Surgical Outcomes After Anterior Controllable Antedisplacement and Fusion Compared with Single Open-Door Laminoplasty: Preliminary Analysis of Postoperative Changes of Spinal Cord Displacements on T2-Weighted Magnetic Resonance Imaging

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■ OBJECTIVE: **This retrospective cohort study aimed to investigate the change of spinal cord displacements and the occurrence of C5 palsy between anterior controllable antedisplacement and fusion (ACAF) (group A) and single open-door laminoplasty (group L).**

■ METHODS: **From January 2016 to December 2017, a total of 80 patients with cervical ossification of the posterior longitudinal ligament (OPLL) were enrolled. All patients underwent computed tomography and magnetic resonance imaging. The types and extent of OPLL, spinal cord rotation, deviation angle, and distance between the vertebral arteries line and spinal cord (DVS) were measured. Patients with postoperative C5 palsy were recorded. Neurologic function was evaluated by Japanese Orthopaedic Association (JOA) score.**

■ RESULTS: **Three days after surgery, patients in group A had better recovery (6.7° ± 2.4°) of spinal cord rotation than group L (3.1° ± 0.8°; $P < 0.05$). Deviation angle showed similar changes to spinal cord rotation. At the final follow-up, patients in group A had decreased DVS (11.0 ± 0.7 mm), whereas patients in group L had increased DVS (15.1 ± 0.8 mm) compared with preoperation ($P < 0.05$). Five patients (1 in group A and 4 in group L) developed postoperative C5 palsy ($P > 0.05$). Patients in group A had a higher JOA score at the final follow-up than those in group L ($P < 0.05$).**

■ CONCLUSIONS: **ACAF could achieve in situ decompression in terms of spinal cord rotation, deviation angle, and spinal cord shift with better clinical outcomes and relatively lower incidence of C5 palsy compared with single open-door laminoplasty.**

INTRODUCTION

Ossification of the posterior longitudinal ligament (OPLL) has been one of the major disorders contributing to cervical myelopathy, which is characterized by ligament tissue ossification and chronic compression and damage to the spinal cord.[1] Surgical management of cervical OPLL mainly aims to decompress the spinal cord and enlarge the volume of the spinal canal using either an anterior approach or a posterior approach.[2] Anterior corpectomy and fusion could relieve the spinal cord by directly resecting the ossified mass. However, this procedure is relatively technically demanding and surgery-related complications such as graft failure, cerebrospinal fluid leakage, and spinal cord injury occur frequently.[2] A posterior approach could decompress the spinal cord safely; however, the possibility of ossification progression, formation of postlaminectomy membrane, and segmental instability exists.[2]

Key words
- Anterior controllable antedisplacement and fusion
- C5 palsy
- Deviation angle
- Shift
- Spinal cord displacement
- Spinal cord rotation

Abbreviations and Acronyms
ACAF: Anterior controllable antedisplacement and fusion
CT: Computed tomography
DVS: Distance between the VAL and spinal cord
JOA: Japanese Orthopaedic Association
MRI: Magnetic resonance imaging
OPLL: Ossification of the posterior longitudinal ligament
VAL: Vertebral arteries line
VOC: Vertebrae-OPLL complex

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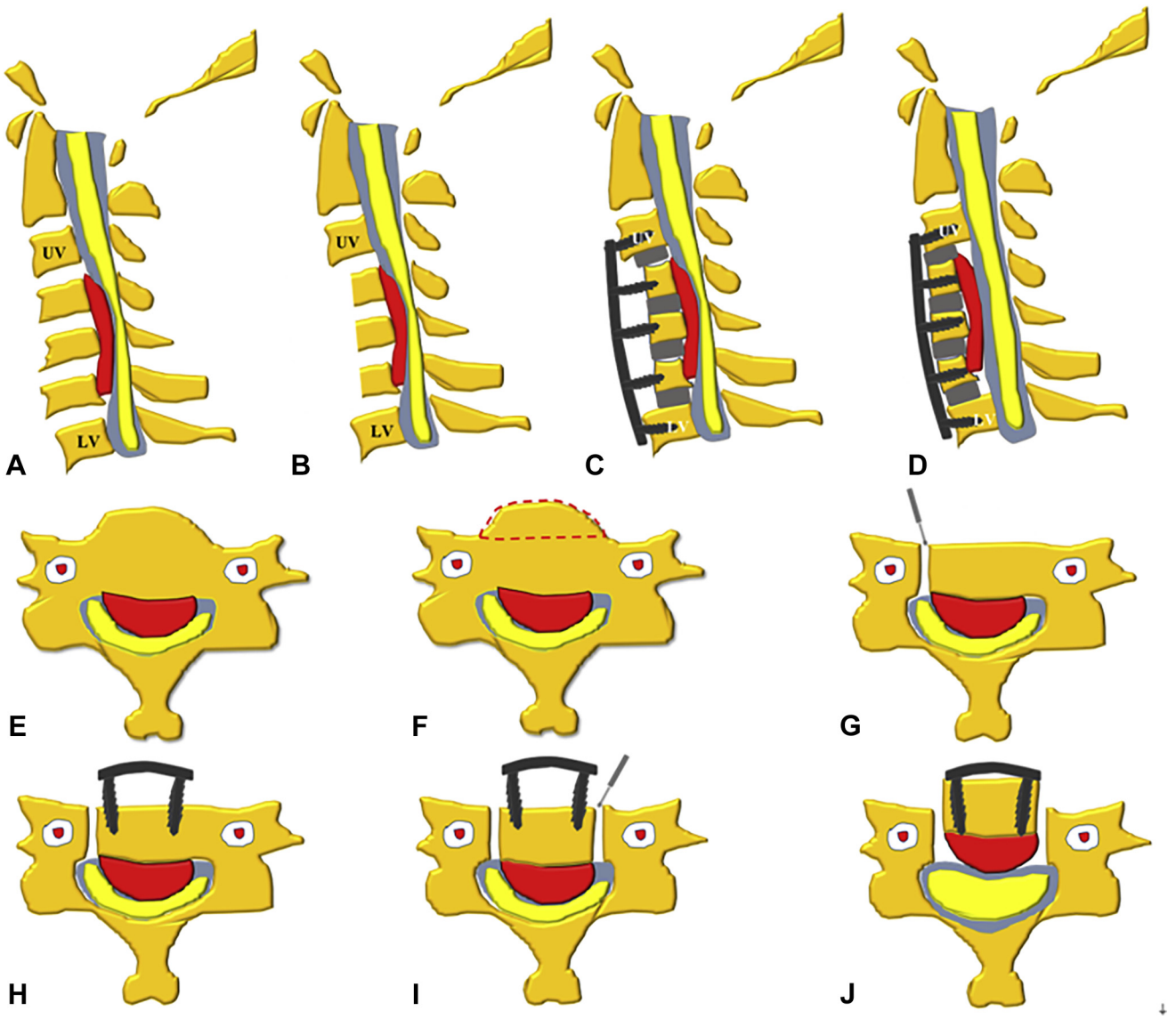

Figure 1. Illustration of anterior controllable antedisplacement and fusion (ACAF) in sagittal (**A**–**D**) and axial (**E**–**J**) views. (**A**) Removal of the disk tissues and osteophytes of the affected segments. (**B**) Removal of the anterior portion of the involving vertebral bodies. (**C**) Prefixation of the cervical plate and screws and slotting on both sides of the affected vertebral bodies. (**D**) Controllable antedisplacement of the vertebrae-OPLL complex (VOC). (**E**) Ossification of the posterior longitudinal ligament (OPLL) at the operative level. (**F**) Removal of the anterior portion of the vertebral body. (**G**) Slotting at one side lateral to the margin of the OPLL. (**H**) Prefixation of cervical plate and screws. (**I**) Slotting at the other side lateral to the margin of the OPLL. (**J**) Controllable antedisplacement of the VOC. LV, lower-end vertebrae; UV, upper-end vertebrae.

To our knowledge, few studies have been published to investigate the effect of the position of the spinal cord on the clinical outcomes after surgery. However, the position of the spinal cord has been also a vital factor for the recovery of neurologic function and should also be paid attention. C_5 nerve palsy (C_5 palsy) is a very common complication for patients with cervical OPLL, especially after a posterior approach, with an average incidence rate of 8.3% (range, 3.2%–28.6%).[3-5] Patients with C_5 palsy frequently suffer from motor deficit and even paralysis.[6,7] Previous studies have reported that cases undergoing especially single open-door laminoplasty are more susceptible to developing C_5 palsy than those undergoing an anterior approach.[8-10] Several hypotheses related to C_5 palsy after laminoplasty include postoperative instability, localized reperfusion of the spinal cord, nerve root traction, or even cervical OPLL.[11-14] Recent work has found a significant association between preoperative spinal cord rotation and C_5 palsy, and patients with higher cord rotation angle have higher occurrence of postoperative C_5 palsy.[15,16] The results

suggest that the position of the spinal cord may correlate closely with C5 palsy. We speculate that the ossified mass would potentially place persistent pressure on the spinal cord and cerebrospinal fluid, which may cause asymmetric shift of the cord after single open-door laminoplasty and further increase the postoperative tension of the nerve root. ACAF has been proposed to treat patients with OPLL and acquired satisfactory outcomes by directly reconstructing the spinal canal and restoring the normal position of the spinal cord.[17] In addition, because of the antedisplacement of the ossified mass, the decompression by anterior controllable antedisplacement and fusion (ACAF) is technically symmetric and the spinal cord returns to its original position after surgery, which we call in situ decompression. In addition, our previous study has reported the occurrence of C5 palsy after ACAF was very low.[18]

Therefore, the purpose of this study was to analyze the changes of rotation angle and shift of spinal cord, and the occurrence of C5 palsy for patients with cervical OPLL after ACAF and single open-door laminoplasty.

METHODS AND MATERIALS

Patient Population

This is a retrospective cohort study, and the medical data of patients with cervical myelopathy who underwent ACAF or laminoplasty because of OPLL from January 2016 to December 2017 in our institution were reviewed. There were no significant differences in terms of the indications of ACAF and single open-door laminoplasty except in patients with cervical kyphosis or cervical deformity. Under this circumstance, we would choose an anterior approach. Only patients undergoing ACAF or single open-door laminoplasty were selected in the period of the study.

The inclusion criteria were 1) those with symptoms of cervical myelopathy because of OPLL (mainly including limb numbness, impaired motor function, and unsteady gait); 2) those treated with ACAF or laminoplasty only; and 3) those with OPLL including the C5-6 level. The exclusion criteria were 1) cervical myelopathy caused by cervical disk herniation or spondylosis; 2) those with a history of cervical trauma, infection, and tumor; 3) those without complete follow-up data; 4) those with clinical symptoms resulting from thoracic or lumbar degenerative disease; 5) those with congenital spinal deformity; 6) those having neurologic diseases such as Parkinson, Alzheimer, dementia, and so forth; 7) those with diabetes or other metabolic diseases without regular treatment and well control; and 8) those with a history of psychosis or alcoholism or drug addiction.

The sample size in each group was determined by the number of eligible cases during the study period, and a total of 80 patients were finally enrolled in this study. According to the types of surgical techniques, patients were divided into the ACAF group (group A) and laminoplasty group (group L). This study was approved by the institutional review board of Changzheng Hospital, and all eligible patients signed the informed consent.

Surgical Technique

The surgical procedures of single open-door laminoplasty used in this clinical study have been well described in previous literature.[19-21] For ACAF surgery, the process of ACAF has been reported previously and is illustrated in Figure 1.[17] Briefly, after general endotracheal anesthesia, the patient was placed in a supine position appropriately with the neck slightly extended. The vertebrae at both ends of the OPLL were defined as the upper- and lower-end vertebrae, respectively, and the surgical exposure range of the ACAF included the cephalic adjacent disk level to the upper-end vertebrae and caudal adjacent disk level to the lower-end vertebrae. The surgical level was confirmed via intraoperative radiography, and a standard right- or left-sided Smith-Robinson incision was conducted to expose the subcutaneous tissue and deep structures. After necessary diskectomies, the resection of the posterior longitudinal ligament at the caudal and cranial ends of the involved levels was performed to facilitate the further hoisting of the vertebrae-OPLL complex (VOC). The proper amount of anterior vertebral bodies of the VOC were resected according to the thickness of the ossified mass and the anteroposterior diameter of the spinal canal. After this, bilateral osteotomies for complete isolation of the VOC from the surrounding bony structures was conducted using a high-speed drill, and this procedure was repeated at each affected level. Simultaneously, the intervertebral carbon fiber cages with autogenic bone was placed at the corresponding levels. The precurved cervical plate was fixed at the caudal and cephalad vertebrae by screws which were inserted halfway for temporary fixation. Finally, the screws were gradually tightened in each vertebral body at the same pace to achieve anteriorly hoisting of the VOC, and allogenic iliac bone was implanted into the groove to ensure fusion. All patients had neurophysiologic monitoring (somatosensory-evoked potentials), spontaneous electromyogram, and/or motor-evoked potentials intraoperatively. All patients were operated by spine surgeons who had at least 10 years' experience in spine surgery from the same surgical team. After surgery, all patients wore a Philadelphia collar routinely postoperatively for at least 3 months.

Clinical Assessment

All patients were followed-up at least 12 months after surgery. The Japanese Orthopaedic Association (JOA) score were used to evaluate neurologic function. The improvement rate of the JOA score was calculated as follows: (final JOA score − preoperative JOA score/17 − preoperative JOA score) × 100%.

Evaluation of C5 Palsy

Postoperative C5 palsy was defined as new development of weakness of the deltoid with or without the biceps brachii, with a manual muscle testing score $\leq$3 on a scale of 5. Patients with palsy first accepted conservative treatment with rehabilitation and administration of glucocorticoids and vitamin B12.

Radiologic Assessment

All patients underwent radiograph, computed tomography (CT) scan, and magnetic resonance imaging (MRI) of the cervical spine before surgery, 3 days after surgery, and at the final follow-up. To correct the intra- and interobserver reliability of the radiologic measurements, 2 experienced observers independently evaluated the radiographs of the patients. Each of them took measurements 3 times, and the mean values were used for statistical analysis.

CT Scanning Measurement. The diagnosis of OPLL was established for all patients based on CT scanning preoperatively. On sagittal

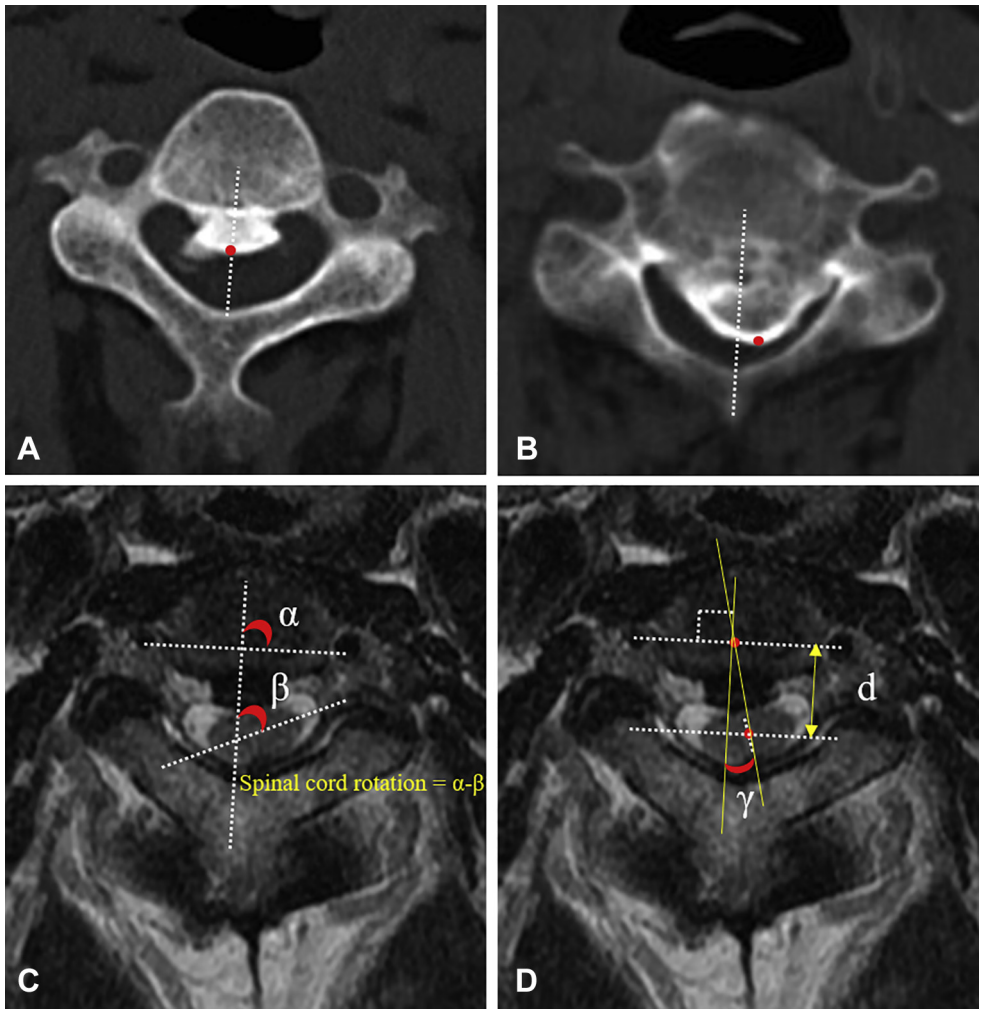

Figure 2. Illustration of the radiologic measurement. (**A** and **B**) Classification of the ossified mass is shown. A *line* connecting the point at the center of the bilateral vertebral artery canals and the *midpoint* of the anterior edge of the lamina was drawn first. Then, if the peak of the ossified mass was on the line, the ossification of the posterior longitudinal ligament was defined as central, and otherwise, lateral. (**C**) The *upper transverse dotted line* (vertebral arteries line [VAL]) indicated the line connecting bilateral vertebra artery holes, and the *subjacent oblique dotted line* indicated the long axial of the compressed spinal cord. Spinal cord rotation angle (β) denoted the angle between the 2 lines. (**D**) The *upper dotted line* is also the VAL, and the *subjacent dotted line* indicated the line parallel to the VAL and passing the center of the cord. The spinal shift (d) was evaluated by the distance between the *2 transverse lines*. The deviation angle (γ) was measure by the *2 longitudinal lines*. The *2 longitudinal lines* indicated the line connecting the center of the cross-section vertebral body and the base of spinal process and the line connecting the center of the vertebral body and spinal cord.

CT image, the extent of OPLL was also defined. OPLL at the narrowest level was classified into 2 types (central and lateral), according to the axial CT images. A line connecting the point at the center of the bilateral vertebral artery canals and the midpoint of the anterior edge of the lamina was drawn first. Then, if the peak of the ossified mass was on the line, the OPLL was defined as central, and otherwise, lateral (Figures 2A and B).

MRI Measurement. Considering the factors of C5 palsy involving the spinal cord at the C3-4, C4-5, and C5-6 levels, all measurements on MRI were obtained at the site of the 3 levels. The mean value was defined as the final value to indicate the mean rotation or shift of the affected spinal cord within the canal.

Spinal Cord Rotation. Spinal cord rotation was used to reflect the rotation of the cord corresponding to the vertebral body from the view of the coronary section and was defined as the angle formed by the line connecting the center points of the bilateral vertebral arteries (vertebral arteries line [VAL]) and the line parallel to the long axis of the spinal cord based on axial planes of T2-weighted

Table 1. Clinical Characteristics of Patients in This Study

Characteristics	Group A (n = 42)	Group L (n = 38)	*P* Value
Age (years)	57.2 ± 12.2	58.1 ± 13.4	0.624
Sex			0.823
Female	19	19	
Male	23	19	
Duration of symptoms (months)	27.1 ± 13.3	26.8 ± 10.1	0.139
Types of OPLL at the narrowest level			0.371
Central	20	14	
Lateral	22	24	
Levels of OPLL			
3	14	11	
4	18	19	
5	10	8	
Duration of follow-up (months)	18.2 ± 2.9	17.7 ± 4.0	0.573
Number of C5 palsies	1	4	0.185

Values are number of participants, mean ± SD, or as otherwise indicated.
Group A, anterior controllable antedisplacement and fusion group; Group L, laminoplasty group; OPLL, ossification of the posterior longitudinal ligament.

imaging, as described by Eskander et al.[15] (spinal cord rotation = $\alpha - \beta$) (Figure 2C). At different time points before and after surgery, spinal cord rotation was measured and compared between the 2 groups. In addition, the change of spinal cord rotation was also calculated at different time points after surgery, which suggested the restoration of the rotary position of the spinal cord after decompression surgeries.

Deviation Angle. The deviation angle was used to suggest the left or right deviation corresponding to the anteroposterior midline of the spinal canal from the view of the sagittal section and was defined as the angle formed by the line perpendicular to the VAL and the line connecting the center point of the minor axis of the spinal cord and the center point of VAL, indicated by yellow dotted lines (Figure 2D). The difference of pre- and postoperative deviation angles was also compared between 2 groups to assess the restoration of the lateral shift of the spinal cord.

Distance Between the VAL and Spinal Cord. The distance between the VAL and spinal cord (DVS) was used to indicate the anteroposterior migration of the spinal cord corresponding to the vertebral body from the view of the transverse section. The center point of the spinal cord was defined as the intersection point of the long and short axes of the cord to indicate the position of the cord, and DVS indicated the distance between the center point and VAL, indicated by d (Figure 2D).

Statistical Analysis

Statistical analyses were performed using SPSS (Version 20.0; IBM Corp., Armonk, New York, USA). The data were presented as mean ± SD. Mann-Whitney U test was used to compare the clinical and radiologic outcomes pre- and postoperatively. The χ^2 test was used in the comparisons of the sex, types of OPLL, and recovery rate between the 2 groups. Values less than 0.05 ($P < 0.05$) were considered statistically significant.

Table 2. Japanese Orthopaedic Association Score of Patients in 2 Groups

Time Points	Group A	Group L	*P* Value
Preoperation	9.3 ± 1.4	9.5 ± 1.3	0.875
3 days after operation	12.6 ± 1.8	11.9 ± 1.2	0.043
Final follow-up of 12 months	14.5 ± 2.3	13.9 ± 1.7	0.029
Recovery rate (%)	67.5 ± 18.8	58.7 ± 14.7	0.002

Values are mean ± SD or as otherwise indicated.
Group A, anterior controllable antedisplacement and fusion group; Group L, laminoplasty group.

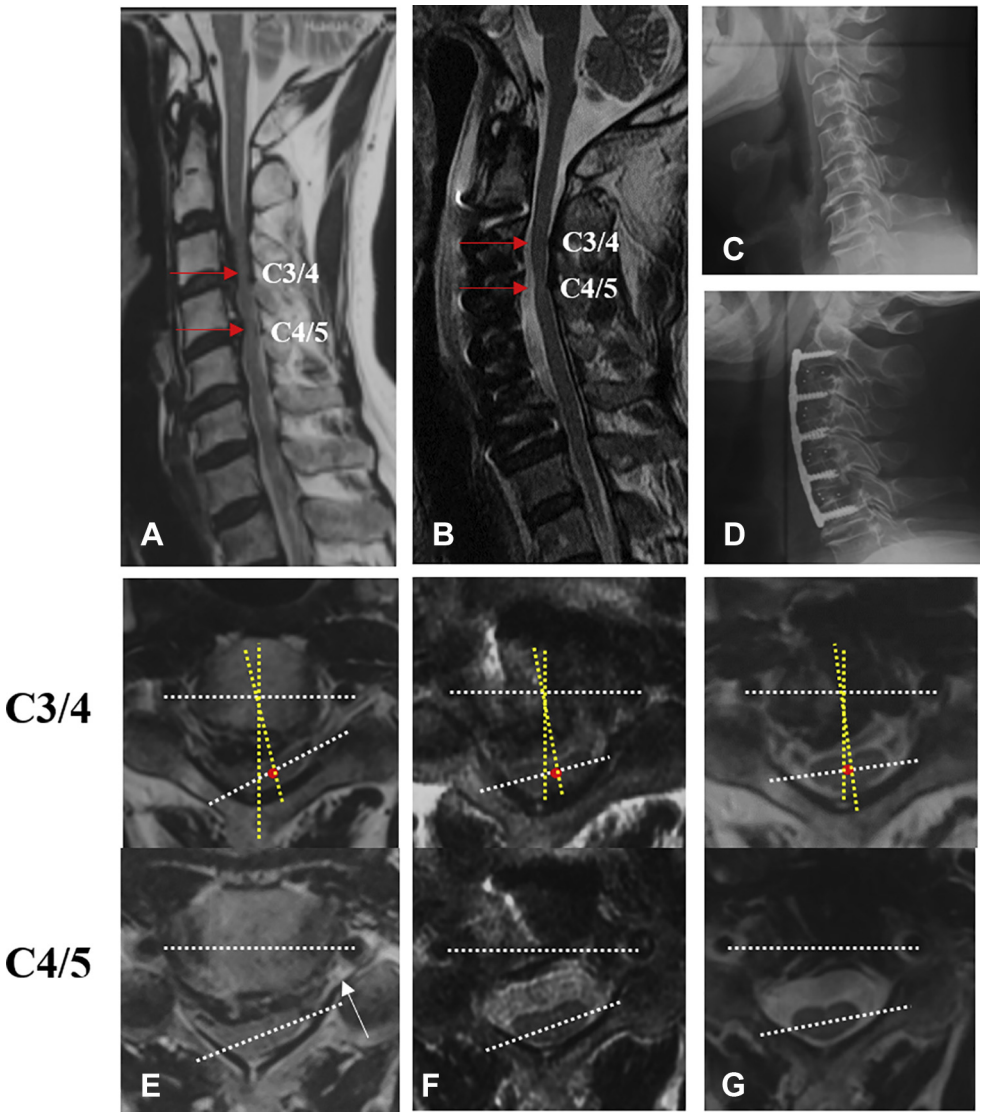

Figure 3. Case 1: a 55-year old man with cervical ossification of the posterior longitudinal ligament (OPLL) suffered from postoperative C5 palsy after anterior controllable antedisplacement and fusion (ACAF). Preoperative magnetic resonance imaging showed the spinal cord was compressed at C3-5 (**A**). ACAF of C2-6 was given, and his spinal cord acquired satisfactory decompression (**B** and **D**). His cervical curvature was lost (**C**). His preoperative spinal cord rotation and deviation angle were 29.2° and 14.1°, respectively (**E**). In terms of the nerve root at the C4-5 level, more traction may exist on the right because of lateral OPLL before surgery (*white arrow*, **E**). Therefore, during the recovery of spinal cord rotation, the nerve root on the palsy side (left) may suffer from more tension because of the clockwise rotation of the cord because of the release of right compression (**F**). Nevertheless, his symptoms disappeared 2 weeks later, and at the final follow-up, both his spinal cord rotation and deviation recovered significantly (**H**).

RESULTS

Patient Characteristics

In total, 9 patients were excluded from this study, including 5 patients because of loss of follow-up, 3 patients with complete imaging information, and 1 patient who refused to further follow-up 6 months after ACAF. Table 1 summarizes the demographic data of patients in this study. There were 42 patients (19 men and 23 women) who underwent ACAF and 38 patients (19 men and 19 women) who underwent laminoplasty. The mean age of patients was 57.2 ± 12.2 years in group A and 58.1 ± 13.4 years in group L. No significant differences were observed between the 2 groups in terms of age, sex, types of OPLL, and duration of symptoms and follow-up (all $P > 0.05$).

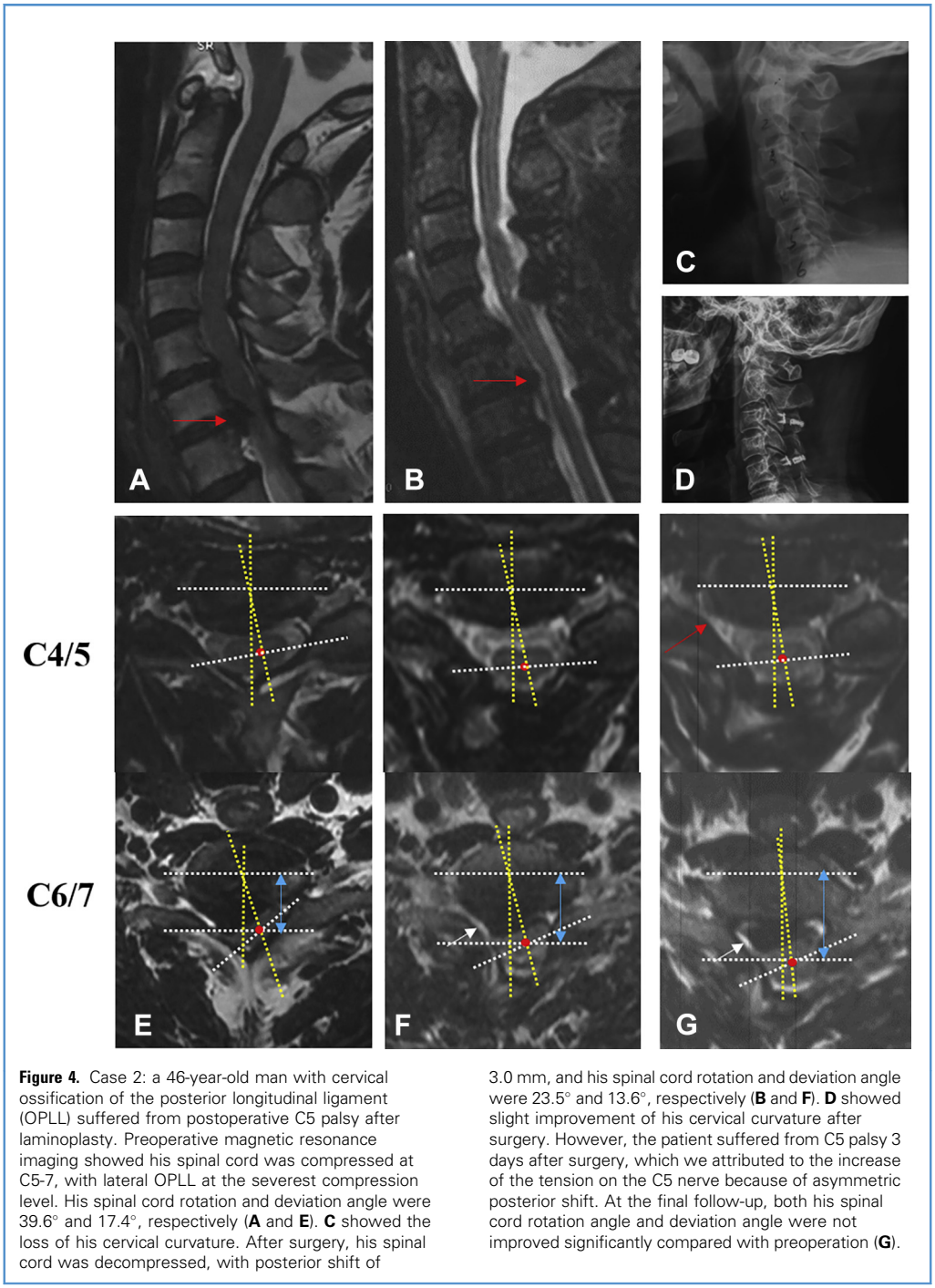

Figure 4. Case 2: a 46-year-old man with cervical ossification of the posterior longitudinal ligament (OPLL) suffered from postoperative C5 palsy after laminoplasty. Preoperative magnetic resonance imaging showed his spinal cord was compressed at C5-7, with lateral OPLL at the severest compression level. His spinal cord rotation and deviation angle were 39.6° and 17.4°, respectively (**A** and **E**). **C** showed the loss of his cervical curvature. After surgery, his spinal cord was decompressed, with posterior shift of 3.0 mm, and his spinal cord rotation and deviation angle were 23.5° and 13.6°, respectively (**B** and **F**). **D** showed slight improvement of his cervical curvature after surgery. However, the patient suffered from C5 palsy 3 days after surgery, which we attributed to the increase of the tension on the C5 nerve because of asymmetric posterior shift. At the final follow-up, both his spinal cord rotation angle and deviation angle were not improved significantly compared with preoperation (**G**).

Clinical Outcomes

Table 2 shows the JOA scores in the 2 groups. No significant difference was observed before surgery. However, patients in group A had a higher JOA score after surgery and at the final follow-up of 12 months than those in group L (both $P < 0.05$). In addition, patients in group A had higher final recovery rate (67.5% ± 18.8%) than those in group L (58.7% ± 14.7%) ($P < 0.05$). Five patients experienced C_5 palsy after surgery. Only 1 patient (2.4%) with C_5 palsy was observed in group A (case 1) (Figure 3), whereas 4 patients (10.5%) in group L had postoperative C_5 palsy (case 2) (Figure 4). However, no significant difference was observed between the 2 groups regarding C_5 palsy ($P = 0.185$). The onset of this symptom occurred several days after surgery in all cases, with a mean

Table 3. Summary of 5 Patients with C5 Palsy After Surgery

Patient Number	Age (years)/Sex	Extent of OPLL	Procedure	Onset Time of C5 Palsy (days)	Duration of Symptoms (days)	Spinal Cord Rotation			Deviation Angle			DVS (mm)		
						Pre.	Post.	Final	Pre.	Post.	Final	Pre.	Post.	Final
1	55/Male	C3-7 (L)	ACAF	2	17	29.2°	14.5°	8.2°	14.1°	9.5°	7.2°	14.5	12.8	11.1
2	46/Male	C5-7 (L)	Laminoplasty	3	180	39.6°	23.5°	14.8°	17.4°	13.6°	10.6°	13.5	16.5	17.3
3	67/Female	C3-6 (C)	Laminoplasty	3	60	12.1°	5.9°	3.1°	2.5°	1.2°	1.0°	10.4	12.8	12.0
4	57/Male	C3-6 (L)	Laminoplasty	5	89	14.9°	6.2°	3.3°	12.1°	5.8°	3.2°	13.7	16.2	15.3
5	66/Male	C3-6 (L)	Laminoplasty	4	34	13.7°	5.7°	2.1°	9.8°	2.9°	2.1°	14.1	16.2	15.2

OPLL, ossification of the posterior longitudinal ligament; Pre., preoperation; Post., 3 days after surgery; DVS, distance between the vertebral arteries line and the center point of the spinal cord; L, lateral; C, central; ACAF, anterior controllable antedisplacement and fusion.

onset time of 3.4 days, as shown in Table 3. All cases recovered completely with conservative treatments such as prompt induction of rehabilitation or administration of glucocorticoids and vitamin B12 at the final follow-up.

Radiologic Assessment

CT Image. There were 22 patients with lateral OPLL and 20 patients with central OPLL in group A, whereas there were 24 with lateral OPLL and 14 with central OPLL in group L ($P > 0.05$). In terms of the extent of OPLL, both groups had the most patients with OPLL of more than 3 segments, and all patients had OPLL involving the C5 segment (Table 1).

MRI Assessment. Table 4 summarizes the radiologic change of the spinal cord based on T2-weighted imaging. No significant differences were observed between the 2 groups regarding preoperative spinal cord rotation, deviation angle, and DVS.

Spinal Cord Rotation. After surgery, patients in group A had a larger change of spinal cord rotation ($6.7° \pm 2.4°$) than those in group L ($3.1° \pm 0.8°$, $P < 0.05$). At the final follow-up, the spinal cord rotation of patients in group A was $1.8° \pm 0.8°$, significantly lower than those in group L ($4.8° \pm 0.3°$, $P < 0.05$). Patients in group A had higher final change of spinal cord rotation than those in group L ($P < 0.05$).

Deviation Angle. Deviation angle showed similar changes to spinal cord rotation between the 2 groups. At the final follow-up, patients in group A had a smaller deviation angle ($4.0° \pm 0.6°$) than those in group L ($9.0° \pm 0.4°$, $P < 0.05$).

DVS. Three days after operation, patients in group A had anterior spinal shift (1.1 ± 0.9 mm), whereas patients in group L had spinal posterior shift (2.3 ± 0.6 mm, $P < 0.05$). At the final follow-up, the spinal anteroposterior shift in group A further increased, with the final change of shift of 2.2 ± 0.7 mm. However, the spinal posterior shift of patients in group L decreased from 15.6 ± 1.1 mm to 15.1 ± 0.8 mm, with the final change of shift of 1.8 ± 1.3 mm.

DISCUSSION

Anterior or posterior approach has been widely used in the treatment of compressive cervical myelopathy, and the sufficient release of the compression of the cord is always the key point. Previous studies have focused mainly on the anterior or posterior shift of the spinal cord after surgery. However, the rotation and lateral deviation of the spinal cord has not been well investigated, which may cause asymmetric decompression and tension of the cord. Theoretically, the spinal should be kept to its original position with normal physiologic curvature and thus the cord can well-perform its function. ACAF, as a novel technique, has been proposed to decompress the compressed spinal cord based on the notion of in situ decompression, and not only could the patients with ACAF acquire sufficient decompression, but also the cord can be restored to its original physiologic position.[18]

A common complication, C5 palsy, has been reported to adversely affect the good outcomes.[22] Among the several causes of C5 palsy, nerve root traction or the tethering effect induced by excessive shift of the spinal cord after surgery has been widely accepted currently.[23-25] Anatomically, the C5 level is located at

Table 4. Magnetic Resonance Imaging Assessment of the Spinal Cord for Patients in 2 Groups at Different Time Points

Parameters	ACAF Group	Laminoplasty Group
Spinal cord rotation		
Pre.	9.1° ± 4.0°	8.9° ± 1.3°
Post.	2.4° ± 2.5°	5.8° ± 1.1°*
Change	6.7° ± 2.4°	3.1° ± 0.8°*
Final follow-up	1.8° ± 0.8°	4.8° ± 0.3°*
Final change	7.3° ± 0.9°	4.1° ± 0.5°*
Deviation angle		
Pre.	23.3° ± 12.0°	21.0° ± 0.8°
Post.	9.4° ± 5.3°	15.7° ± 0.5°*
Change	13.9° ± 8.6°	5.4° ± 0.7°*
Final follow-up	4.0° ± 0.6°	9.0° ± 0.4°*
Final change	19.3° ± 0.3°	12.0° ± 0.5°*
DVS (mm)		
Pre.	13.2 ± 1.1	13.3 ± 0.9
Post.	12.1 ± 1.2	15.6 ± 1.1*
Change	1.1 ± 0.9	2.3 ± 0.6*
Final follow-up	11.0 ± 0.7	15.1 ± 0.8*
Final change	2.2 ± 0.7	1.8 ± 0.13

ACAF, anterior controllable antedisplacement and fusion; Pre., preoperation; Post., 3 days after surgery; DVS, distance between the vertebral arteries line and the center point of the spinal cord.
*$P < 0.05$.

the apex of cervical lordosis, and the length of the C5 nerve is also relatively short and the angle is more obtuse from the spinal cord, which makes C5 nerve more vulnerable to bearing maximized tension because of the migration of the spinal cord after surgery.[26,27] Radcliff et al.[28] found that wider laminectomy at C5 and increased preoperative spinal canal diameter were also associated with an increased risk of postoperative C5 palsy. In fact, C4 nerve roots also have almost the same characteristics as the C5 nerve root. However, a paresis of the diaphragm is not detected as often because it is mostly clinically not apparent, whereas C5 represents a nerve root which results in clinically obvious impairments.

Several studies have reported that asymmetric spinal cord decompression correlates closely with the occurrence of C5 palsy. Odate et al.[29] revealed that extremely wide and asymmetric decompression may also cause postoperative C5 palsy after anterior decompression and fusion, which may cause asymmetric shift of the cord. Similar to that, asymmetric spinal cord drift after single open-door laminoplasty may also increase the risk of C5 palsy compared with symmetric spinal cord drift.[8] Other studies have reported a similar positive association among C5 laminectomy width, posterior spinal cord drift, and risk of C5 palsy.[11,30,31] Several studies have reported asymmetric decompression of the spinal cord may trigger iatrogenic spinal cord rotation.[8,29,32] A study by Eskander et al.[15] suggested that greater degrees of spinal cord rotation before surgery and subsequent cord shift after surgery would increase the traction of the C5 nerve root, leading to a greater risk of developing postoperative C5 palsy. These results indicated that except excessive shift and the change of rotation of the cord because of asymmetric decompression may also be critical factors for the occurrence of postoperative C5 palsy.

Therefore, this study focused on the rotation and shift of the spinal cord in patients with cervical OPLL who underwent ACAF or single open-door laminoplasty. Based on the types of initial surgical procedure, we divided patients into group A (ACAF) and group L (single open-door laminoplasty). Because a vast majority of C5 palsies occur within 1 week after surgery, we evaluated the radiologic changes of patients at preoperation, 3 days after operation, and at least 12 months after surgery. The results revealed that patients in group A had a significantly lower incidence of C5 palsy (2.4%) than those in group L (10.5%); however, no statistical significance was observed, which we attributed to the relatively small sample size. The mean onset time of C5 palsy was 3.4 days after surgery, which was consistent with previous studies.[33,34] The overall patients in group A acquired better recovery in terms of spinal cord rotation and deviation angle compared with group L. Although all patients completely recovered at the final follow-up, the patients' satisfaction and quality of life were significantly affected. The results in this study suggest that although preoperative spinal cord rotation was a high risk of C5 palsy after surgery, worse postoperative recovery may also increase the risk. Therefore, we recommend that more attention should be paid to restore rotation and deviation of the spinal cord during the procedure of decompression because the preoperative condition of patients is uncontrollable. Interestingly, in this study, 4 of 5 patients with C5 palsy had lateral OPLL at the narrowest level, which suggested the type of OPLL may also correlate with C5 palsy.

We chose spinal cord rotation as the key measurement in this study for the following reasons. First, spinal cord rotation has proven to be a strong and significant predictor of C5 palsy postoperatively, and the larger the preoperative spinal cord rotation, the higher the incidence of postoperative C5 palsy.[15] Here, we used spinal cord rotation to indicate the axial rotation position of the spinal cord relative to the vertebral body, and we think from the results in this study that the correction of spinal abnormal rotation may decrease the incidence of C5 palsy. Different from previous studies, we measured spinal cord rotation at 3 levels of the cord, including the C5 level, which we think could reflect the mean rotation of the cervical spinal cord within the spinal canal. Second, the parameter is easy to acquire. We think the decompression of the cord should not be limited to only releasing the compression, but to restoring the normally spatial position of the cord within the canal. Therefore, considering the lateral (left or right) shift of the cord because of lateral-type OPLL or postoperative asymmetric spinal cord decompression by laminoplasty, we first proposed a novel parameter, deviation angle, in this study and found the change of deviation angle was similar to that of spinal cord rotation.

Of note, there was only 1 patient who underwent C5 palsy in group A. However, he had complete recovery 17 days after ACAF,

whereas patients with laminoplasty experienced a longer time for recovery. There are 2 reasons which may explain the lower occurrence of C5 palsy and shorter recovery time by ACAF. First, unlike laminoplasty, ACAF enlarges the spinal canal to its original volume without resecting the dorsal structure of the spinal canal. In addition, the VOC is hoisted as a whole anteriorly in ACAF, serving as part of the wall of the reconstructed spinal canal, which we think is crucial for reducing the excessively posterior shift of the spinal cord compared with laminoplasty. Most importantly, ACAF is an in situ decompression to the spinal cord. The spinal cord remains in its original position and is kept in good lordosis after ACAF. Although no study has claimed that the spinal cord must be kept in a normal position, good curvature, and even physical lordosis, in theory it should be.[18] In addition, our recent study found that the curvature of the spinal cord was a critical factor affecting patient prognosis because the spinal cord bore the least axial tension in its physical lordosis (data not shown). Second, the decompression of the spinal cord by ACAF is symmetric, which facilitates to correct the abnormal rotation of the spinal cord and decrease the occurrence of C5 palsy. The reason for the patient with C5 palsy after ACAF may correlate with the sudden correction of the severe spinal cord rotation and deviation angle after surgery, which could cause reperfusion to the cord or kinking of the C5 nerve root after the acute release of traction.[33] However, the shorter recovery time of his symptoms may be attributed to the advantages previously mentioned by ACAF. A study by Yang et al.[18] also proved that during ACAF, all the posterior and anterior risk factors could be avoided, including no spinal cord posterior shifts, no iatrogenic foraminal stenosis, no posterior column change, and no excessive intervertebral height increase.

We further investigated the spinal anterior or posterior shift between the 2 groups and found that patients in group A experienced anterior shift of the cord (1.1 $\pm$ 0.9 mm) 3 days after surgery, whereas patients in group L had posterior shift of the cord (2.3 $\pm$ 0.6 mm). Although patients in both groups had spinal cord shift, the anterior shift by ACAF was absolutely different from the posterior shift by the posterior approach. Because we chose the center of the minor axis of the cord to locate the spinal cord in this study, the anterior shift of the cord resulted from the expansion of the cord after the release of anterior compression, and the spinal cord was restored to its original position. However, the posterior shift by posterior decompression was related to the dorsal migration of the spinal cord away from its original position, which may cause C5 palsy.[3] The current study also evaluated the JOA score between the 2 groups and found that patients undergoing ACAF acquired a higher JOA score at the final follow-up compared with those who underwent laminoplasty. Further, the recovery rate of the JOA score in group A was 67.5% $\pm$ 18.8%, significantly higher than that in group L (58.7% $\pm$ 14.7%, $P < 0.05$). These results indicated that ACAF is a relatively effective surgical technique that can achieve satisfactory clinical outcomes in the treatment of OPLL.

However, this study has several limitations. First, because ACAF is a new surgical technique, the number of patients was small, and the follow-up period was relatively short. Studies with more cases and longer follow-up would be required in the future. Second, this study was retrospective and single center, and a prospective, multicenter, randomized study should be performed.

CONCLUSIONS

ACAF could achieve in situ decompression by restoring the original position of the spinal cord in terms of spinal cord rotation, deviation, and anterior or posterior shift of the spinal cord, with better clinical outcomes and relatively lower occurrence of C5 nerve palsy compared with single open-door laminoplasty in the treatment of cervical OPLL. In addition, these types of displacements of the spinal cord have been shown to potentially impact the appearance of C5 nerve palsy. The investigation may serve as a basis for further study.

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