Transcranial motor evoked potential waveform changes in corrective fusion for adolescent idiopathic scoliosis

Kazuyoshi Kobayashi, MD, Shiro Imagama, MD, Zenya Ito, MD, Kei Ando, MD, Tetsuro Hida, MD, Kenyu Ito, MD, Mikito Tsushima, MD, Yoshimoto Ishikawa, MD, Akiyuki Matsumoto, MD, Yoshihiro Nishida, MD, and Naoki Ishiguro, MD

Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, Nagoya, Japan

OBJECTIVE Corrective surgery for spinal deformities can lead to neurological complications. Several reports have described spinal cord monitoring in surgery for spinal deformity, but only a few have included patients younger than 20 years with adolescent idiopathic scoliosis (AIS). The goal of this study was to evaluate the characteristics of cases with intraoperative transcranial motor evoked potential (Tc-MEP) waveform deterioration during posterior corrective fusion for AIS.

METHODS A prospective database was reviewed, comprising 68 patients with AIS who were treated with posterior corrective fusion in a prospective database. A total of 864 muscles in the lower extremities were chosen for monitoring, and acceptable baseline responses were obtained from 819 muscles (95%). Intraoperative Tc-MEP waveform deterioration was defined as a decrease in intraoperative amplitude of $\geq 70\%$ of the control waveform. Age, Cobb angle, flexibility, operative time, estimated blood loss (EBL), intraoperative body temperature, blood pressure, number of levels fused, and correction rate were examined in patients with and without waveform deterioration.

RESULTS The patients (3 males and 65 females) had an average age of 14.4 years (range 11–19 years). The mean Cobb angles before and after surgery were 52.9° and 11.9° , respectively, giving a correction rate of 77.4%. Fourteen patients (20%) exhibited an intraoperative waveform change, and these occurred during incision (14%), after screw fixation (7%), during the rotation maneuver (64%), during placement of the second rod after the rotation maneuver (7%), and after intervertebral compression (7%). Most waveform changes recovered after decreased correction or rest. No patient had a motor deficit postoperatively. In multivariate analysis, EBL (OR 1.001, $p = 0.085$) and number of levels fused (OR 1.535, $p = 0.045$) were associated with waveform deterioration.

CONCLUSIONS Waveform deterioration commonly occurred during rotation maneuvers and more frequently in patients with a larger preoperative Cobb angle. The significant relationships of EBL and number of levels fused with waveform deterioration suggest that these surgical invasions may be involved in waveform deterioration.

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KEY WORDS adolescent idiopathic scoliosis; Tc-MEP; transcranial motor evoked potential; waveform deterioration; posterior corrective fusion; spine

CORRECTIVE surgery for spinal deformity can lead to neurological complications.⁶ During the surgical procedure, a neurological deficit may occur in association with screw insertion and rod placement; thus, intraoperative spinal cord monitoring is important

for performing safe spinal surgery.^{11,17,28,29} Somatosensory evoked potentials (SSEPs) came into use for monitoring during spine and spinal cord surgery in the 1980s.^{2,9,35} In the early 1990s, spinal cord evoked potentials (SCEPs) after brain stimulation (D-wave) were introduced for moni-

ABBREVIATIONS AIS = adolescent idiopathic scoliosis; EBL = estimated blood loss; EMG = electromyography; SCEP = spinal cord evoked potential; SSEP = somatosensory evoked potential; Tc-MEP = transcranial motor evoked potential.

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toring motor pathways.^{15,16} Other monitoring methods have also been developed, include free-running electromyography (EMG), SCEP after stimulation of the spinal cord, SCEP after stimulation of the peripheral nerve, and transcranial motor evoked potentials (Tc-MEPs).^{1,19–21} Multimodal monitoring is more effective than single-mode monitoring, with combinations of Tc-MEPs and D-waves,^{24,33} and Tc-MEP and SSEP have been found to be reliable.⁶ Tc-MEPs are increasingly used to assess the functional integrity of motor pathways and are particularly effective for corticospinal tract monitoring because they can be easily monitored and have high sensitivity and specificity.^{11,17,28,29}

Spinal cord monitoring is widely used in surgery for spinal deformity,^{23,25,27,30,31,35} but only a few studies have included patients with adolescent idiopathic scoliosis (AIS).^{7,18} Studies of intraoperative factors such as operative time, estimated blood loss (EBL), body temperature, and changes in blood pressure are particularly rare in patients who are younger than 20 years and have AIS. Therefore, the purpose of this study was to examine intraoperative Tc-MEP waveform deterioration during posterior corrective fusion for AIS, with the aim of understanding neurophysiological changes during surgery and measures for prevention of waveform deterioration.

Methods

Patient Population

A total of 73 surgeries for AIS were performed at our hospital from January 2009 to December 2014. Five patients were excluded from the study: 4 who were treated via an anterior approach and 1 who underwent revision surgery. The subjects of the study were the remaining 68 patients (3 males and 65 females) who were treated using a posterior-only approach in a prone position under Tc-MEP monitoring. A total of 864 muscles in the lower extremities were chosen for monitoring. Of these muscles, acceptable baseline Tc-MEP responses were obtained from 819 muscles (95%). The mean age at the time of surgery was 14.4 years (range 11–19 years). Preoperative motor status and comorbidities were not used in the exclusion criteria. There were no preoperative motor deficits. This study was approved by the ethics committee of our university hospital.

Radiographic Analysis

All patients underwent standing anteroposterior, side-bending, and manual traction radiography preoperatively, and standing anteroposterior radiography postoperatively. The flexibility index was calculated as (preoperative Cobb angle – side-bending or traction Cobb angle) × 100/preoperative Cobb angle. The curve correction (%) was calculated as (preoperative Cobb angle – postoperative Cobb angle) × 100/preoperative Cobb angle.

Surgical Procedure

In all cases, pedicle screws were inserted and polyethylene tape was simultaneously passed under the lamina. All vertebrae were held by pedicle screws or tapes. After posterior iliac crest bone graft, rods bent into a good

sagittal alignment were placed on the concave side and correction was performed through a rotation maneuver. Ponte osteotomy was performed if required. Distraction was applied to the pedicle screws, and the concave side of the curve was corrected. For the convex side, the rods were located in situ after posterior iliac crest bone and local bone graft, and correction was performed by applying compression between the pedicle screws.¹⁰

Anesthetic Management and General Conditions During Surgery

A minimal dose of benzodiazepine was used as pre-anesthetic 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/hr), and vecuronium (0.01–0.04 mg/kg/hr). Concomitant hypotensive anesthesia was given as appropriate with continuous prostaglandin E1 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 CO₂ 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 blood pressure monitoring. Systolic blood pressure variation was measured during surgery, and systolic blood pressure was determined at the time of waveform deterioration.

Stimulation and Recording Methods

We used an MS120B electrical stimulator (Nihon Kohden) to perform transcranial stimulation. The stimulation parameters were 5 stimuli in a row at 2-msec intervals, a constant biphasic current of 200 mA for 500 µsec, a 50- to 1000-Hz filter, and a 100-msec 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 (version 05.10, Nihon Kohden), which is expandable to 32 channels, muscle action potentials were recorded from the upper and lower extremities via a pair of needle electrodes. The bilateral trapezius, triceps, deltoid, biceps, brachioradialis, abductor digit minimi, extensor carpi ulnaris, adductor longus, quadriceps femoris, hamstring, tibialis anterior, gastrocnemius, abductor hallucis, and anal sphincter muscles were used as target muscles. Tc-MEP data from these muscles were used for analysis. Multimodal monitoring was used in all cases, with a particular combination of brain stimulated SCEPs (D-wave) and SSEPs. Free-running EMG from all the above muscles was monitored throughout the operation.

Monitoring and Alert Parameters

The Tc-MEP baseline was taken immediately after documented surgical exposure of the spine. Waiting until this point for baseline measurements reduced the effects on Tc-MEP responses because of body and spinal

cord temperature changes occurring with exposure. Signals were rechecked after surgical exposure, screw insertion, decompression, and wound closure. Surgeons were informed of an acute change in the Tc-MEP response. A decrease in amplitude of $\geq 70\%$ from the Tc-MEP baseline was considered to be significant.¹⁴ If a waveform deteriorated during surgery due to anesthesia-related factors, systolic blood pressure was raised, or hypotensive anesthesia was reversed. If the deterioration occurred due to technical factors surgery was interrupted, the position of an inserted screw was confirmed, or release of correction was performed. After these approaches, the patient was warmed, irrigation was performed with warm saline, and steroids were administered. If the waveform did not recover, a wake-up test was performed, and if there was no improvement, surgery was terminated.

Statistical Analysis

Analysis was performed using SPSS (version 22 for Windows, IBM). Differences between 2 groups were analyzed using the Mann-Whitney U-test, Student t-test, or Fisher exact test, and differences among 3 groups were analyzed using the Kruskal-Wallis test; $p < 0.05$ was considered to be significant in all analyses. Odds ratios and their 95% confidence interval were estimated using a multivariate logistic regression model to evaluate the association of waveform deterioration with demographic factors, perioperative factors, and outcomes.

Results

Clinical and Operative Data

The preoperative characteristics of the patients are shown in Table 1. The patients' curves were assessed according to Lenke classification.²² Eighteen patients had Type 1 curves; 10 patients, Type 2; 10 patients, Type 3; 3 patients, Type 4; 18 patients, Type 5; and 9 patients had Type 6 curves. Preoperatively, the mean Cobb angle was 52.9° (range 30° – 96°), the manual traction Cobb angle was 26.7° (range 6° – 73°), and the mean flexibility index was 50.2° (range 7.4° – 81.4°) on traction radiographs. Postoperatively, the mean Cobb angle was 11.9° (range 1° – 41°) and the correction rate was 77.4% (range 45.0% – 97.6%). The average operation time was 296 minutes (range 159–606 minutes), and the average EBL was 744 ml (range 85–3300 ml). The average extent of fusion was 10 levels (range 5–15 levels).

Derivation, Waveform Deterioration, and Postoperative Motor Deficits

Of the 68 patients, 14 (20%) had intraoperative waveform deterioration of $\geq 70\%$ in Tc-MEP amplitude from baseline, including bilaterally in 6 patients (Table 2). The relationship between preoperative Cobb angle and waveform deterioration is shown in Fig. 1. Among the 14 patients, the Lenke types were 1 ($n = 3$), 2 ($n = 3$), 3 ($n = 2$), 4 ($n = 2$), 5 ($n = 2$), and 6 ($n = 2$). Waveform deterioration occurred before screw insertion ($n = 2$), after screw insertion ($n = 1$), after rotation maneuver ($n = 9$), in rod placement after rotation maneuver ($n = 1$), and after compression ($n = 1$). Waveform deterioration fully recovered

TABLE 1. Preoperative demographic data

Item	Value
Mean age in yrs	14.8 (2.7)
Female/male ratio	65/3
Lenke curve type	
1	18
2	10
3	10
4	3
5	18
6	9
Mean preop Cobb angle, major curve ($^\circ$)	52.9 (12.4)
Mean preop traction Cobb angle, major curve ($^\circ$)	26.7 (10.8)
Mean flexibility correction rate at major curve (%)	
Traction	50.2 (13.2)
Side bending	35.7 (9.3)

Mean data are shown as the mean (SD).

during surgery after maneuver interruption in 6 patients and release of correction in 2 patients. Deterioration partially improved in 4 patients, in which postoperative leg pain and numbness occurred in 3 patients as neurological deficits, but none of these patients had postoperative motor deficits and the symptoms disappeared within 3 months after surgery. Consequently, the sensitivity was 100%, specificity was 83%, the positive predictive value (PPV) was 79%, and the negative predictive value (NPV) was 100% (Table 3).

Comparison of Patients With and Without Waveform Deterioration

Age, intraoperative body temperature at the time of waveform deterioration, systolic blood pressure at the time of waveform deterioration, variation in blood pressure during surgery, flexibility, and correction rate did not differ significantly between patients with ($n = 14$) and without ($n = 54$) waveform deterioration. In D-wave, SSEPs, and free-running EMG modalities, there were no waveform changes. The thoracic main curve showed a tendency to differ between these groups ($p = 0.09$) and there were significant differences in terms of operative duration, EBL, preoperative Cobb angle, and number of levels fused (all $p < 0.05$) (Table 4). In a multivariate regression model, $EBL \geq 1000$ ml (OR 1.001, 95% CI 1.001–1.003; $p = 0.085$) and number of levels fused ≥ 10 (OR 1.535, 95% CI 1.011–2.331; $p = 0.045$) were associated with waveform deterioration (Table 5).

Details of Patients With Neurological Events

In this series, 3 patients had neurological events of bilateral lower-leg pain and numbness postoperatively, but there were no motor deficits. All 3 patients experienced waveform deterioration. The symptoms continued for 1 month in 1 patient (Case 5, Table 2) and for 3 months in 2 patients (Cases 8 and 13, Table 2). At 6 months postoperatively, all symptoms had disappeared.

TABLE 2. Details of the 14 cases with intraoperative waveform deterioration

Case No.	Age (yrs), Sex	Lenke Type	Fusion Range	Timing of Waveform Deterioration	Muscles of Waveform Deterioration	Cobb Angle (°)		Curve Correction (%)	Intraop Wave Recovery	Postop Deterioration
						Preop	Postop			
1	14, F	1	T4–L2	After screw insertion	Rt AL quad	48	15	69	FR	None
2	14, F	1	T2–12	After rotation maneuver	Rt AL, TA, Gc	50	10	80	FR	None
3	13, F	1	T2–L1	Before screw insertion	Rt AL, AH	61	12	80	FR	None
4	12, F	2	T2–L1	After rotation maneuver	Bilat AH	68	13	81	FR	None
5	12, F	2	T2–L1	After rotation maneuver	Lt AL, quad, TA, Gc	39	12	69	FR: lt AL, quad; PR: lt TA, Gc	Bilat leg pain (1 mo)
6	12, F	2	T2–L1	After rotation maneuver	Rt ham	55	5	91	PR: rt ham	None
7	12, F	3	T4–L1	After rotation maneuver	Lt quad	49	5	90	FR	None
8	13, F	3	T4–L4	After rotation maneuver	Bilat AL, lt quad, ham, Gc	84	15	82	FR: lt quad; PR: bilat AL, lt ham, Gc	Bilat leg pain (3 mos)
9	14, F	4	T3–L5	In rod placement after rotation maneuver	Bilat quad, TA, Gc	96	41	57	FR	None
10	19, F	4	T4–L1	Before screw insertion	Lt Gc	50	12	76	FR	None
11	14, F	5	T10–L3	After rotation maneuver	Bilat TA, Gc	51	5	90	FR	None
12	13, F	5	T11–L4	After compression	Bilat AL, quad, TA, Gc, AH	56	12	79	FR	None
13	14, F	6	T2–L3	After rotation maneuver	Bilat AL, quad, TA, Gc, AH	52	12	77	FR: bilat AL, quad; PR: bilat TA, Gc, AH	Bilat leg pain (3 mos)
14	14, F	6	T11–L4	After rotation maneuver	Lt AH	48	7	85	FR	None

AH = abductor hallucis; AL = adductor longus; FR = full recovery; Gc = gastrocnemius; ham = hamstring; PR = partial recovery; quad = quadriceps femoris; TA = tibialis anterior.

Illustrative Case

Case 8

This 13-year-old girl had a preoperative main Cobb angle of 84° due to AIS (Fig. 2A). Preoperative motor and sensory examination findings were normal. The patient underwent posterior spinal fusion with instrumentation from T-4 to L-4 with posterior osteotomy around the apex of the deformity (T-11, T-12, and L-1) due to the stiffness of the curve and fused segments. She had acceptable baseline Tc-MEP values bilaterally (Fig. 2C, open arrow). After a rotation maneuver, Tc-MEP wave deterioration occurred beyond the 70% criterion bilaterally for the adductor longus, left quadriceps, hamstrings, and gastrocnemius (Fig. 2C, arrowhead). Maneuver interruption and release of correction was performed, but a wakeup test was not performed. The waveform eventually improved to > 50% of baseline for the left quadriceps muscle, while others were not improved (open arrowhead). Postoperative neurological examination showed continued left leg pain lasting 3 months but not producing motor deficits. The postoperative Cobb angle was 15°, with a curve correction rate of 82% (Fig. 2B).

Discussion

Spinal cord monitoring is commonly used in surgery for spinal deformity. In 92 patients with scoliosis, Kamata et al. found waveform changes in 11 (12%) and no motor deficits using spinal cord–tibial nerve potentials.¹³ In 102 patients with scoliosis, Tsuji et al. found Tc-MEP waveform changes in 20 patients (19.6%), with 3 patients

having transient motor deficits.³⁶ In a multicenter study of 204 scoliosis cases, Ito et al. showed that multichannel monitoring using at least 8 channels is desirable for intraoperative spinal cord monitoring and has a sensitivity of 100% and a specificity of 95%.¹² Bhagat et al. reported an incidence of significant alerts of 7.1% using combined monitoring with SSEPs and MEPs in 354 consecutive

FIG. 1. Preoperative Cobb angles in patients with and without waveform deterioration. The percentage indicates the incidence of waveform deterioration (cases with waveform deterioration/all cases).

TABLE 3. Analysis of monitoring results

Result	Neurological Event		Total
	Absent	Present	
Waveform deterioration	11	3	14
No waveform deterioration	54	0	54
Total	65	3	68

Sensitivity, 100%; specificity, 83%; positive predictive value, 79%; negative predictive value, 100%.

cases with spinal deformity.³ Ferguson et al. found significant neuromonitoring changes in 47 (9.1%) of 519 AIS cases using Tc-MEP,⁸ and Schwartz et al. found relevant signal changes in 38 (3.4%) of 1121 AIS cases using both Tc-MEP and SSEP.³⁴ All of these reports examined spinal deformity including AIS, but there have been no studies in patients with AIS to evaluate the characteristics of cases with Tc-MEP waveform deterioration during surgery and compare patients with and without waveform deterioration. Therefore, in the current study, we examined Tc-MEP waveform deterioration during surgery for AIS in patients younger than 20 years. In intraoperative monitoring, a waveform amplitude decrease from 50% to 80% of baseline is suitable as a primary warning criterion for reduction of the false-positive rate.⁴ Persistent intraoperative amplitude reductions of greater than 50% are associated with postoperative motor deficits,³⁸ and a 70% decrease in amplitude in routine spinal cord monitoring has been suggested as an alarm point, including in surgery for spinal deformity.¹⁴ Therefore, in our series, we set the critical level to a 70% decrease in amplitude.

Tc-MEP monitoring provides accurate real-time feedback on injury with a sensitivity and specificity of about 100%,^{11,21} but this high sensitivity is also associated with frequent false-positive wave changes that disrupt surgery.^{11,21,24} In our series, the sensitivity was 100% and the specificity was 83%, with a false-positive rate of 17%. Compared with previous reports of intramedullary spinal cord tumor surgery and surgery for ossification of the posterior longitudinal ligament,²⁸ the false-positive rate in our series was relatively low. However, reliability may be improved using multimodal (D-wave and SSEP) and multichannel monitoring. Compared with other monitoring, Tc-MEP has high sensitivity for spinal cord ischemia or compression failure and is a reliable monitor of motor function.^{26,30,37} Clinically, however, Tc-MEP waveform deterioration does not always reflect the postoperative motor deficit, with a discrepancy between waveform change and loss of motor function.³⁰

In our series, in 14 patients with waveform deterioration, 3 had numbness and pain of the lower extremities, but none had a motor deficit. These findings are consistent with previous reports.³⁰ Adolescent patients also tend to be less vulnerable to motor deficits than adults with spinal cord tumor and ossification of the posterior longitudinal ligament, and this may also account for the absence of postoperative motor deficit. Only Tc-MEP showed waveform deterioration among multiple modalities, but this finding requires examination in a greater number of cases. MEPs have high

TABLE 4. Comparison of background data in patients with and without waveform deterioration

Variable	Deterioration (n = 14)	No Deterioration (n = 54)	p Value
Demographic factors			
Mean age (yrs)	13.8 (1.6)	14.6 (1.9)	NS
Mean preop Cobb angle, major curve (°)	59.1 (13.9)	51.7 (11.6)	0.049
No. of patients w/ thoracic main curve	10 (71%)	25 (46%)	0.094
Mean flexibility correction rate (%)			
Traction	49.6 (12.8)	50.3 (13.4)	NS
Side bending	36.1 (9.7)	34.8 (8.5)	NS
Periop factors			
Mean intraop body tempera- ture (°C)	36.6 (0.4)	36.7 (0.5)	NS
Mean SBP in correction (mm Hg)	104 (10)	100 (9)	NS
Mean variation in SBP (mm Hg)	16 (6)	15 (5)	NS
Mean op duration (mins)	347 (130)	283 (62)	0.047
Mean EBL (ml)	1113 (851)	642 (408)	0.031
Mean fusion range (levels)	10.8 (2.6)	9.3 (2.4)	0.017
Outcome			
Mean postop Cobb angle (°)	12.6 (8.5)	11.8 (5.6)	NS
Mean correction rate (%)	78.6 (9.1)	77.0 (11.3)	NS

NS = not significant; SBP = systolic blood pressure.

Data are shown as the means (SD).

sensitivity and give frequent false-positive results. Also, motor status was intact preoperatively and postoperatively in all of our patients, with only leg pain and numbness in 3 patients postoperatively, which may account for the absence of changes in other monitoring modalities.

A rotation maneuver leading to rotation of the spinal cord may alter blood flow and neural plasticity²⁶ and induce ischemic or circulation deficits and compressive insults of the spinal cord.^{30,37} These effects may underlie the mechanism of waveform deterioration. Nerve root compression on the concave side of the scoliotic curve after correction can lead to nerve root palsy in 2.9% of cases during deformity surgery.³² The correction procedure may also induce spinal cord compression caused by pedicle forcing.¹³

TABLE 5. Multivariate logistic prediction model of risk for waveform deterioration

Variable	OR	95% CI	p Value
Estimated blood loss (≥1000 ml)	1.001	1.001–1.003	0.085
Fusion range (≥10 levels)	1.535	1.011–2.331	0.045

All variables were treated as continuous variables. The odds ratio is the increase in odds per unit increase in the predictor. Regression coefficients have been zero corrected.

FIG. 2. Case 8. **A:** Preoperative posteroanterior radiographs obtained in a 13-year-old girl with AIS. The curve magnitudes were 84° thoracic, 47° upper thoracic, and 51° lumbar. **B:** A reliable baseline was obtained using Tc-MEP monitoring (*open arrow*). After the rotation maneuver, Tc-MEP showed wave deterioration beyond the 70% criterion bilaterally. **C:** Adductor longus, left quadriceps, hamstrings, and gastrocnemius (*arrowhead*) values. The left quadriceps eventually improved to > 50% baseline, but others did not improve (*open arrowhead*). In postoperative standing posteroanterior radiographs, the curve magnitudes were 15°, giving a curve correction rate of 82%.

In our cases, waveform deterioration commonly occurred during a rotation maneuver, and all of the aforementioned mechanisms may have occurred. Waveform deterioration also occurred bilaterally, which may be due to blood flow disorder or ischemia of the spinal cord, and laterally, as a possible result of nerve root compression. These findings are also consistent with previous reports.^{26,32,37} Even more interesting, in 1 patient (Case 9), waveform deterioration occurred at the time of right-side (convex) rod in situ replacement after the rotation maneuver. In this case, since we had not performed correction for the right-side rod, it is possible that waveform deterioration occurred with a delay after the left-side (concave) rod rotation maneuver. Therefore, waveform deterioration may occur immediately after a rotation maneuver or it may be delayed.

Waveform deterioration showed significant relationships with EBL, operation time, and number of levels fused, which suggests that surgical invasion may also be involved. Tc-MEP is useful for detection of early spinal cord impairment caused by ischemia in the spinal cord,³⁰ and excessive bleeding during surgery might have led to changes in spinal cord blood flow. However, blood pressure at the time of correction and variation in blood pressure did not differ significantly between patients with and without waveform deterioration, and thus this process did not occur with a change in hemodynamics. On the other hand, in our series, the preoperative Cobb angle was significantly greater in cases with waveform deterioration. Waveform deterioration has previously been shown to occur significantly more frequently in cases of severe scoliosis with a Cobb angle $\geq 70^\circ$.¹³ A large preoperative Cobb angle is likely to increase the number of levels fused and require additional osteotomy for further correction, and this may increase the operation time and EBL. In multivariate logistic analysis, number of levels fused had an OR of 1.535 and EBL had an OR of 1.001. These values are relatively low, but the results indicate that surgical invasiveness is a significant risk factor for waveform deterioration.

Maneuver interruption and laminectomy at the apical lesion have been proposed as measures to be taken at the time of the waveform deterioration during surgery,¹³ in addition to a wakeup test.^{5,6} Ziewacz et al. developed an evidence-based algorithm for the design, development, and implementation of checklists for responding to intraoperative neuromonitoring alerts in spine surgery.³⁹ In our series, we used maneuver interruption or release of correction, which led to reversal of waveform deterioration during surgery in 10 patients and partial improvement in 4 patients. Postoperatively there was no motor deficit, but pediclectomy, laminectomy, and a wakeup test are required if a waveform does not improve.

Conclusions

In 68 patients with AIS who underwent posterior corrective fusion, 14 had intraoperative waveform deterioration in 864 monitored muscles. Postoperative leg pain and numbness occurred in 3 of these cases as neurological deficits, but no case with waveform deterioration had a postoperative motor deficit. Waveform deterioration commonly occurred during a rotation maneuver and was associated with surgical invasion. Waveform deterioration may also occur just after the rod rotation maneuver, at the time of contralateral rod in situ replacement. This might be related to the occurrence of postoperative transient leg pain and numbness as neurological deficits.

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Disclosures

The authors report no conflict of interest concerning the materi-

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Author Contributions

Conception and design: all authors. Acquisition of data: Kobayashi. Analysis and interpretation of data: Kobayashi. Drafting the article: Kobayashi. Critically revising the article: Kobayashi. Reviewed submitted version of manuscript: Kobayashi. Approved the final version of the manuscript on behalf of all authors: Imagama. Statistical analysis: Kobayashi. Administrative/technical/material support: Kobayashi. Study supervision: Kobayashi.

Correspondence

Shiro Imagama, Department of Orthopedic Surgery, Nagoya University Graduate School of Medicine, 65 Tsurumai Showa-ward, Aichi 466-8550, Japan. email: imagama@med.nagoya-u.ac.jp.