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SURGERY

A Prospective Comparative Study of 2 Minimally Invasive Decompression Procedures for Lumbar Spinal Canal Stenosis

Unilateral Laminotomy for Bilateral Decompression (ULBD) Versus Muscle-Preserving Interlaminar Decompression (MILD)

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Study Design. A prospective comparative study.

Objective. To compare prospectively 2 different types of minimally invasive surgery for lumbar spinal canal stenosis (LSCS): unilateral laminotomy for bilateral decompression (ULBD), and muscle-preserving interlaminar decompression (MILD).

Summary of Background Data. Although previous studies have reported several procedures of minimally invasive surgery for the treatment of LSCS, no articles prospectively compared 2 different procedures.

Methods. From 2005 to 2009, we prospectively enrolled 50 patients with LSCS for the treatment with ULBD, and 50 patients for MILD. The patients' symptoms were evaluated using Japanese Orthopedic Association (JOA) score, JOA Back Pain Evaluation Questionnaire, and visual analogue scale before and 2 years after operation. For radiological evaluation, changes in disc height, sagittal translation, and lateral wedging at the decompressed segment, as well as lumbar lordosis were investigated using plain radiographs.

Results. Ninety-nine of 100 patients were followed for a minimum of 2 years. No significant differences were found in the recovery rate of JOA score, improvement of JOA Back Pain Evaluation Questionnaire, and changes of the visual analogue scale between the 2 groups. Radiologically, no significant differences were present in the postoperative degenerative changes in disc height, sagittal translation, and lateral wedging. In multilevel surgical procedures; however, clinical scores in low back pain, and lumbar function were significantly greater in the ULBD group than those in the MILD group. The lateral wedging change at L2–L3 and L3–L4 more frequently occurred in the ULBD group than in the MILD group. On the contrary, the number of patients who demonstrated the postoperative sagittal translation at L4–L5 was significantly greater in the MILD group than in the ULBD group.

Conclusion. Both MILD and ULBD were efficacious procedures for improving neurological symptoms in patients with LSCS. In multilevel decompression surgical procedures, ULBD was superior to MILD in terms of improvement of low back pain and lumbar function at the 2-year time point.

Key words: prospective comparative study, lumbar spinal canal stenosis, minimally invasive surgery, unilateral laminectomy for bilateral decompression, muscle-preserving interlaminar decompression.

Level of Evidence: 3

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Lumbar spinal canal stenosis (LSCS) due to degenerative changes in the spinal structures is the most common condition leading to decompressive surgery. Various studies have investigated surgical and conservative methods for the treatment of LSCS.[1–3] Conventionally, laminectomy is the most popular surgery involving extensive removal of the posterior structure including the lamina, spinous processes, interspinous ligaments, and facet joints. However, Katz *et al*[4] reported that the reoperation rate is high after the conventional laminectomy because of postoperative back pain. Therefore, several decompressive procedures involving minimally invasive surgery (MIS) have been studied to overcome these problems, including surgically induced damage to the posterior lumbar structure and related low back pain.[5,6]

Unilateral laminotomy for bilateral decompression (ULBD) has been developed as an MIS procedure, which can preserve contralateral structures and thus benefits spinal stability after surgical procedures.[7,8] Muscle-preserving interlaminar decompression (MILD) has been described as another type of MIS for LSCS, which can provide sufficient neural decompression with minimum damage to the posterior stabilizing structures.[9] The trend for these minimally invasive techniques is reasonable because a smaller access point should result in smaller scars, diminished local pain, reduced blood loss, reduced damage to the spinal structures, and reduced surgically induced instability. Although the outcomes of these MIS procedures seem to be similar, no study has compared 2 minimally invasive decompression procedures for the treatment of LSCS due to degeneration of the lumbar spine. The aim of this study was to compare prospectively the clinical and radiological outcomes of ULBD with those of MILD and to clarify the advantages and disadvantages of each procedure.

MATERIALS AND METHODS

Patients and Methods

This study was a prospective, comparative, single-institutional trial of 2 surgical procedures for the treatment of LSCS. The inclusion criteria were as follows: (1) neurogenic claudication as defined by leg pain limiting standing, ambulation, or both; (2) magnetic resonance imaging or myelogram confirmation of compressive canal stenosis; and (3) failure of conservative therapy after an adequate trial. The exclusion criteria were spondylolisthesis classified as Meyerding grade 2, 3, or 4[10] and degenerative scoliosis with a Cobb angle greater than 15°, radiculopathy caused by extra- or intraforaminal stenosis, and a history of previous lumbar spine surgery or injury. Prior to this study, a priori analyses were performed to determine the appropriate sample size under the assumption that the visual analogue scale (VAS) score of the better group was 30, the VAS score of the worse group was 45, and the standard deviation was 22; the significance level was set at 5%, the detection power at 90%, and the dropout rate at 5%. The sample size was estimated to be 50 patients per arm.

Choice of Surgical Procedure

After sufficient informed consent was obtained from 100 consecutive patients, 50 patients with odd patient identification numbers were enrolled in the ULBD group, and 50 patients with even identification numbers were enrolled in the MILD group between 2005 and 2009. No patients or surgeons disagreed with the selected surgical procedure.

Operative Techniques

Unilateral Laminotomy for Bilateral Decompression

The microsurgical procedure was performed as described by Spetzger *et al*[7] (Figure 1A). The supraspinous and interspinous ligaments were preserved during the surgical procedure. In this procedure, we generally approached from the most symptomatic side. Briefly, after the paraspinal muscles were dissected from the midline, the interlaminar space was exposed. Under microscopic view, laminotomy was performed by removing a portion of the superior and inferior lamina at the segment as well as a small portion of the medial facet. The ligamentum flavum and its bony attachments were removed to expose the dural sac. After the first laminotomy was performed on one side, the operating table was tilted down contralaterally, and the microscope was angled toward the medial side. Using a high-speed drill burr, the deep cortical surface of the contralateral lamina was undercut, and drilling was extended to the contralateral lateral recess. Finally, the ligamentum flavum and its bony attachment edge were removed. The nerve roots on both sides were confirmed to be completely decompressed (Figure 1B).

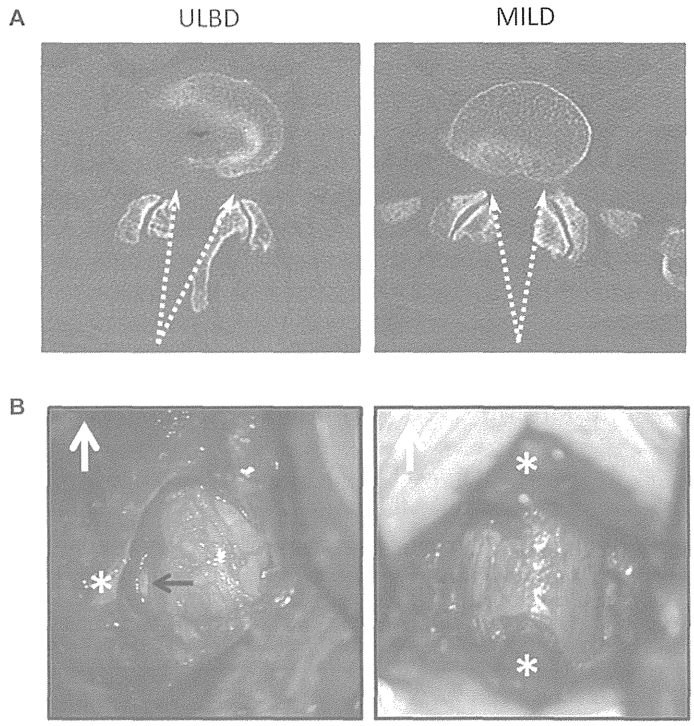

Figure 1. **A**, Computed tomographic scans of ULBD and MILD procedures. In the approach of the ULBD, the paraspinal muscles were dissected from the midline and the interlaminar space was exposed. A laminotomy was performed by removing a portion of the superior and inferior laminae at the segment, and a small portion of the medial facet. Deep cortical surface of contralateral lamina was undercut and drilling was extended to the contralateral medial facet. In the approach of the MILD, the interspinous ligament is divided on the midline, and the operative field is broadened by laterally expanding the space between each split half of the ligaments. Partial laminotomy of the caudal half of the upper adjacent lamina, a dome-like expansion is performed by removing the inner laminar plate to the extent where the cranial margin of the ligamentum flavum is freed. **B**, Intraoperative photographs of ULBD and MILD procedures. White arrows denote cranial side; black arrow, nerve root of the contralateral side in ULBD. *Spinous processes. ULBD indicates unilateral laminotomy for bilateral decompression; MILD, muscle-preserving interlaminar decompression.

Muscle-Preserving Interlaminar Decompression

This procedure was established by Hatta *et al*[9] (Figure 1A). Briefly, after a 30-mm midline skin incision was made, centered at the interspinous level to be decompressed, the supraspinous ligament was longitudinally split down the middle. Both the caudal part of the upper adjacent spinous process and the cranial part of the lower adjacent spinous process were exposed by detaching the supraspinous ligament. The exposed portions of the spinous processes were removed using the drill burr. The surgical field was gradually expanded by retracting the split ligaments and bilateral paravertebral muscles laterally using a Gelpi self-retaining retractor. After partially drilling the spinous processes, the cranial third of the lower adjacent lamina was removed to free the caudal margin of the ligamentum flavum. After partial laminotomy of the caudal half of the upper adjacent lamina, a dome-like expansion was performed by removing the inner laminar plate to the extent where the cranial margin of the ligamentum flavum was freed. The bilateral facet joint was undercut to expose the lateral margin of the ligamentum flavum. The ligament was then easily removed using a curette or a fine Kerrison rongeur. The nerve roots on both sides were confirmed to be completely decompressed (Figure 1B).

Evaluation

Clinical Outcomes

The Japanese Orthopedic Association (JOA) scoring system was used for the clinical evaluations before and after surgery. The recovery rate was calculated using the method of Hirabayashi *et al.*[11] The JOA Back Pain Evaluation Questionnaire (JOABPEQ) sections[12] including evaluations of low back pain, lumbar function, walking ability, social life function, and mental health as well as a VAS (from 0 to 10, with 10 being the worst pain) for low back pain and lower extremity pain and numbness were also investigated before and after surgery. JOABPEQ is a patient-based, multidimensional, scientific scoring system that is useful for evaluating a variety of lumbar diseases.[12] Furthermore, referring to the previous articles,[12–14] the effectiveness rate for each domain of the JOABPEQ and the improvement in each score on the VAS were measured.

Radiological Evaluation

The radiological evaluations were performed by 2 independent spine surgeons. Lumbar lordosis was measured between the upper endplates of L1 and S1 using the standing lateral radiographs. To evaluate the postoperative degenerative change at each operated segment, a decrease in the intervertebral disc height (DH) and increases in the sagittal translation (ST) and lateral wedging (LW) at 2 years after the operation were measured using radiographical images in a neutral position and were compared with the preoperative status. If either a DH more than 2 mm, an ST more than 2 mm, or LW of more than 3° was observed, a postoperative degenerative change was considered to be present.

Statistical Analysis

Student *t* test for continuous variables, a Mann-Whitney *U* test for discontinuous variables, and a χ^2 test for categorical

TABLE 1. Demographics and Patient's Data

	ULBD Group (n = 50)		MILD Group (n = 50)		*P*
Identification number of our hospital	Odd		Even		...
Age (yr)	69.5 ± 8.7		68.1 ± 9.0		0.43
Male (%)	68%		56%		0.11
No. of patients with preoperative spondylolisthesis	8 cases		9 cases		0.39
Decompressed segment(s)	1 segment	25 cases	1 segment	27 cases	0.55
	2 segments	16 cases	2 segments	18 cases	
	3 segments	9 cases	3 segments	5 cases	
Operating time (min)	181 ± 64.6		179 ± 67.9		0.88
Blood loss (mL)	114 ± 114		112 ± 63.8		0.91
Postoperative complications					
Hematoma requiring removal	0/0%		1/2%		0.16
Insufficient decompression	1/2%		0/0%		0.16
Newly acquired facet joint cyst at the decompressed level	0/0%		1/0%		0.16
Adjacent segment disorder	1/2%		2/4%		0.28

Values denote mean ± standard deviation unless otherwise indicated.
ULBD indicates unilateral laminotomy for bilateral decompression; MILD, muscle-preserving interlaminar decompression.

TABLE 2. Comparison of the ULBD and the MILD Group in Clinical and Radiological Outcomes*

	ULBD Group (n = 47)	MILD Group (n = 47)	*P*
JOA Score (pts)/(%)			
Before surgery	14.5 ± 5.1	14.3 ± 5.1	0.84
2 yr postoperatively	25.6 ± 3.5	24.7 ± 5.1	0.31
Recovery rate	74.4 ± 27.0	72.5 ± 27.9	0.73
JOABPEQ Score (pts)			
Low back pain			
Before surgery	40.4 ± 38.6	49.8 ± 36.0	0.17
2 yr postoperatively	80.2 ± 32.8	74.8 ± 33.3	0.38
Effective rate (%)	78.4	66.7	0.12
Lumbar function			
Before surgery	54.4 ± 30.8	58.5 ± 28.1	0.59
2 yr postoperatively	78.6 ± 30.1	73.4 ± 26.6	0.16
Effective rate (%)	48.6	43.6	0.33
Walking ability			
Before surgery	28.1 ± 19.9	24.0 ± 20.3	0.31
2 yr postoperatively	71.1 ± 31.1	67.9 ± 32.4	0.82
Effective rate (%)	80.9	76.6	0.30
Social life function			
Before surgery	33.2 ± 20.8	38.1 ± 17.0	0.30
2 yr postoperatively	68.3 ± 23.2	65.2 ± 25.1	0.55
Effective rate (%)	65.2	63.8	0.44
Mental health			
Before surgery	42.0 ± 19.6	41.8 ± 16.9	0.73
2 yr postoperatively	60.7 ± 20.8	57.5 ± 18.4	0.30
Effective rate (%)	45.4	38.3	0.24
Visual Analogue Scale (mm)			
Low back pain			
Before surgery	64.1 ± 28.1	57.0 ± 24.7	0.11
2 yr postoperatively	25.7 ± 29.4	32.2 ± 33.7	0.35
Pre-post†	39.8 ± 38.8	24.8 ± 38.2	0.07
Buttock and/or lower extremity pain			
Before surgery	71.3 ± 21.9	67.4 ± 20.4	0.22
2 yr postoperatively	31.0 ± 30.4	26.7 ± 30.9	0.43
Pre-post†	40.3 ± 31.2	40.7 ± 35.4	0.93
Buttock and/or lower extremity numbness			
Before surgery	70.3 ± 25.4	70.1 ± 23.8	0.84
2 yr postoperatively	31.3 ± 35.4	31.6 ± 33.2	0.58
Pre-post†	39.9 ± 36.7	38.5 ± 38.5	0.75
Lumbar lordosis (L1–S1 angle)			
Before surgery	36.9 ± 10.2	39.7 ± 13.3	0.28
2 yr postoperatively	37.6± 11.1	42.3 ± 12.8	0.07
Pre-post†	0.6 ± 5.6	2.7 ± 4.4	0.06
Postoperative Degenerative Change			
IDH	**4/8.5%**	**10/20.8%‡**	**0.04**
ST	**0/0%**	**4/8.3%‡**	**0.02**
LW	**6/12.8%‡**	**1/2.1%**	**0.02**
Total	9/21.3%	10/20.8%	0.48

Values denote mean ± standard deviation.

**Bold values are the outcomes that showed statistically significant differences.*

†'Pre-post' means 'the difference of the postoperative values from the preoperative values'.

‡$P < 0.05$.

ULBD indicates unilateral laminotomy for bilateral decompression; MILD, muscle-preserving interlaminar decompression; JOA, Japanese Orthopedic Association; IDH, intervertebral disc height; ST, sagittal translation; LW, lateral wedging; pts, patients.

data were used for statistical analysis. All *P* values less than 0.05 were considered significant.

RESULTS

Of the 100 included patients, 99 completed the 2-year follow-up (follow-up rate, 99.0%). One patient in the ULBD group died of a cause unrelated to LSCS and surgery. The patient demographic and clinical data are summarized in Table 1. The demographic data were similar between the 2 groups. One patient in the MILD group required removal of hematoma 6 hours after the surgery due to low back pain with neurological deterioration, which were resolved immediately after the removal. After hospital discharge, 5 patients (5.0%) underwent secondary lumbar surgery. One patient in the ULBD group required additional decompression with fusion because of insufficient decompression and instability of the operated segment. In the MILD group, decompression and fusion with instrumentation was required for 1 patient with a newly acquired facet cyst. One patient in the ULBD group and 2 patients in the MILD group deteriorated because of herniated nuclear pulposus or canal stenosis at the segment different from the first operated level and underwent a secondary surgery: hemilaminotomy or decompression with fusion.

The clinical and radiological outcomes are summarized in Table 2. The clinical outcomes showed significant improvement in the JOA, JOABPEQ, and VAS scores in both groups after surgery. The effectiveness rate for low back pain was relatively higher in the ULBD group than the MILD group, but there were no statistically significant differences in any other items. Postoperative degenerative changes developed in 9 patients in the ULBD group and 10 patients in the MILD group. None of these patients required secondary surgery. The number of patients who showed a decrease in DH and an increase in ST was greater in the MILD group than in the ULBD group, whereas the incidence of increased LW was lower in the MILD group.

Additionally, we compared the clinical and radiological outcomes of MILD and ULBD in 2 subgroups: single-level surgery and multilevel surgery. In the single-level subgroup, there were no significant differences in the clinical or radiological outcomes of the 2 methods (Table 3, left). The frequency of postoperative degenerative changes was similar between the 2 groups. In the multilevel subgroup (Table 3, right), the effectiveness rates for low back pain and lumbar function in the JOABPEQ scores and improvement in the VAS scores significantly differed. However, there were no significant differences in the recovery rate of the JOA score, the effectiveness rates for other domains, or improvement of the VAS score in the buttock and/or lower extremity symptoms. The radiological results of the multilevel subgroup indicated that the numbers of patients with decreased DH and increased ST were significantly greater in the MILD group than the ULBD group. Additionally, lumbar lordosis (L1–S1 angle) was significantly more increased in MILD group. There was a trend toward a higher incidence of LW increase in the ULBD group than the MILD group, although there was no significant difference.

We also evaluated the radiological degenerative changes at each decompressed segment (Table 4). Increased LW at L2–L3 and L3–L4 occurred more frequently in the ULBD group. In contrast, the number of patients with a postoperative increase in ST at L4–L5 was significantly greater in the MILD group. There was no significant difference in the occurrence of decreased DH at any segment between the 2 groups.

DISCUSSION

LSCS is the most common indication for decompressive spinal surgery in the elderly population. Many authors have debated various types of surgical procedures for LSCS since wide laminectomy was first reported by Verbiest.[15] in 1954. From the 1980s onward, however, biomechanical studies have demonstrated the importance of the posterior column, including the interspinous ligaments, the facet joints, and the capsules, in maintaining spinal stability.[16–18] Johnsson *et al*[19] have reported that wide laminectomy induces the recurrence of stenosis due to postoperative instability of the spine in more than half of the population.

In the 1990s, Nakai *et al*[20] introduced a less-invasive laminotomy procedure called "wide fenestration," in which only the medial parts of the inferior facets and the adjoining ligamentum flavum are removed. This technique can successfully improve neurological symptoms with less damage to the posterior spinal structures. Okawa *et al*[16] have also confirmed the importance of preserving the facet joints using cadaveric mechanical testing and have shown the advantage of the wide fenestration technique for spinal stability after the decompression procedure. Therefore, it is critically important for surgeons to attempt to preserve the posterior structures during decompressive surgical procedures for the treatment of LSCS. In the late 1990s to 2000s, less invasive decompressive procedures for LSCS were further developed. Spetzger *et al*[7] introduced the unilateral approach (ULBD) for the treatment of LSCS with successful clinical outcomes. Hong *et al*[21] have reported that ULBD is superior to bilateral laminotomy regarding the preservation of spinal stability after surgery, also noting that it provides sufficient decompression that is equal to bilateral fenestration. These studies suggest that the postoperative improvement of the symptoms and function is closely associated with preservation of the stability at the operated segment.

This study evaluated the 2 different MIS procedures: ULBD and MILD. The 2 procedures showed similar and favorable improvement in the clinical outcomes after surgery. When compared with previous studies, the clinical outcomes of ULBD and MILD in this study were similar to those of other MIS procedures.[22] However, the rate of secondary operation for recurrence at the decompressed segment was dramatically smaller in both the ULBD (2%) and MILD (2%) procedures than traditional laminectomy as proposed by Herkowitz (17%).[23] Although there were no significant differences in clinical outcomes between the 2 procedures, both ULBD and MILD provide an appropriate and sufficient decompression with less invasion of the posterior structure of the lumbar spine.

For the treatment of multiple-level LSCS, however, significant differences were found in the effectiveness rates for both low back pain and lumbar function in the JOABPEQ and the VAS of low back pain. ULBD seemed to result in more favorable outcomes in these items postoperatively. Notably, patients with postoperative degenerative changes had poorer outcomes regarding improvement of low back pain and lumbar function than those without degenerative changes. Evaluations of the radiological outcomes occasionally demonstrated increased LW at the upper and middle lumbar spine following ULBD as a degenerative change. In ULBD group, the preoperative coronal alignment in patients with increased LW and those without increased LW were similar (Cobb angle: 6.2° *vs*. 6.3°). Therefore, the increased LW is considered to occur mainly because of surgical encroachment to the facet joint by the ULBD procedure: the operated side may sink because of iatrogenic damage to the ipsilateral facet at L2–L3 or L3–L4 where the transverse facet angle is smaller than the lower lumbar facets.[24] For cases with an extremely small facet angle at the upper and middle lumbar spine, MILD can be more suitable than ULBD to avoid the occurrence of the increased LW.

In contrast, the increase in ST was observed at L4–L5 more often after MILD compared with ULBD. Interestingly, the patients with increased ST tended to have a large degree

TABLE 3. Outcomes Comparison Between ULBD and MILD Groups in the Single-Level and Multilevel Subgroups*

	Single-Level Subgroup			Multilevel Subgroup		
	ULBD Group (n = 22)	MILD Group (n = 25)	*P*	ULBD Group (n = 25)	MILD Group (n = 22)	*P*
Age (yr)	68.9± 8.7	66.8 ± 9.0	0.42	71.8 ± 7.2	69.1 ± 6.8	0.19
JOA Score (pts)/(%)						
Before surgery	17.2 ± 4.2	15.2 ± 5.0	0.15	11.6 ± 5.0	14.0 ± 5.1	0.11
2 yr postoperatively	25.6 ± 4.1	24.5 ± 4.8	0.41	25.8 ± 2.7	25.0 ± 5.4	0.52
Recovery rate	71.7 ± 33.5	71.1 ± 25.1	0.94	80.6 ± 17.0	74.0 ± 31.3	0.37
JOABPEQ Score (pts)						
Low back pain						
Before surgery	34.4 ± 39.1	42.2 ± 36.3	0.38	45.7 ± 38.2	58.4 ± 34.7	0.20
2 yr postoperatively	75.2 ± 36.5	74.3 ± 33.7	0.85	84.6 ± 28.8	75.3 ± 33.6	0.34
Effective rate (%)	72.2	78.3	0.33	**84.2‡**	**52.6**	**0.02**
Lumbar function						
Before surgery	56.8 ± 31.0	51.3 ± 29.6	0.55	52.4 ± 31.2	66.6 ± 24.3	0.14
2 yr postoperatively	78.7 ± 30.9	73.4 ± 28.8	0.27	78.6 ± 30.0	73.3 ± 24.5	0.20
Effective rate (%)	87.5	76.2	0.19	**66.7‡**	**33.3**	**0.02**
Walking ability						
Before surgery	29.8 ± 20.7	29.2 ± 21.0	0.95	26.5 ± 19.4	18.1 ± 18.0	0.11
2 yr postoperatively	71.8 ± 32.0	65.5 ± 36.0	0.54	70.5 ± 30.9	70.6 ± 28.3	0.99
Effective rate (%)	81.8	72.0	0.13	80.0	81.8	0.43
Social life function						
Before surgery	36.1 ± 19.7	40.0 ± 18.8	0.72	30.7 ± 22.1	35.9 ± 14.8	0.30
2 yr postoperatively	65.9 ± 25.1	65.6 ± 24.6	0.98	70.4 ± 22.1	64.7 ± 26.1	0.45
Effective rate (%)	59.1	60.0	0.47	70.8	68.2	0.42
Mental health						
Before surgery	43.7 ± 19.3	39.9 ± 17.2	0.40	40.4 ± 20.2	44.0 ± 16.6	0.79
2 yr postoperatively	58.4 ± 20.6	55.7 ± 17.7	0.46	62.8 ± 20.8	59.5 ± 19.4	0.50
Effective rate (%)	31.6	40.0	0.29	56.0	36.4	0.09
Visual Analogue Scale (mm)						
Low back pain						
Before surgery	65.6 ± 28.7	60.1 ± 24.2	0.31	62.7 ± 28.1	53.5 ± 25.4	0.17
2 yr postoperatively	26.7 ± 30.9	25.4 ± 25.7	0.75	24.9 ± 28.4	39.9 ± 40.1	0.32
Pre-post†	38.9 ± 36.7	34.7 ± 29.9	0.63	**37.8‡ ± 42.3**	**13.5 ± 43.8**	**0.04**
Buttock and/or lower extremity pain						
Before surgery	69.5 ± 23.4	64.7 ± 20.6	0.28	72.9 ± 20.9	70.4 ± 20.3	0.62
2 yr postoperatively	31.8 ± 32.6	23.3 ± 28.6	0.33	31.4 ± 28.8	30.6 ± 33.7	0.95
Pre-post†	37.6 ± 28.5	41.4 ± 32.8	0.69	41.5 ± 33.1	39.8 ± 38.8	0.63

(*Continued*)

TABLE 3. (*Continued*)

	Single-Level Subgroup			Multilevel Subgroup		
	ULBD Group (n = 22)	MILD Group (n = 25)	P	ULBD Group (n = 25)	MILD Group (n = 22)	P
Buttock and/or lower extremity numbness						
Before surgery	62.5 ± 28.6	64.0 ± 23.1	0.93	77.2 ± 20.4	77.0 ± 23.1	0.72
2 yr postoperatively	30.9 ± 35.8	26.9 ± 33.2	0.89	33.0 ± 37.2	37.0 ± 33.1	0.31
Pre-post†	31.6 ± 30.8	37.2 ± 33.7	0.68	44.2 ± 39.8	40.0 ± 44.1	0.56
Lumbar lordosis (L1–S1 angle)						
Before surgery	36.0 ± 7.7	41.7 ± 11.8	0.07	37.8 ± 12.2	37.4 ± 14.9	0.72
2 yr postoperatively	37.5 ±7.6	43.2 ± 11.4	0.07	37.7 ± 14.8	41.3 ± 13.8	0.31
Pre-post†	1.6 ± 4.8	1.5 ± 3.9	0.96	**−0.18 ± 6.7**	**3.9‡ ± 4.4**	**0.02**
Postoperative Degenerative Change						
IDH	3/13.6%	3/11.5%	0.44	**1/4%**	**7‡/31.8%‡**	**0.01**
ST	0/0%	1/3.8%	0.16	**0/0%**	**3‡/13.6%‡**	**0.04**
LW	1/4.5%	0/0%	0.16	5/20%	1/4.5%	0.06
Total	4/18.2%	3/11.5%	0.28	5/20%	7//31.8%	0.28

Values denote mean ± standard deviation unless otherwise indicated.
**Bold values are the outcomes that showed statistically significant differences.*
†'Pre-post' means 'the difference of the postoperative values from the preoperative values'.
‡$P < 0.05$.
ULBD indicates unilateral laminotomy for bilateral decompression; MILD, muscle-preserving interlaminar decompression; JOA, Japanese Orthopedic Association; IDH, intervertebral disc height; ST, sagittal translation; LW, lateral wedging.

of lordosis (the averaged L1–S1 angle: 47.7°) preoperatively. Hyperlordotic spine in elderly patients frequently accompanies "kissing" spinous processes. Removal of half of the spinous processes in the MILD procedure can cause further increased lumbar lordosis and can also impair load transfer through the posterior structures, which may induce a translational change in hyperlordotic patients undergoing multilevel decompressive surgery. Herkowitz[23] and Iguchi *et al*[25] have demonstrated that alternations in segmental translation are frequently compatible with the clinical observation of low back pain. Consistent with these reports, the increase in ST in the MILD group following multilevel surgery may have been closely associated with the postoperative low back pain and lumbar function because there was a significant difference compared with the ULBD group. Therefore, it is suggested that ULBD can be preferably chosen for hyperlordotic patients with multilevel stenosis.

In our study, 2 patients (1 in ULBD and 1 in MILD group) required secondary surgery at the operated segment. One patient in ULBD group, who had pre-existing spondylolisthesis with translational instability, presented radicular pain at the 6-month time point due to residual compression that resulted from insufficient decompression and instability. This patient had an extremely deep lateral recess at L4–L5, and we could not sufficiently decompress the medial parts of the contralateral supra-articular process *via* the unilateral approach. Typically, unilateral laminotomy is performed through the narrow canal space for the decompression of the contralateral side, and the surgeon may have difficulty undercutting the medial portion of the opposite facet joint. A second patient experienced radicular pain due to a postoperatively acquired facet cyst at 1 year after MILD. The patient had preoperative instability: hypermobility of the operated segment due to spontaneous fusion of the lower adjacent segment. Ikuta *et al*[26] reported that the prevalence of postoperative intraspinal facet cysts, including asymptomatic cysts, was 8.6% within 1 year after decompression surgery for lumbar spinal stenosis and that the development of postoperative facet cysts was related to the presence of the pre- and/or postoperative segmental spinal instability. We treated these 2 patients with additional decompression and fusion because both of the patients had instability at the operated segment and also because additional decompression could further enhance the instability. It is suggested that decompression combined with fusion can be considered as the first surgery for such patients.

Recently, other types of MIS procedure have been reported, including endoscope-assisted ULBD using tubular retractor.[27,28] In this MIS procedure, small incision using paramedian approach can reduce the damage on paraspinal muscle. In addition, the angled endoscope offers easy access to the contralateral side for decompression.[28] Therefore, this endoscopic ULBD may further improve the clinical outcomes

TABLE 4. Degenerative Change of Each Operated Segment in the ULBD and the MILD Group*

	ULBD	MILD	*P*
L2–L3			
No. of operated segments	12	5	
IDH	2/16.7%	0/0%	0.08
ST	0/0%	0/0%	1.00
LW	1/8.3%	0/0%	0.17
Total	**3†/25.0%†**	**0/0%**	**0.04**
L3–L4			
No. of operated segments	27	21	
IDH	2/7.4%	4/19.0%	0.13
ST	0/0%	1/4.8%	0.16
LW	**3†/11.1%†**	**0/0%**	**0.04**
Total	5/18.5%	4//19.0	0.48
L4–L5			
No. of operated segments	37	42	
IDH	0/0%	6/14.3%	0.006
ST	**0/0%**	**3†/7.1%†**	**0.04**
LW	2/5.4%	1/2.4%	0.25
Total	2/5.4%	7/16.7%	0.06
L5–LS			
No. of operated segments	8	7	
IDH	0/0%	0/0%	...
ST	0/0%	0/0%	...
LW	0/0%	0/0%	...
Total	0/0%	0/0%	...

**Bold values are the outcomes that showed statistically significant differences.*
†$P < 0.05$.
ULBD indicates unilateral laminotomy for bilateral decompression; MILD, muscle-preserving interlaminar decompression; IDH, intervertebral disc height; ST, sagittal translation; LW, lateral wedging.

after the decompressive surgery. However, the reported clinical scores of endoscopic procedure at 2 years (the averaged recovery rate in JOA score: 61.3%, low back pain in JOABPEQ scores: approximately 80 points)[28] seems similar to those of our cases using conventional ULBD procedures. Further prospective comparative studies would be required to see the advantage of endoscopic procedure using tubular retractor for the clinical symptoms.

This study has some limitations. This investigation was based on a short-term evaluation, and the sample size was calculated using power analysis for VAS score: not for all the outcomes evaluated in this study. Additionally, we did not compare the 2 MIS procedure with other MIS. Therefore, further studies with longer follow-up and larger sample size may bring other interesting findings. With regard to the surgical selection, we did not conduct a complete randomization for patient allocation to each group using a random number table. However, because we prospectively determined the surgical procedure based on identification number, we think that there was very little bias in the patient allocation. In the minimally invasive procedures, such as ULBD or MILD, there could be a learning curve for the surgeons that possibly affect the surgical outcomes. However, the 4 attending surgeons in this study were well-experienced to these procedures prior to the study: there were no significant differences in operating time and intraoperative bleeding between early cases and late cases in either group.

CONCLUSION

The trends suggested in this study indicate that both types of MIS can provide satisfactory outcomes for patients with LSCS and that ULBD for the lower lumbar spine and MILD for the upper-middle lumbar spine likely prevent postoperative degenerative changes, at least during short-term follow-up.

➢ Key Points

- This is the first study prospectively comparing 2 different types of MIS for the treatment of LSCS; ULBD and MILD.
- This prospective comparative study demonstrated that clinical and radiological outcomes were almost similar between the ULBD and the MILD group.
- In patients who received multilevel decompression, improvement of scores of low back pain and lumbar function was greater in ULBD group.
- The radiological evaluation indicated that the ULBD for the upper-middle lumbar spine and the MILD for the lower lumbar spine can cause the postoperative degenerative change.

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Yoshiyasu Arai, Takashi Hirai, Toshitaka Yoshii, equally contributed to this study.

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CERVICAL SPINE

Dynamic Changes in Spinal Cord Compression by Cervical Ossification of the Posterior Longitudinal Ligament Evaluated by Kinematic Computed Tomography Myelography

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Study Design. A prospective clinical study.
Objective. To investigate the dynamic causative factor in the pathogenesis of myelopathy in patients with cervical ossification of the posterior longitudinal ligament (OPLL) using kinematic computed tomography (CT) myelography.
Summary of Background Data. Kinematic CT myelography is useful for dynamically evaluating the cervical spine with high-resolution images, particularly in bony compressive lesions. However, no studies have evaluated the dynamic factors in patients with OPLL using kinematic CT myelography.
Methods. From 2008 to 2013, 51 consecutive patients with OPLL who presented with myelopathy were prospectively enrolled in this study. The patients were examined with kinematic (flexion-extension) CT myelography using a multidetector CT scanner. The range of motion at C2–C7 from flexion to extension was measured in the sagittal view. The segmental range of motion, anterior-posterior diameter and cross-sectional area (CSA) of the spinal cord were measured at the level where the spinal cord was most compressed by OPLL.
Results. The neurological condition of the patients evaluated by Japanese Orthopaedic Association scores were 10.8 ± 2.4 points. The mean range of motion at C2–C7 and at the most compressed segment were 23.1 ± 11.7 and 7.0 ± 4.4°, respectively. Both the anterior-posterior diameter and the CSA at the most compressed levels were significantly decreased during neck extension compared with flexion. Interestingly, the anterior-posterior diameter and the CSA were decreased during neck flexion in 13.7% (7/51) of the patients. All 7 of these patients had massive OPLL with an occupying rate 60% or more. The dynamic change rate of CSA (flexion/extension) was significantly smaller in patients with an OPLL occupying rate 60% or more compared with patients with an occupying rate less than 60%.
Conclusion. Although spinal cord compression was increased during neck extension in most of the patients, greater levels of compression could be placed on the spinal cord during neck flexion when the patients had OPLL with a high occupying rate.
Key words: ossification of the posterior longitudinal ligament, computed tomography myelography, kinematic study, compressive myelopathy.
Level of Evidence: 4
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Cervical spondylosis and ossification of the posterior longitudinal ligament (OPLL) are common degenerative spine diseases that cause progressive neurological dysfunction in middle-aged and elderly patients.[1,2] Static factors, such as congenital canal narrowing, degenerative intervertebral discs, osteophyte formation, and thickening of ligamentum flavum, are important in the pathogenesis of cervical myelopathy. However, dynamic factors induced by cervical spinal motion, such as anterior or posterior translation of vertebrae, disc protrusion, and buckling of the flavum,[3] are known to contribute to the development and progression of neurological symptoms in cervical spondylotic myelopathy (CSM)[4,5] and cervical OPLL.[6–8] Various radiological examinations, including plain radiograph, computed tomography (CT), and magnetic resonance imaging (MRI), have been performed to evaluate the static structural abnormality of the cervical spine and spinal canal.[9–11] To evaluate the dynamic factors in patients with CSM, several authors have reported that kinematic MRI is a useful modality that demonstrates physiological alterations of the spinal canal and spinal cord in different neck positions (flexion-extension).[12–14]

Recently, other studies have shown the efficacy of kinematic CT myelography to investigate dynamic factors in patients with CSM.[15,16] The authors evaluated the dynamic changes in spinal cord compression using reconstructed images obtained with multidetector-row CT after myelography. In comparison with kinematic MRI, kinematic CT myelography offers several advantages, including a shorter scanning time, thinner axial slices, and high image resolution, particularly in bony or calcified compressive lesions.[15,16] However, to our knowledge, no studies have evaluated dynamic factors in patients with OPLL using kinematic CT myelography.

The decision to choose surgical intervention for patients with cervical myelopathy is based on the appropriate clinical diagnosis and confirmation at imaging studies. It is known that the amount of spinal cord compression can change depending on the neck position.[3,17] Therefore, the dynamic imaging study can provide important information to make a treatment decision. In this study, we investigated the dynamic changes in spinal cord compression in patients with myelopathy caused by cervical OPLL using reconstructed kinematic CT myelography images.

MATERIALS AND METHODS

From April 2008 to April 2013, 51 consecutive patients with OPLL who presented with myelopathy secondary to OPLL were prospectively enrolled in this single-institution study. In this study, spondylosis without OPLL, trauma, infection, calcification of ligamentum flavum, tumor, and cases with a history of previous cervical spine surgery were excluded. The patients' neurological condition was assessed using the Japanese Orthopaedic Association (JOA) score.[18] Cervical plain radiographs and MRI images were obtained in a neutral position before admission. Ossification types determined by lateral radiograph were classified as continuous, segmental, mixed, and other according to the criteria proposed by the Investigation Committee on the Ossification of Spinal Ligaments of the Japanese Ministry of Public Health and Welfare.[19,20] The level of the greatest spinal cord compression by OPLL was determined using the midsagittal images of the neutral MRI. The occupying rate of OPLL at the most compressed level was calculated as the thickness of the OPLL/anterior-posterior (A-P) diameter of the spinal canal ×100 (%) using lateral radiograph.[21] This study was approved by an institutional review board.

Kinematic CT Myelography

The examinations were performed under supervision of 4 spine specialists. After 15 mL of the contrast medium iohexol (Omnipaque, Daiichi Pharmaceutical Co., Tokyo) was injected into the lumbar cerebrospinal fluid space, a dynamic motion study was performed using multidetector CT (Aquilion64, TOSHIBA Medical System Inc., Tokyo). The CT images were obtained in both the neck flexion and extension positions to the greatest extent possible, as limited by the patients. The scanning parameters were as follows: 120 kV, 100 to 300 mA, 0.5-mm thickness for slice data, and 0.5 mm thickness for reconstruction. The scanning time for the cervical spine in each position was less than 10 seconds. No patients displayed neurological deterioration during the kinematic CT examinations.

Evaluation

Using the reconstructed CT images obtained with this method, the range of motion (ROM) at C2–C7 from flexion to extension was evaluated in the midsagittal view by measuring the angle between the lower endplate of the C2 and C7 vertebrae. The segmental ROM was measured in the same fashion between the lower endplates of the upper and lower vertebrae at the level where the spinal cord was most compressed by OPLL. The A-P diameter of the spinal cord was measured in the midsagittal view at the level of the greatest spinal cord compression by OPLL (Figure 1A). Additionally, the cross-sectional area (CSA) of the spinal cord was measured in the axial view at the most compressed level using image analysis software (Figure 1B; ImageJ: NIH, Bethesda, MD). We evaluated the dynamic changes in the A-P diameter and the CSA of the spinal cord and defined their rate based on the following formula: the A-P diameter (or CSA) in flexion/the A-P diameter (or CSA) in extension. The data were collected prospectively. The paired *t* test and Pearson correlation test were used for statistical analysis. *P* values less than 0.05 were considered significant.

RESULTS

The study included 39 males and 12 females (63.5 ± 8.7 yr old, range: 40–79). There were 18 patients with segmental-type OPLL, 33 patients with mixed-type OPLL, and no patients with the continuous type. The JOA score for the

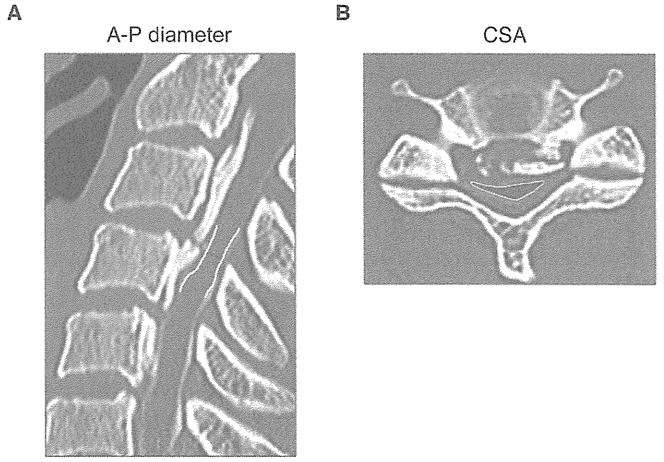

Figure 1. A, The A-P diameter of the spinal cord measured in the midsagittal view at the level of the greatest spinal cord compression by OPLL. **B**, The CSA of the spinal cord was measured in the axial view at the most compressed level. OPLL indicates ossification of the posterior longitudinal ligament; A-P, anterior-posterior; CSA, cross-sectional area.

patients' neurological condition was 10.8 ± 2.4 points (4.5–14.5 points). The level of the greatest spinal cord compression by OPLL was C2–C3 in 2 patients, C3–C4 in 18 patients, C4–C5 in 11 patients, C5–C6 in 15 patients, and C6–C7 in 5 patients. The occupying rate of OPLL at the most compressed level was 47.1 ± 12.7% (Table 1).

In the kinematic CT myelography, the mean ROM at C2–C7 from flexion to extension was 23.1 ± 11.7°. The segments of the greatest spinal cord compression of all patients included in this study were mobile without complete bridging of OPLL between the upper and lower vertebrae. The segmental ROM at the most compressed level was 7.0 ± 4.4° (Table 2).

The A-P diameters of the spinal cord at the most compressed levels were significantly decreased during neck extension compared with neck flexion ($P < 0.01$; Figure 2A, B). The spinal cord was more compressed by the OPLL during neck extension in 86.3% (44/51) of the patients (Figure 2A; Table 2). Similarly, the CSAs at the most compressed levels were also significantly decreased during neck extension when compared with flexion ($P < 0.01$; Figure 3A, B). The CSAs were decreased during neck extension in 86.3% (44/51) of the patients (Figure 3A; Table 2). We also evaluated the correlation between the severity of the neurological impairment and the dynamic change of the A-P diameter and CSA of the spinal cord (the difference between flexion and extension). However, no significant correlation was found between the dynamic change and the JOA neurological score ($P > 0.05$).

TABLE 1. Patients' Data

N	51
Age (yr)	63.5 ± 8.7 (range: 40–79)
Male/female	39/12
Types of OPLL	
Segmental type	18
Mixed type	33
Continuous type	0
JOA neurological score (/17 points)	10.8 ± 2.4 (range: 4.5–14.5)
Level of the greatest spinal cord compression	
C2–C3	2
C3–C4	18
C4–C5	11
C5–C6	15
C6–C7	5
Occupying rate of OPLL (%)	47.1 ± 12.7

Types of OPLL were classified using lateral radiograph.[19,20] Neurological dysfunction was assessed using JOA score for the cervical spine.[18] The occupying rate of OPLL was calculated as the thickness of the OPLL/anterior-posterior diameter of the spinal canal × 100 (%) using lateral radiograph.[21]

OPLL indicates ossification of the posterior longitudinal ligament; JOA, Japanese Orthopaedic Association.

TABLE 2. Kinematic CT Myelography

	Flexion	Extension
Lordosis at C2–C7 (°)	−6.1 ± 11.0	17.4 ± 11.5
ROM at C2–C7 (°)	23.1 ± 11.7	
Lordosis at the greatest compressed level (°)	−2.8 ± 6.1	4.1 ± 5.8
ROM at the greatest compressed level (°)	7.0 ± 4.4	
A-P diameter of spinal cord (mm)	3.4 ± 1.3*	3.0 ± 1.2
No. of patients with increased spinal compression		
Occupying ratio ≥60% (N = 11)	7	4
Occupying ratio <60% (N = 40)	0	40
CSA of spinal cord (mm²)	39.3 ± 10.5*	34.3 ± 10.3
No. of patients with increased spinal compression		
Occupying ratio ≥60% (N = 11)	7	4
Occupying ratio <60% (N = 40)	0	40

$^*P < 0.01$.

ROM indicates range of motion; A-P diameter, anterior-posterior diameter of spinal cord at the greatest compressed level in the midsagittal view; CSA, cross-sectional area of the spinal cord at the greatest compressed level in the axial view.

Although the compression of the spinal cord was increased in most of the patients in this study (Figure 4A), the A-P diameter and the CSA of the spinal cord were decreased during neck flexion in 13.7% (7/51) of the patients (Figure 4B; Table 2). Notably, all 7 of these patients had massive OPLL, with a 60% or more occupying rate (an average of 64.3 ± 5.0%), which was significantly higher than the rate in the other 44 patients (44.3 ± 11.3%). Furthermore, we compared the

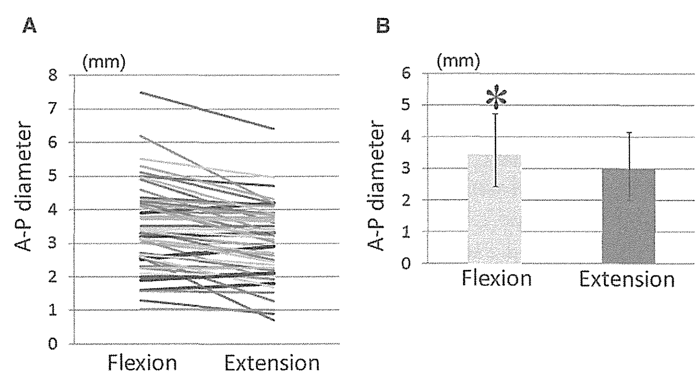

Figure 2. A, The dynamic changes in anterior-posterior diameter of the spinal cord (from flexion to extension). The black lines: patients with the greater spinal cord compression during neck flexion. **B**, The A-P diameter of the spinal cord at the level of the greatest spinal cord compression was significantly decreased during neck extension when compared with neck flexion ($^*P < 0.01$). A-P indicates anterior-posterior.

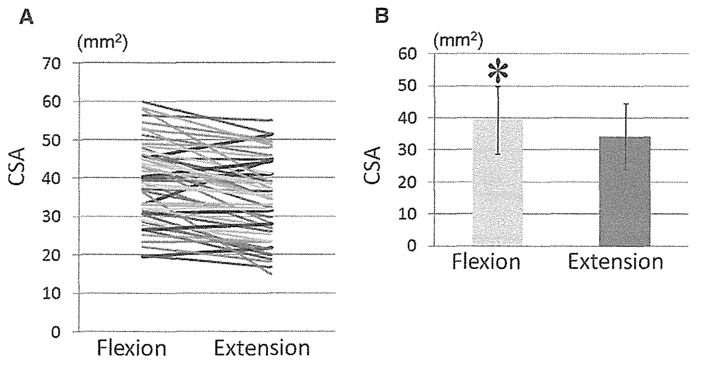

Figure 3. **A**, The dynamic changes in CSA of the spinal cord (from flexion to extension). The black lines indicate patients with the greater spinal cord compression during neck flexion. **B**, The CSA of the spinal cord at the most compressed level was significantly decreased during neck extension when compared with neck flexion (* $P < 0.01$). CSA indicates cross-sectional area.

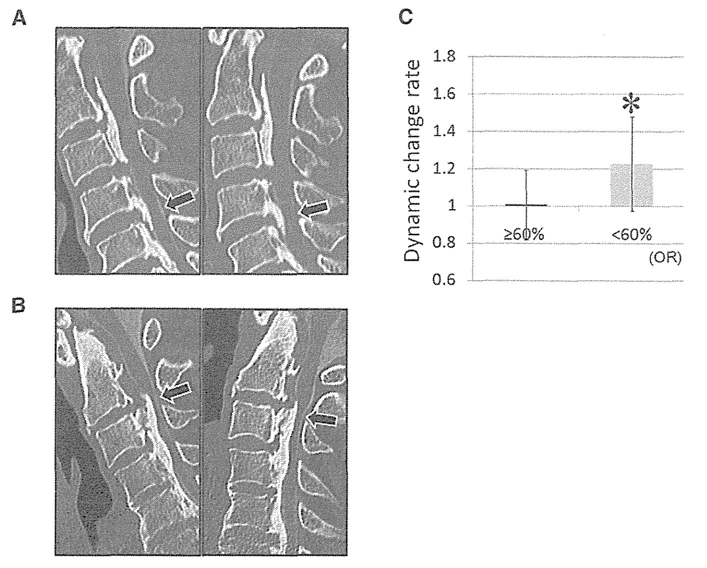

Figure 4. **A**, A case of increased spinal cord compression in neck extension. **B**, A case of increased spinal cord compression in neck flexion. The black arrows indicate the levels where the spinal cord was most compressed by OPLL. **C**, The dynamic change rate of CSA of the spinal cord (flexion/extension): patients with OPLL OR ≥ 60% *vs.* patients with OR < 60% (* $P < 0.05$). OPLL indicates ossification of the posterior longitudinal ligament; CSA, cross-sectional area; OR, occupying rate.

dynamic change rate of the A-P diameter and CSA (flexion/extension) between the subgroups: patients with a 60% or more OPLL occupying rate *versus* those with less than 60% OPLL. The dynamic change rate was significantly lower in patients with an OPLL occupying rate 60% or more ($P < 0.05$) (Figure 4C), suggesting that severe spinal cord compression during neck flexion tends to occur more frequently in patients with massive OPLL.

We further compared the different types of OPLL: segmental type and mixed type (Table 3). The proportion of males was higher in the mixed type of OPLL. Although the age and JOA neurological score were similar in the both types, the occupying rate was significantly higher in the mixed type ($P < 0.05$). In the kinematic CT myelography, the ROM at C2–C7 and at the level with greatest spinal cord compression tended to be higher in the segmental type; however, significant differences were not found. The A-P diameter and CSA of the spinal cord were significantly decreased during neck extension in both the segmental and mixed types. However, the increased spinal cord compression during neck flexion was more frequently observed in the mixed type OPLL (6/33 cases: 18.2%) than in the segmental type (1/18 cases: 5.6%).

DISCUSSION

This study prospectively investigated 51 patients with OPLL with relatively severe myelopathy (average JOA score: 10.8 points) using kinematic CT myelography. In all of the included patients, the OPLL was segmental type or mixed type, and the segments with the greatest spinal cord compression were mobile, with an average ROM of 7.0°. Static spinal cord compression is known to be an important factor in the development of myelopathy caused by OPLL, including the occupying rate of OPLL and the residual space for the spinal cord.[22–25] Matsunaga *et al*[24] reported that patients developed myelopathy at high rates when the space available for the spinal cord was less than 6 mm, whereas the patients with the space available for the spinal cord 14 mm or more did not. Dynamic factors are also important in the mechanism of neurological symptoms in OPLL.[6,7,24] A cadaveric study conducted by Inufusa *et al*[3] showed that the spinal canal area changed more than 20% by neck motion (flexion-extension). Furthermore, a larger ROM of the cervical spine is associated with the development of myelopathy,[24] whereas symptomatic myelopathy does not often develop when the ROM of the cervical spine is highly restricted by continuous OPLL.[26] As Azuma *et al*[6] have previously reported, both static cord compression and dynamic factors have an important role in the pathogenesis of myelopathy.

In this study, we used kinematic CT myelography for the evaluation of dynamic changes in spinal cord compression caused by OPLL. MRI is the most universally used diagnostic tool for investigating cervical myelopathy.[11] Previous reports have described the efficacy of functional studies using MRI to evaluate dynamic factors in patients with cervical myelopathy.[12–14] However, it is difficult to precisely assess the spinal cord CSA during flexion and extension because of image resolution limitations in MRI. Conventional myelography can offer a dynamic evaluation of the cervical spine. However, it is difficult to obtain sufficient information to evaluate the dynamic changes precisely in spinal cord compression because conventional myelography lacks axial images.

Recent studies have shown the usefulness of kinematic CT myelography to investigate the contributions of dynamic factors to the development of myelopathy in patients with CSM.[15,16] Machino *et al*[15] has shown that the spinal cord CSA is significantly decreased during neck extension at each level of the cervical spine. Although CT myelography requires a dural puncture and radiation exposure, high-resolution multidetector CT offers some advantages. The use of multidetector CT after myelography provides clearly contrasted

TABLE 3. Comparison of Different Types of OPLL

	Segmental Type	Mixed Type
N	18	33
Age (yr)	65.6 ± 7.5	63.2 ± 9.1
Male/female	12/6	27/6
JOA neurological score (/17 points)	10.9 ± 2.3	10.8 ± 2.4
Occupying rate of OPLL (%)	40.1 ± 12.4	50.8 ± 11.4*
ROM at C2–C7 (°)	26.0 ± 11.1	21.6 ± 11.9
ROM at the greatest compressed level (°)	7.6 ± 3.7	6.6 ± 4.8
A-P diameter of spinal cord		
Flexion-extension (mm)	4.0 ± 1.5†/3.3 ± 1.5	3.1 ± 1.0†/2.9 ± 0.9
No. of patients with increased spinal compression (during flexion/during extension)	1/17	6/27
CSA of spinal cord		
Flexion-extension (mm²)	39.9 ± 11.2†/34.2 ±11.8	38.9 ± 10.4†/34.4 ± 9.6
No. of patients with increased spinal compression (during flexion/during extension)	1/17	6/27

$P < 0.05$ (segmental vs. mixed).

†$P < 0.05$ (flexion vs. extension).

OPLL indicates ossification of the posterior longitudinal ligament; ROM, range of motion; A-P diameter, anterior-posterior diameter of spinal cord at the greatest compressed level in the midsagittal view; CSA, cross-sectional area of the spinal cord at the greatest compressed level in the axial view; JOA, Japanese Orthopaedic Association.

images of the vertebrae, spinal cord, cerebrospinal fluid space, and compressive factors in axial and sagittal reconstructed slices. CT myelography is particularly useful for evaluating the bony compressive focus in such disorders as OPLL. In addition, there is less possibility for neurological deterioration during the examination because the scanning time is short. Indeed, in the patients examined using kinematic CT myelography in this study, we did not observe any symptom deterioration.

In this investigation of dynamic factors in patients with OPLL using kinematic CT myelography, spinal cord compression was significantly increased during neck extension in both the segmental and mixed-type OPLL. The amount of the dynamic change in spinal cord compression did not show significant correlation with the neurological scores, because various factors influence the severity of the neurological dysfunction.[2,27,28] However, as shown in several studies, increased spinal cord compression during neck extension is known as a common dynamic factor in patients with cervical myelopathy.[12,13,15,16] During neck extension, both anterior (*e.g.*, OPLL) and posterior factors (*e.g.*, buckling of the ligamentum flavum) contribute to increased spinal cord compression (pincer effect).[14,17] We sometimes encounter patients with OPLL with progressive myelopathy whose spinal cord compression is mild in a neutral position. The dynamic imaging study is considered useful for evaluating such patients. It has also been reported that the number of levels of spinal cord compression can be increased during neck extension compared with the neutral position.[16] Therefore, kinematic CT myelography can provide critical information for determining the number of levels that should be treated during surgery.

Although spinal cord compression was increased during neck extension in most of the patients with OPLL, greater amounts of compression may be placed on the spinal cord during neck flexion in patients having OPLL with a high occupying rate. In this study, increased cord compression during neck flexion was found in 7 of the 51 (13.7%) patients. The rate of increased compression during neck flexion in patients with OPLL seems to be higher than that in patients with CSM (3%–5%).[12,14] Interestingly, all 7 of these patients had massive OPLL with an occupying rate 60% or more. In addition, the OPLL occupying rate in the patients with increased cord compression during neck flexion was significantly higher than other patients. In comparison of different types of OPLL, the occupying rate was significantly higher in the mixed-type OPLL; thus the severe spinal cord compression during neck flexion occurred more frequently in patients with mixed-type OPLL. In patients with massive OPLL, the anterior factor (*i.e.*, OPLL) is considered to influence the pathogenesis of increased compression during neck flexion more significantly than the posterior factor.[14] Posterior laminoplasty is often used to treat OPLL in clinical settings,[8,29,30] and it is usually performed under neck flexion because the spinal cord is more easily and safely decompressed during neck flexion in most patients. However, care should be taken during surgery to avoid excessive neck flexion, which can increase spinal cord compression and possibly cause intraoperative neural injury in patients with massive OPLL.[31]

Previous studies have reported that the surgical outcome after posterior decompression (*i.e.*, laminoplasty) tends to be insufficient in patients with OPLL with a large occupying rate.[21,24,25,32] Several authors demonstrated that the occupying rate (≥60% or <60%) was clinically important to determine the surgical procedure (anterior or posterior).[24,32] Therefore, we focused on the occupying rate of OPLL and used 60% as the cutoff point in this study. As this study shows, patients with massive OPLL can experience severe spinal cord compression even in the neck flexion position; in these cases, the anterior factor is a major cause of compression. Surgically treating patients with massive OPLL with posterior decompression, which only removes the posterior elements, can result in residual dynamic spinal cord compression by OPLL during neck flexion.[17] As previously reported, direct decompression through an anterior approach or posterior decompression with fusion may lead to better neurological recovery for patients with OPLL with a high occupying rate.[7,21]

We note some limitations of this study. Kinematic CT myelography has some drawbacks; in particular, the use of contrast medium and radiation exposure carry the risk of adverse effects for patients. However, the high-resolution images and the low risk of neurological deterioration during examination are great merits of kinematic CT myelography. In this study, the kinematic studies were performed only during neck flexion and extension and not at the neutral position. Examinations in 3 different positions may show interesting patterns of dynamic changes in spinal cord compression; however, increasing the number of positions for examination further increases patients' risk of radiation exposure. Despite these limitations, kinematic CT myelography was useful for evaluating the dynamic causative factors in the pathogenesis of myelopathy induced by OPLL, and it provided high-quality functional images without any neurological deterioration during the examinations.

CONCLUSION

We evaluated patients with OPLL with myelopathy using kinematic CT myelography. This functional study demonstrated the dynamic changes in spinal cord compression, which was significantly increased during neck extension. In contrast, greater levels of compression may be placed on the spinal cord during neck flexion when the patients have OPLL with a high occupying rate.

➢ Key Points

- ❑ This study primarily evaluated dynamic factors in the pathogenesis of myelopathy in patients with cervical OPLL using kinematic CT myelography.
- ❑ This functional imaging study demonstrated that the spinal cord compression at the most compressed levels was significantly increased during neck extension compared with flexion.
- ❑ Spinal cord compression can increase during neck flexion when patients have OPLL with a high occupying rate.
- ❑ This study shows that dynamic factors play an important role in the development of myelopathy in patients with OPLL.

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CERVICAL SPINE

Efficacy of Biphasic Transcranial Electric Stimulation in Intraoperative Motor Evoked Potential Monitoring for Cervical Compression Myelopathy

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Study Design. Retrospective analysis of prospectively collected data from consecutive patients undergoing 2 methods of transcranial electrical motor evoked potential (TCE-MEP) monitoring during cervical spine surgery.

Objective. To investigate the efficacy of biphasic transcranial electric stimulation, the deviation rate, amplitude of TCE-MEPs, complications, and sensitivity and specificity of TCE-MEP monitoring were compared between the biphasic and conventional monophasic stimulation methods.

Summary of Background Data. With biphasic stimulation, unlike monophasic stimulation, measurement time can be reduced considerably because a single stimulation elicits bilateral responses almost simultaneously. However, no study has yet reported a detailed comparison of the 2 methods.

Methods. *Examination 1:* Amplitude and derivation rate of TCE-MEPs was compared for monophasic and biphasic stimulation in the same 31 patients with cervical compression myelopathy. *Examination 2:* Sensitivity, specificity, and complications of TCE-MEP monitoring were compared in 200 patients with cervical compression myelopathy who received monophasic or biphasic stimulation (100 patients each) during intraoperative monitoring.

Results. *Examination 1:* Derivation rates of biphasic stimulation in the deltoid, biceps brachii, abductor digiti minimi, and flexor hallucis brevis muscles were the same or higher than for monophasic stimulation. TCE-MEP amplitudes elicited by biphasic stimulation compared with monophasic stimulation were significantly larger in the biceps (paired t, $P < 0.0001$), but similar in the other 3 muscles. *Examination 2:* In the biphasic and monophasic stimulation groups, warnings were issued to surgeons in 10 and 11 cases, for a sensitivity of 100% for both groups and specificity of 97.8% and 96.7%, respectively. No complications related to stimulation were observed in any of the 200 patients.

Conclusion. Biphasic stimulation had similar or higher derivation rates and equivalent sensitivity and specificity than monophasic stimulation. No complications were observed for either stimulation method. Biphasic stimulation is an effective TCE-MEP monitoring method for cervical spine surgery that may also reduce measurement time.

Key words: biphasic transcranial electric stimulation, intraoperative monitoring of spinal cord, patients with cervical compression myelopathy, sensitivity, specificity.

Level of Evidence: 4

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The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.

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Intraoperative spinal cord monitoring is attracting attention because of its key role in preventing neurological impairment during spinal cord surgery.[1,2] Monitoring of transcranial electrical motor evoked potentials (TCE-MEP, compound muscle action potentials) is one of the most widely used intraoperative monitoring techniques today, and by measuring multiple electromyograms it can monitor each bilateral and segmental function of gray as well as white matter. TCE-MEP monitoring offers many advantages including noninvasive monitoring of motor systems.[3–8] Transcranial stimulation predominantly stimulates the brain on the anode side, evoking large muscle evoked potentials on the contralateral side.[9,10] Consequently, in conventional monophasic stimulation,[11] it is necessary to switch the polarity of stimulation (from right anode–left cathode to right cathode–left anode)[12] to study muscle responses on both sides.[13,14] In biphasic stimulation, on the contrary, a second reversed-phase stimulation follows immediately after the first stimulation, thus stimulating both sides of the brain almost simultaneously. Consequently, this method enables the evaluation of spinal cord functions on both sides using a train of biphasic stimulus pulses without the need to reverse the polarity. This is likely to reduce intraoperative measurement time and thus interruption time. However, no previous TCE-MEP study has compared biphasic and conventional monophasic stimulation in detail.

In examination 1 of this study, to elucidate the efficacy of biphasic stimulation, we performed both biphasic and monophasic stimulation in patients with cervical compression myelopathy and compared the derivation rate and amplitude of TCE-MEP responses obtained by the 2 methods. In examination 2, we performed either method for intraoperative monitoring in 200 patients with cervical compression myelopathy (100 patients for each method) to assess the accuracy of the monitoring system and examine complications.

MATERIALS AND METHODS

Examination 1

We recruited 31 patients with cervical compression myelopathy who had received TCE-MEP intraoperative monitoring at our hospital between September 2010 and June 2011. Patients requiring reoperation were excluded. Neuromaster MEE-1200 and MS-120B (Nihon Kohden, Tokyo, Japan) systems were used for the measurement and analysis of evoked potentials. This study was approved by the Ethics Committee of the School of Medicine, Tokyo Medical and Dental University, and was performed with written informed consent from patients and followed all the guidelines for experimental investigation with human subjects required by the institutional guidelines.

All patients received general anesthesia through continuous intravenous injection of propofol (4.5 mg/kg/hr), and the injected dose was adjusted to maintain the bispectral index on the bispectral monitor in a range of 40 to 60. The muscle relaxant rocuronium bromide was administered at the minimum amount (17.1 ± 21.3 mg [mean ± standard deviation], range 0–50 mg). The analgesic remifentanil (0.25–0.5 μg/kg/min) was administered continuously. L-shaped stimulation electrodes for transcranial stimulation were inserted into the scalp to rest on the skull. Stimulation sites were symmetrical, at 2-cm anterior and 5-cm symmetric to Cz (international 10–20 system). Approximately, 30 minutes after the induction of anesthesia when the effect of the muscle relaxant had reduced and the depth of anesthesia stabilized, the 2 methods of stimulation were performed and TCE-MEPs were measured.

For monophasic stimulation, through the right anode and left cathode stimulation electrodes, a train of 5 monophasic rectangular pulses, 200-mA intensity and 0.5-millisecond duration, were applied at a frequency of 1 Hz with interstimulus intervals of 2 milliseconds. After 5 to 10 pulses,

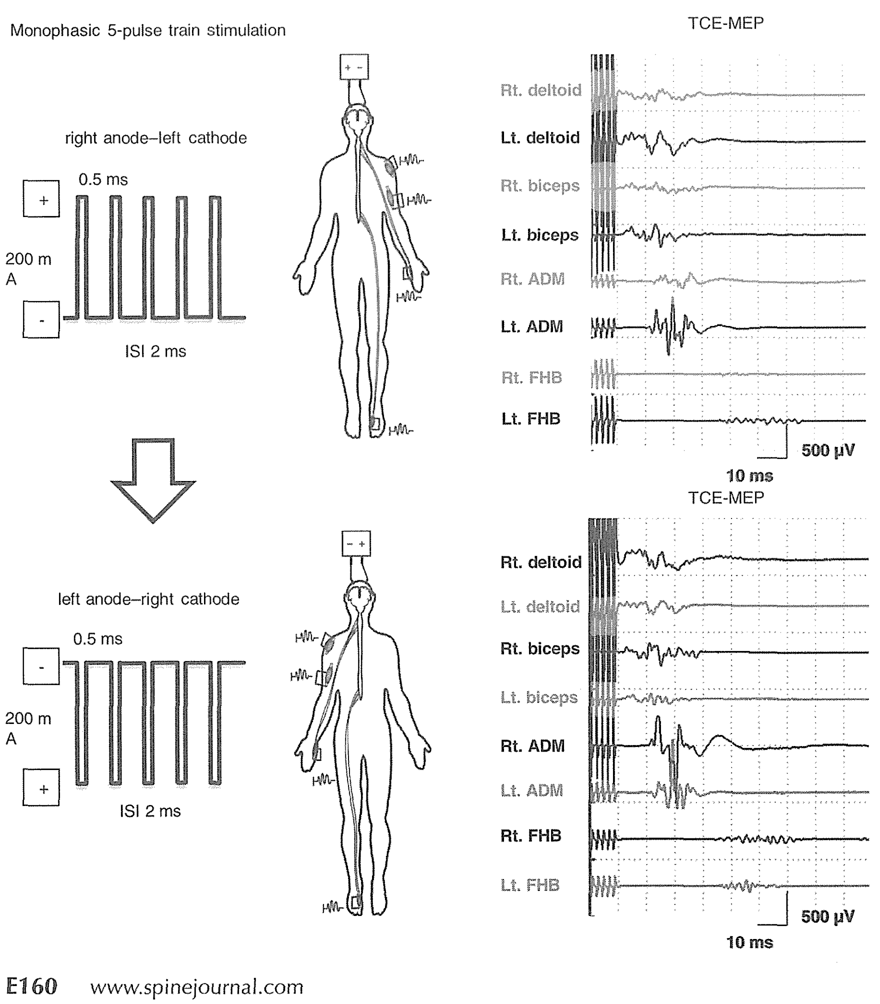

Figure 1. Stimulus condition, recorded muscles, and TCE-MEPs for monophasic stimulation. Polarity must be switched to study muscle responses on both sides. TCE-MEP indicates transcranial electrical motor evoked potential; FHB, flexor hallucis brevis; ADM, abductor digiti minimi; rt., right; lt., left.

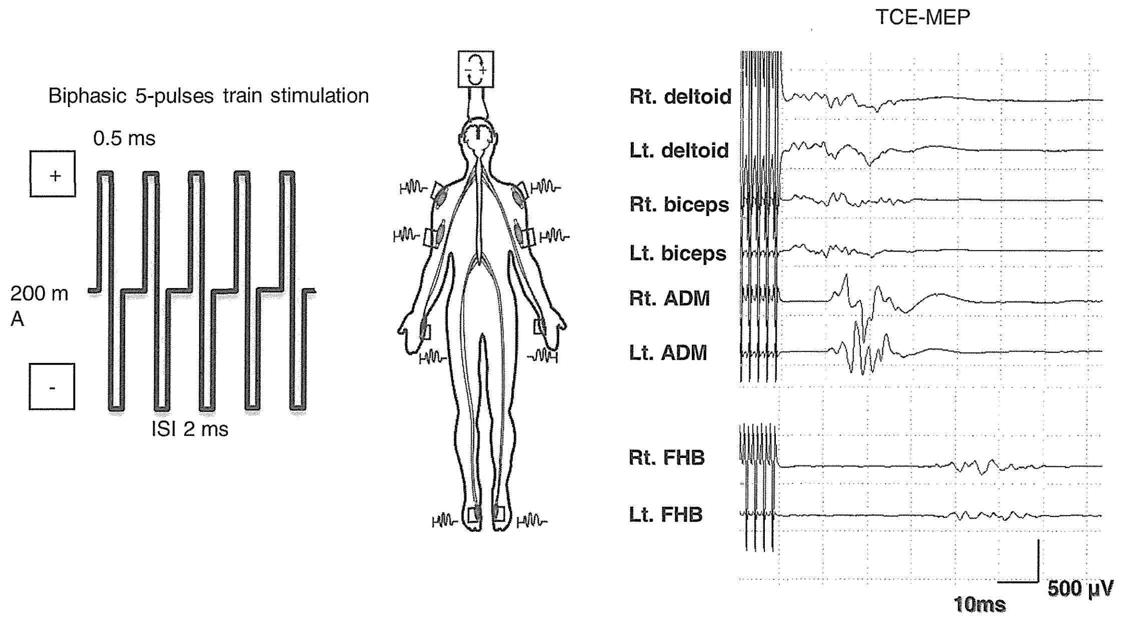

Figure 2. Stimulus condition, recorded muscles, and TCE-MEPs for biphasic stimulation. TCE-MEPs are elicited almost simultaneously on both sides. TCE-MEP indicates transcranial electrical motor evoked potential; FHB, flexor hallucis brevis; ADM, abductor digiti minimi; rt., right; lt., left.

mean values were obtained. After polarity was reversed, TCE-MEP was measured under the same conditions (Figure 1). For biphasic stimulation, a 200-mA and 0.5-millisecond rectangular pulse, as in monophasic stimulation, was immediately followed by an opposite rectangular pulse to produce 1 biphasic pulse. A train of 5 pulses were applied at a frequency of 1 Hz with an interstimulus interval of 2 milliseconds, and after 5 to 10 pulses, mean values were obtained (Figure 2). In both methods, TCE-MEPs were recorded bilaterally from the deltoid (Del), biceps brachii (Bic), abductor digiti minimi (ADM), and flexor hallucis brevis (FHB) muscles. For monophasic stimulation, the TCE-MEP study was conducted using the left muscle responses by right anode stimulation and the right muscle responses by left anode stimulation. Data were analyzed using GraphPad Prism5 statistical software (GraphPad Software, Inc., San Diego, CA).

Parameters assessed were age, sex, type of disorder, and upper and lower extremity motor function scores obtained preoperatively in accordance with the Japanese Orthopedic Association Score System for Cervical Myelopathy (upper and lower extremity JOAs) (see Supplemental Digital Content 1, Table 1 available at http://links.lww.com/BRS/A851).[15] Intraoperative derivation rates and peak-to-peak amplitudes of Del, Bic, ADM, and FHB were compared between the 2 methods. Because a certain amplitude level is needed in TCE-MEP monitoring for successful evaluation of spinal cord motor function, amplitudes that were not stably 5 μV or more were regarded as "no derivation."

Examination 2

We recruited 200 patients with cervical compression myelopathy who had received either monophasic (100 patients) or biphasic (100 patients) stimulation between May 2007 and April 2010 or August 2009 and June 2012, respectively, at our hospital. Patients requiring reoperation were excluded. Electromyograms were recorded using Neuropack (MEB-2200) or Neuromaster (MEE-1200) from Nihon Kohden Co. Method of anesthesia, TCE stimulation, and MEP recording were the same as those in Examination 1. Moreover, in all cases TCE-MEP was combined with transcranial electrical simulated spinal cord evoked potential (TCE-SCEP) monitoring (single rectangular pulse, 200-mA intensity, 0.5-millisecond duration, and 3-Hz frequency). TCE-SCEP was recorded by bipolar derivation from epidural electrodes (Unique Medical, Tokyo, Japan) placed before surgery, using a Tuohy needle in the lower thoracic epidural space (Th11–T12). The distance between the electrodes was 15 mm. Consecutive potentials (20–50) were averaged and recorded.

Because our hospital had previously experienced cases of tooth damage or tongue injury during transcranial stimulation, wads of gauze rolled into a cylindrical shape were used as a bite block in all cases. In the monophasic stimulation group, the operating surgeon was warned only when the TCE-MEP wave disappeared concomitant with an amplitude decrease of 50% or more on TCE-SCEP. For the biphasic stimulation group, we adopted warning thresholds reported by Sakaki *et al.*[16] We defined TCE-MEPs recorded from the muscles innervated by the spinal levels exposed to surgical invasion (*e.g.*, upper limb muscles in cervical spine surgery) as segmental potentials. Similarly, TCE-MEPs recorded from the muscles innervated distal to the levels of the spinal cord exposed to decompression (*e.g.*, lower limb muscles in cervical spine surgery) were used as spinal tract potentials. Surgeons were warned when the TCE-MEP amplitude for the spinal segments became 30% of the control amplitude or when the TCE-MEP amplitude for the spinal tract disappeared concomitant with a

TCE-SCEP amplitude decrease of 50% or more. At the time of warning, if a certain surgical maneuver or potential causal factor of neurological impairment was identified, surgery was discontinued until the amplitude recovered or the causal factor was removed. The number of warnings, cases of postoperative neuronal impairment, and monitoring-related complications were compared between the 2 groups.

Moreover, to estimate the sensitivity and specificity of TCE-MEP monitoring properly after each stimulation methods, intraoperative amplitude change on TCE-MEP without using TCE-SCEP were re-evaluated retrospectively in both stimulation groups, adopting the same warning thresholds.[16]

This study was approved by the Ethics Committee of the School of Medicine, Tokyo Medical and Dental University, and was performed with written informed consent and followed all the guidelines for experimental investigation with human subjects required by the institutional guidelines.

RESULTS

Examination 1

Among the 31 cases, 20 involved cervical spondylotic myelopathy, 1 cervical disc herniation, 4 ossification of the posterior longitudinal ligament of the cervical spine, 4 cervical spinal cord tumor (all extramedullary tumor), 1 cervical spondylotic amyotrophy, and 1 ossification ligamentum flavum of the cervical spine. Patients were 22 males and 9 females aged 63.1 ± 16.0 (26–89) years with upper and lower extremity JOA motor function scores of 1.87 ± 1.30 (−1–4) and 1.87 ± 1.14 (0–4) points, respectively.

Among a total of 62 muscles on both sides tested, potentials were not evoked by monophasic stimulation in 3 Del (derivation rate 95.2%), 2 Bic (96.8%), 4 ADM (93.5%), and 6 FHB (90.3%) muscles or by biphasic stimulation in 3 Del (95.2%), 2 Bic (96.8%), 2 ADM (96.8%), and 4 FHB (93.5%) muscles. When the relation between JOA motor function score of the upper extremity and TCE-MEPs of the upper extremity muscles (Del, Bic, and ADM) were analyzed, both types of stimulation evoked potentials in all muscles on both sides in all patients with an upper extremity JOA motor function score of 4–3 but not in those with a score of zero.

With regard to the relation between lower extremity JOA motor function score and FHB potentials, monophasic stimulation evoked potentials in all muscles on both sides in all patients with a lower extremity JOA motor function score of 4–3 and biphasic stimulation evoked potentials in those with a score of 4–2. In both methods, the derivation rate was 50% in patients with a score of 0.

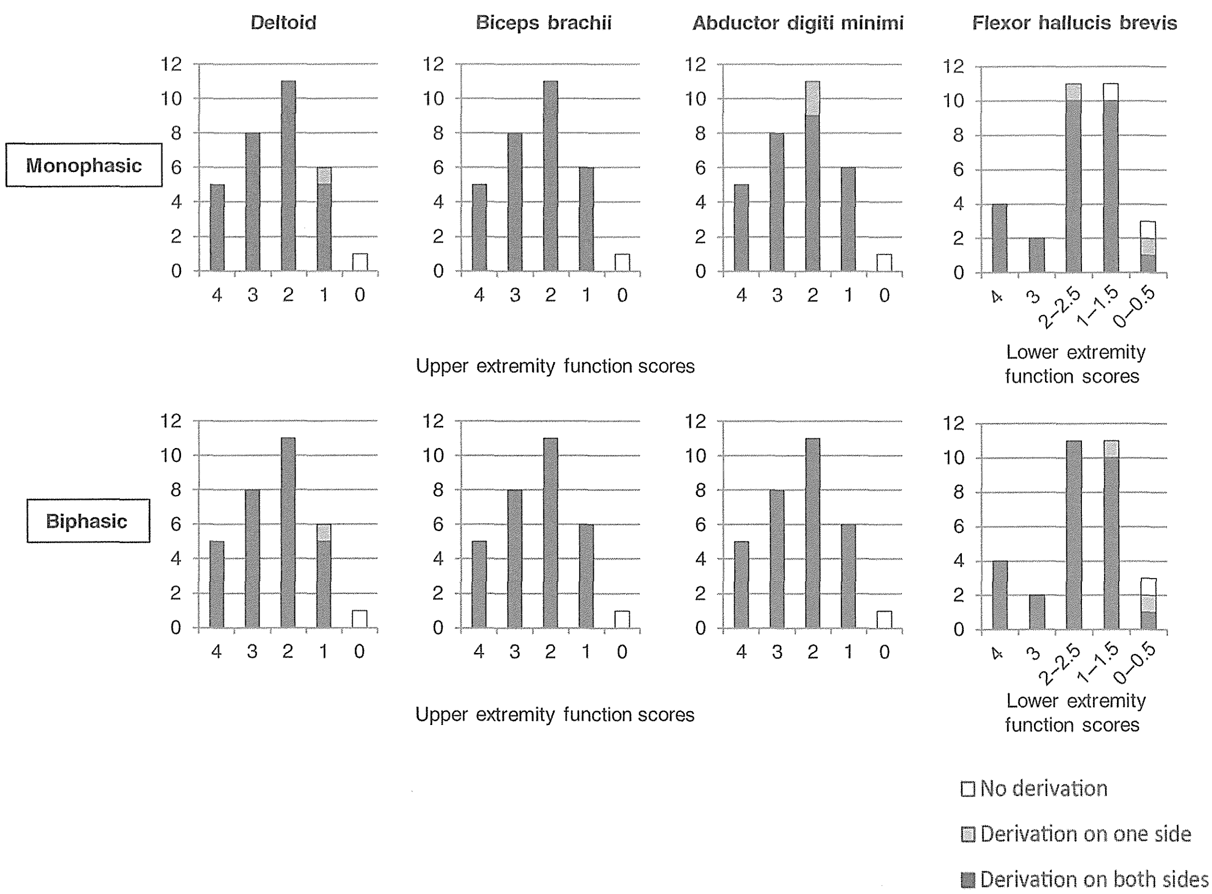

Figure 3. Relation between JOA upper extremity motor function score and upper extremity TCE-MEPs, and lower extremity JOA motor function score and FHB TCE-MEPs. TCE-MEP indicates transcranial electrical motor evoked potential; JOA, Japanese Orthopedic Association; FHB, flexor hallucis brevis.