≥ 6 mm in diameter) placement are particularly important to prevent spinal cord injury after removal of the spinous process [11]. Because the deterioration of TcMEP amplitude easily occurs during each maneuver for T-OPLL, rescue procedure such as prompt rod placement must be needed depending on amplitude changes (Table 2).

There are potentially significant limitations to this study. These include limitations related to the small subject number, potential changes in surgical, anesthetic and rehabilitation management, and variations in techniques among surgeons and anesthesiologists. However, we were able to detect intraoperative TcMEP changes in detail, to show the

Fig. 4 Case 2. **a, b** The patient was a 31-year-old man with beak-type OPLL at the T2/3 and 8/9 regions and progressive myelopathy. **c** Only a right AH wave was detected at the start of surgery

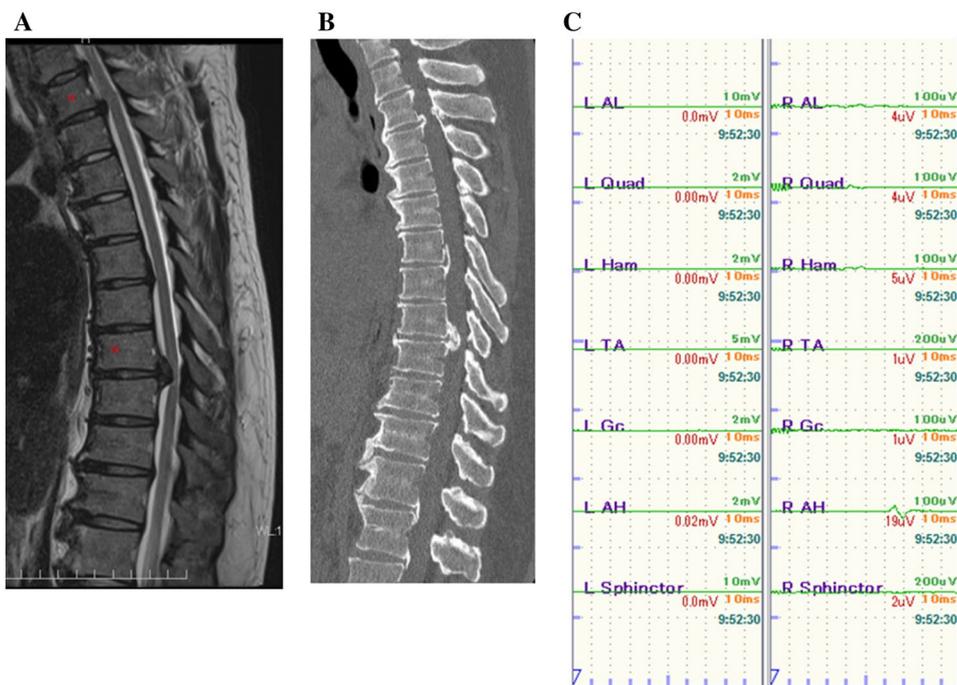


Fig. 5 **a** Surgery for posterior correction and fusion at T6–11 was performed under regular TcMEP monitoring. **b** TcMEP amplitude decreased from baseline during exposure. **c** Amplitude recovered following temporary rod placement. **d** Amplitude decreased again during decompression

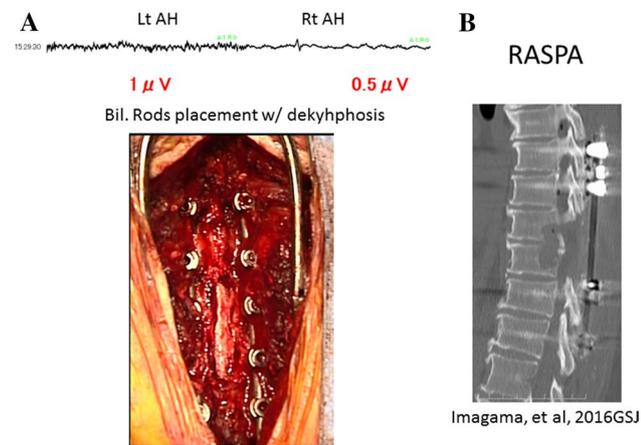
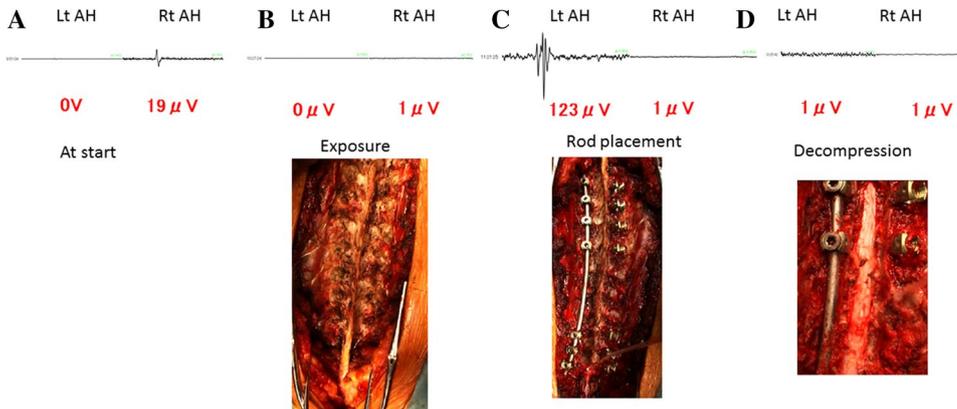


Fig. 6 **a, b** Amplitude did not recover after bilateral rod placement

efficacy of AH muscles for this purpose, and to make prompt procedural changes after detection of a TcMEP change.

In conclusion, AH muscles are effective for functional assessment of corticospinal conduction, even in T-OPLL patients with severe myelopathy. Rates of amplitude appearance were significantly reduced in cases with high BMI, positive PST, modified McCormick scale IV, and low pre-operative JOA score. Amplitude deterioration occurred at the time of exposure, in addition to during removal of the spinous process and decompression. Rapid rigid rod placement is important for spinal cord recovery when amplitude deterioration occurred.

Compliance with ethical standards

Conflict of interest The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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