

Accuracy of Bony Gutter Placement in Cervical Laminoplasty Assisted by 3-D Print Modeling, and Associations with Posterior Spinal Cord Shift and Radiculopathy

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Abstract:

Introduction: We evaluated the positioning of the bony gutter (PBG) in cervical laminoplasty aided by three-dimensional (3-D) printed models, and assessed associations between PBG accuracy, posterior shift of the spinal cord (PSSC), and clinical results.

Methods: Of 35 patients who underwent cervical laminoplasty for cervical myelopathy between January 2013 and September 2015, 20 were treated using a conventional free-hand technique (Group A). For the other 15 patients (Group B), surgeons also used 3-D printed models to select a PBG on the edge of the medial aspect of the zygapophyseal joint to maximize the angle of the opened lamina (AOL). We measured the PBG and AOL on axial computed tomography images, and the PSSC on midsagittal magnetic resonance imaging obtained before and 7 days after surgery. Clinical outcomes were evaluated by Japanese Orthopaedic Association (JOA) scores and recovery rates, and by the incidence of postoperative radiculopathy. We compared the PBG, AOL, PSSC, and clinical outcomes between the groups.

Results: The PBG was significantly lower in Group B than in Group A at the C4 left and right sides ($P = 0.033$, $P < 0.0001$) and C6 left side ($P = 0.004$), and the AOL was larger at the C4 right side, C5 left and right sides, C6 left side, and C7 right side ($P = 0.040$, 0.043 , 0.016 , 0.016 , and 0.027 , respectively). Group B had a higher percentage of on-target PBGs at the right sides of C4 and C5 and the left side of C7 ($P = 0.005$, 0.037 , and 0.028), a larger PSSC at C4 and C5 ($P = 0.023$, 0.008), and a higher incidence of radiculopathy ($P = 0.026$). Groups A and B did not differ significantly in JOA score or recovery rate.

Conclusions: Three-dimensional modeling improved PBG accuracy. However, maximizing the spinal canal increased the PSSC and subsequent radiculopathy.

Keywords:

Cervical laminoplasty, three-dimensional printed model, surgical accuracy, radiculopathy

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Introduction

Cervical laminoplasty provides stable long-term neurologic improvement for cervical myelopathy, with benefits lasting 10 years or more¹⁻³. However, patients may develop postoperative complications such as radiculopathy, drop-arm syndrome (C5 palsy), or drop-finger syndrome (C8 palsy), and other C5, C8, or T1 symptoms with complaints of new pain or dysesthesia in the deltoid muscle, the ring and little finger, or the ulnar aspect of the forearm. The reported incidence of C5 palsy is 4.6% (range, 0% to 30%)⁴, and the reported incidence of C8 or T1 symptoms is 24.2%⁵. Postop-

erative radiculopathy is thought to result from damage to the root or segmental spinal cord, but the exact mechanisms are unclear⁴. C5 palsy can result from a posterior shift of the spinal cord (PSSC) after laminoplasty^{4,6,7}. Baba et al. reported a significantly larger PSSC at C4/5 in patients with postoperative C5 palsy compared to those without palsy (odds ratio, 12.066; $P = 0.029$; 95% confidence interval, 1.295-112.378), indicating that the tethering phenomenon is a likely risk factor for postoperative C5 palsy⁸. On the other hand, Uematsu et al. reported a significantly higher incidence of radiculopathy after cervical laminoplasty when the bony gutter was cut on the lateral side of the medial aspect

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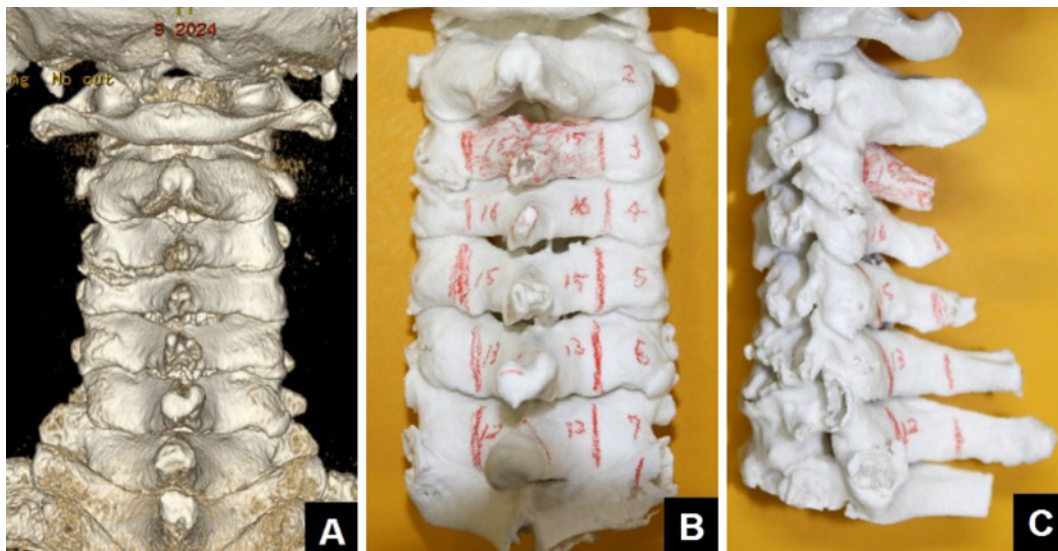


Figure 1. 3-D printed model and surgical methods. (A) Preoperative 3-D CT. (B, C) A life-sized 3-D printed cervical model showing the measurements and markup for surgical planning.

of the zygapophyseal joint⁹). However, it is not possible to evaluate PSSC after laminoplasty without knowing the precise location of the bony gutter.

Models created by three-dimensional (3-D) printing allow surgeons to develop a more precise surgical strategy for an individual patient¹⁰⁻¹²). However, the accurate placement of bony gutters in cervical laminoplasty has rarely been studied in the context of surgery assisted by 3-D printed modeling. This study evaluated the accuracy of the positioning of the bony gutter (PBG), which should be on the edge of the medial aspect of the zygapophyseal joint, in cervical laminoplasty when the surgeon used a 3-D printed model of the patient's cervical spine for surgical planning and reference. We also analyzed associations between PBG accuracy and the PSSC or clinical outcome.

Materials and Methods

Subjects

This study assessed patients with cervical spondylotic myelopathy (CSM) or ossification of the posterior longitudinal ligament (OPLL) who underwent C4-7 or C4-6 laminoplasty with a C3 laminectomy between January 2013 and September 2015¹³). After excluding patients who underwent other cervical spine surgeries, such as anterior decompression and fusion, 35 patients were included in the study. All patients were evaluated by computed tomography (CT) and magnetic resonance imaging (MRI).

The patients were divided as follows: Group A included 20 patients (13 men and seven women; 10 with CSM and 10 with OPLL; average age, 58.5 years) who were treated from January 2013 to June 2014 using a traditional free-hand technique. Group B included 15 patients (12 men and three women; six with CSM and nine with OPLL; average age, 62.7 years) who were treated from July 2014 to Sep-

tember 2015 following surgical strategies planned with the aid of 3-D printed models. The patients in Group B gave informed consent for their inclusion in a study using 3-D printed models.

3-D model printing

Prior to surgery, the data for 3-D printing was collected by CT (GE Healthcare, Waukesha, WI, USA) with a 1-mm layer thickness. C1-T1 data was saved in the DICOM format, and the DICOM data was saved as STL files through ZedView software (Lexi Inc., Japan) to create a 1:1 model using 3-D printers (ProJet 360, 3D System Inc., Rock Hill, SC, USA). The time from the initial CT scan to the finished model was approximately 6-8 h. The model was used as a template to plan the surgical strategy and identify the optimal PBG (Fig. 1B, C), and was also used to help the surgeon identify and visualize the anatomy more intuitively than would normally be possible during the operation.

Determining the target PBG

Surgeons planned the distance between the edge of the medial aspect of the bilateral zygapophyseal joints (BZJ) and the optimal PBG using preoperative CT images. For patients in Group B, surgeons also used 3-D printed models (Fig. 1A-C). The target PBG was selected on the edge of the medial aspect of the zygapophyseal joint of the cervical spine to maximize the angle of the opened lamina (AOL).

Operative technique and postoperative management

For all patients, a laminectomy was performed at C3, and the insertion of the semispinalis cervicis muscle in C2 was preserved completely as previously described¹³). We performed a C4-C7 or C4-C6 laminoplasty by a procedure adapted from spinous process-splitting laminoplasty using hydroxyapatite spinous process spacers¹⁴), and the spinous process was split using a thread-wire saw¹⁵). The bony gutter

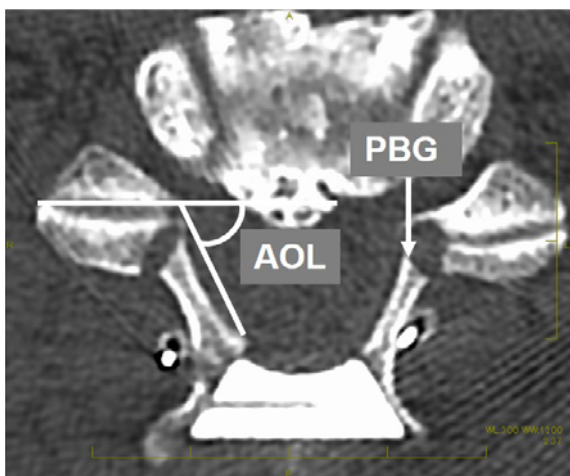


Figure 2. Position of the bony gutter (PBG) and angle of the opened lamina (AOL).

Axial CT image. The optimal PBG was located on the edge of the medial aspect of the zygapophyseal joint of the cervical spine to maximize the AOL. The accuracy of the PBG was measured as the distance between the bony gutter and the targeted PBG, to the medial (positive mm) or lateral side (negative mm), at each vertebral level.

was positioned on the edge of the medial aspect of the zygapophyseal joint (Fig. 1B). We used various sizes of hydroxyapatite spinous process spacers (18 to 28 mm) to adjust the BZJ distance and the opened laminae to maximize the AOL at each cervical level. A suction tube placed between the laminae and the deep muscle to drain postoperative bleeding was removed within 2 days after the operation. Postoperative collars were not used. Patients began exercises one day after surgery and were allowed to sit up or walk on the second day after surgery. The same operative technique and postoperative management were used in the both Groups A and B.

Measurement of PBG accuracy and AOL

We used MPR Works software (GE Healthcare) to analyze the AOL and PBG on axial CT images of the cervical spine obtained the day after surgery. We assessed the accuracy of the placement of the bony gutter by measuring the medial-side (plus mm) or lateral-side (minus mm) distance from the target to the actual PBG at each vertebral level (Fig. 2). We also measured the expanded AOL at each spinal level (Fig. 2).

Measurement of PSSC after laminoplasty

All patients underwent MRI (Exelart 1.5T MRI system; Toshiba Co., Ltd., Japan) of the cervical spine prior to and 7 days after surgery. All T2-weighted midsagittal magnetic resonance (MR) images were measured using DICOM Works software as described previously⁶. Spinal cord decompression was analyzed by measuring the PSSC, defined as the difference between the preoperative and postoperative distance from the posterior edge of each vertebral body (C3

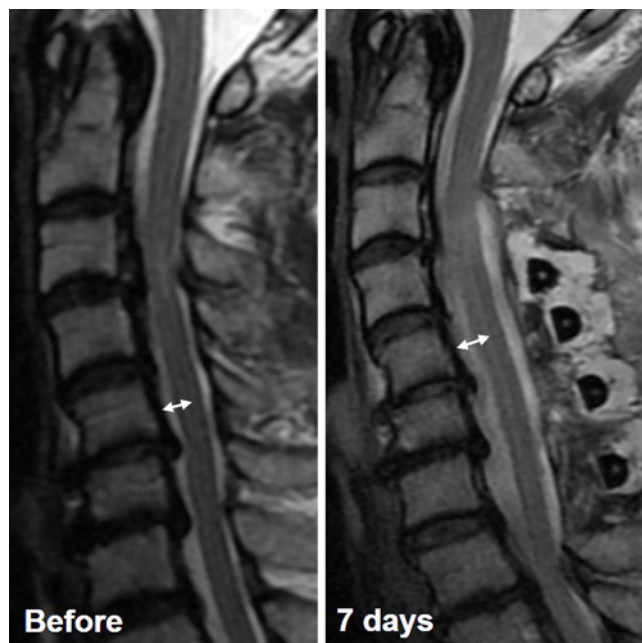


Figure 3. Posterior shift of the spinal cord (PSSC).

The PSSC was calculated as the difference between the preoperative and postoperative distances from the posterior edge of the vertebral body to the center of the spinal cord (white arrows), measured for each level from C3 to C7 on preoperative and postoperative midsagittal MR images: posterior shift (mm) = (distance at 7 days after surgery) – (distance before surgery).

to C7) to the center of the spinal cord, on MRI: PSSC (mm) = (distance at 7 days after surgery) – (distance before surgery) (Fig. 3).

Evaluation of clinical outcomes

The severity of the clinical symptoms was evaluated by the Japanese Orthopaedic Association (JOA) score prior to surgery and at the final follow-up, and by the JOA recovery rate. Postoperative C5 palsy and C5 symptoms were evaluated as previously described⁶. A new deterioration of the deltoid or biceps brachii muscle strength (less than 1 degree of manual muscle test) was defined as C5 palsy, and newly appeared dysesthesia in the deltoid muscle without motor palsy was defined as a C5 symptom. C8 palsy or a C8 or T1 symptom was defined as a new deterioration of the finger extensor muscle strength or a new pain or dysesthesia after surgery in the ring and little fingers and the ulnar aspect of the forearm⁵. Patients were evaluated for radiculopathy each day after the operation.

Statistical analysis

SPSS ver.12.0J (SPSS Inc., Chicago, IL, USA) was used for data input and statistical calculations. We compared the Groups A and B using the Mann-Whitney *U* test for quantitative data and the chi-squared test for qualitative data. We compared the cases with and without radiculopathy using the Mann-Whitney *U* test for the JOA recovery rate. We used the Spearman's rank correlation coefficient to analyze

Table 1. Patient Characteristics.

	Group A (20 patients)	Group B (15 patients)	P value
Age, y	58.5±17.4	62.7±11.5	0.499
Males, % of group	65%	86.7%	0.458
BMI, kg/m ²	20.1±11.2	26.1±3.0	0.030 [†]
Diagnosis (CSM:OPLL)	10:10	6:9	0.734
Time of operation, min	128.3±40.0	174.1±36.4	0.001 [†]
Blood loss, g	73.0±75.8	158.7±190.4	0.347
Follow-up, months	37.2±22.5	38.4±8.1	0.199
Surgeon's experience, y	14.9±2.8	12.9±2.3	0.080

CSM, cervical spondylotic myelopathy; OPLL, ossification of the posterior longitudinal ligament

[†]Mann-Whitney *U* test, *P*<0.05.

correlations between the PSSC, including the amount of shift and the level of greatest shift (C5 or C6), and the PBG and AOL in both groups. Values were expressed as mean ± S.D. *P* < 0.05 was considered significant.

Results

Patient characteristics in Groups A and B (Table 1)

Groups A and B did not differ significantly in age, sex, diagnosis, blood loss during surgery, follow-up period, or the surgeon's years of experience. Compared to Group A, Group B had a significantly higher BMI (*P* = 0.030) and more time in surgery (*P* = 0.001).

PBG and AOL (Table 2)

Groups A and B did not differ significantly in average BZJ distance. Laminoplasties in the 35 patients required placing 132 bony gutters in Group A and 114 in Group B. The PBG was significantly lower in Group B than in Group A at the left and right sides of C4 (*P* = 0.033, *P* < 0.0001) and the left side of C6 (*P* = 0.004). Compared to Group A, Group B had a significantly higher percentage of accurately targeted PBGs at the right side of C4 (*P* = 0.005), right side of C5 (*P* = 0.037), and left side of C7 (*P* = 0.028), and a significantly larger AOL at the right side of C4 (*P* = 0.040), left and right sides of C5 (*P* = 0.043, *P* = 0.016, respectively), left side of C6 (*P* = 0.016), and right side of C7 (*P* = 0.027).

PSSC (Table 3) and correlations with the PBG and AOL (Table 4)

The PSSC was significantly larger in Group B than in Group A at C4 and C5 (*P* = 0.023, 0.008, respectively). Single-correlation analyses revealed a significant negative correlation between the PSSC and PBG, and revealed significant positive correlations between the PSSC at the C5 and C6 levels and the AOL at the right side of C4, C5, C6, and C7 (Fig. 4). In patients with radiculopathy, the PSSC was greater than 3.0 mm and the AOL was greater than 60° at the C5 and C6 levels.

Clinical outcomes (Table 5)

Groups A and B did not differ significantly in JOA scores before surgery or at the final follow-up, or in JOA recovery rates. Compared to Group A, Group B had a significantly higher rate of radiculopathy (*P* = 0.026). Group B included two cases of C5 palsy and two of C8 palsy (Table 5). C5 palsy in two cases occurred at 1 day and 5 days after surgery. They recovered within postoperative 2 weeks. Their preoperative JOA scores were 16 and 7.5, and postoperative JOA scores were 16.5 and 8.5, respectively. C8 palsy in two cases occurred at 2 days after surgery. One patient recovered within postoperative 16 months. Another patient did not recover after surgery. Their preoperative JOA scores were 12.5 and 11, and postoperative JOA scores were 11 and 12, respectively. The cases with radiculopathy and without radiculopathy did not differ significantly in JOA recovery rates (*P* = 0.082).

Discussion

To our knowledge, this is the first study to analyze the placement of bony gutters in laminectomies performed with or without the aid of a 3-D printed model. The PBG was closer to the target location in Group B, in which surgeons were assisted by 3-D print modeling. However, maximizing the spinal canal increased the PSSC, leading to radiculopathy.

The accuracy of PBG placement was significantly higher in surgeries assisted by 3-D print modeling compared to conventional techniques alone. The 3-D printer uses the patient's data to create an accurate model of the anatomical structure of the spine, allowing the surgeon to develop the surgical strategy with great precision¹². The model also gives the surgeon a clear sense of the anatomical structure and provides a visual and tactile reference during the operation. The 3-D printed model and the 3-D perspective photograph provide much more information than a normal 2-D perspective photograph, helping the surgeon to understand the patient's specific bone anatomy and characteristics¹⁶. During the discussion and consent of complex surgical cases, the 3-D printed model helps the surgeon predict the difficulty of

Table 2. PBG and AOL in Groups A and B.

	Group A (20 patients)	Group B (15 patients)	P value
Bony gutters, <i>n</i>	132	114	-
Average BZJ distance (mm)			
C3	26.6±2.1	26.4±2.8	0.961
C4	26.7±2.14	26.5±2.2	0.657
C5	25.6±2.7	26.2±2.8	0.780
C6	24.1±2.4	25.0±2.6	0.364
C7	21.5±3.2	20.1±3.6	0.633
Average PBG distance (mm)			
C4 Left	1.5±1.8	0.2±1.0	0.033 [†]
Right	2.9±2.2	0.4±1.2	<0.001 [†]
C5 Left	0.6±1.7	-0.1±1.4	0.202
Right	1.2±2.5	-0.1±0.9	0.080
C6 Left	0.4±2.3	-0.5±1.1	0.321
Right	1.1±1.5	-1.4±1.5	0.004 [†]
C7 Left	1.3±3.6	-0.4±1.2	0.216
Right	-0.4±1.6	-0.4±2.9	0.660
PBG, % at target			
C4 Left	50	73.3	0.284
Right	16.7	66.7	0.005*
C5 Left	60	60	1.000
Right	40	80	0.037*
C6 Left	63.2	78.6	0.455
Right	52.6	50	1.000
C7 Left	33.3	90.9	0.028*
Right	60	63.6	1.000
Average AOL, °			
C4 Left	62.7±7.7	62.4±8.6	0.817
Right	56.1±7.7	63.9±9.3	0.040 [†]
C5 Left	60.4±7.4	68.1±10.2	0.043 [†]
Right	62.4±6.1	68.6±7.6	0.016 [†]
C6 Left	62.1±7.5	69.3±7.7	0.016 [†]
Right	60.8±15.2	68.3±9.6	0.084
C7 Left	60.5±7.6	66.2±5.6	0.216
Right	62.1±7.2	71.5±8.1	0.027 [†]

[†]Mann-Whitney *U* test or *Chi-squared test, P<0.05.

BZJ, bilateral zygapophyseal joints; PBG, position of the bony gutter; AOL, angle of the opened lamina

Table 3. PSSC in Groups A and B.

	Group A (20 patients)	Group B (15 patients)	P value
C3	0.8±1.0	1.3±0.9	1.22
C4	1.6±1.2	2.7±1.3	0.023 [†]
C5	1.9±1.4	3.3±1.6	0.008 [†]
C6	2.0±1.6	3.3±1.8	0.064
C7	1.2±1.6	2.1±1.8	0.080

[†]Chi-squared test, P<0.05.

PSSC, posterior shift of the spinal cord

the operation, develop a preoperative plan, and select the best surgical option¹⁷⁾. In this study, we clarified the accuracy of the position of the gutter was different at each the cervical level. This can be explained by the different BZJ distance at each cervical level (Table 2). Another factor can be explained by the effect of cervical degeneration. Cervical myelopathy, a common degenerative spinal disease that in-

terferes with normal activity¹⁸⁾, is partly due to compression of the cervical spinal cord by spinal canal stenosis, which can arise from developmental canal stenosis, intervertebral disc protrusion into the spinal canal, or thickening of the ligamentum flavum¹⁹⁾. Degenerative cervical changes can also appear in intervertebral discs and the zygapophyseal joint, and these changes progress with age^{20,21)}. Furthermore, 3-D printed models can improve the safety of the surgical procedure, reduce muscle tissue exposure, and shorten operation time¹²⁾. However, compared to Group A, Group B had a significantly longer time in surgery. The PBG was closer to the target location in Group B. Therefore, the depth of the medial aspect of the zygapophyseal joint in Group B was larger than that in Group A. This is considered to be one of the reasons underlying the longer time in surgery.

A study of patients treated by posterior atlantoaxial internal fixation reported that the use of 3-D printed models re-

Table 4. Correlations between PSSC at C5 and C6 and PBG and AOL in Both Groups.

Partial correlation coefficient:	PSSC at the C5 level			PSSC at the C6 level		
	r	P value	n	r	P value	n
PBG						
C4						
Left	-0.214	0.231	33	-0.322	0.067	33
Right	-0.371	0.033*	33	-0.367	0.036*	33
C5						
Left	-0.092	0.599	35	-0.215	0.216	35
Right	-0.212	0.222	35	-0.429	0.010*	35
C6						
Left	-0.239	0.181	33	-0.230	0.199	33
Right	-0.397	0.022*	33	-0.545	0.001	33
C7						
Left	-0.058	0.825	17	-0.303	0.237	17
Right	-0.310	0.226	17	-0.148	0.337	17
AOL						
C4						
Left	-0.332	0.59	33	-0.077	0.669	33
Right	0.419	0.015*	33	0.658	<0.0001*	33
C5						
Left	-0.088	0.614	35	0.026	0.882	35
Right	0.302	0.078	35	0.448	0.007*	35
C6						
Left	0.207	0.247	33	0.227	0.204	33
Right	0.345	0.049*	33	0.406	0.019*	33
C7						
Left	0.113	0.667	17	0.262	0.309	17
Right	0.265	0.305	17	0.573	0.026*	17

P<0.05. The relationships between PSSC and PBG and AOL were analyzed by Spearman's rank partial correlation analysis. P values below 0.05 () indicate significance. AOL, angle of opened lamina; PBG, position of the bony gutter; PSSC, posterior shift of the spinal cord; r, correlation coefficient.

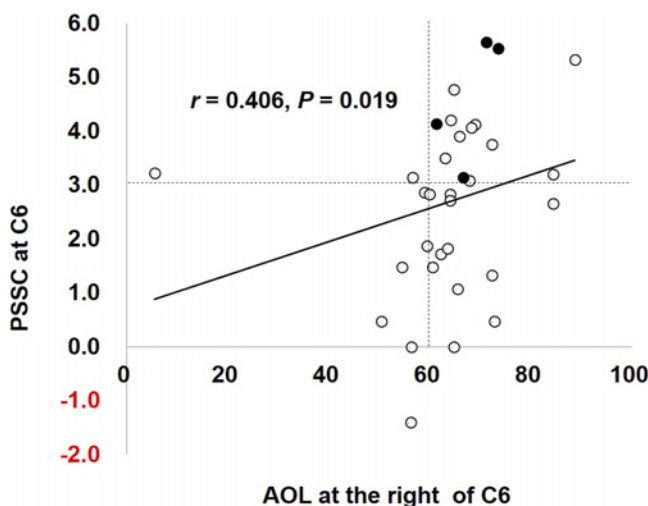


Figure 4. Correlation between the posterior shift of the spinal cord (PSSC) at the C6 level and the angle of the opened lamina (AOL) in both groups. Single-correlation analyses revealed a significant positive correlation between PSSC at the C6 level and the AOL at the right side of C6. Black circles indicate cases with radiculopathy after laminoplasty; these cases had a PSSC >3.0 mm and an AOL >60°.

Table 5. Clinical Outcomes in Groups A and B.

	Group A (20 patients)	Group B (15 patients)	P value
JOA (preoperative)	10.1±3.2	11.3±3.2	0.407
JOA (final)	13.1±3.5	12.6±3.1	0.961
JOA recovery rate, %	50.8±31.6	24.7±41.8	0.591
Radiculopathy, % (n)	0 (0)	26.7 (4)	0.026*
C5 palsy, % (n)	0 (0)	13.3 (2)	0.176
C8 or T1 symptoms, % (n)	0 (0)	13.3 (2)	0.176

JOA, Japanese Orthopaedic Association score

*Chi-squared test, P<0.05.

duced the surgical time and blood loss compared to conventional techniques alone¹²⁾; however, we obtained the opposite results (Table 1). The present study demonstrated that maximizing the spinal canal increased the PSSC, leading to radiculopathy. Previous studies of C5 palsy identified OPLL and open-door laminoplasty as risk factors²²⁾. Kudo et al. reported a significantly higher incidence of C8 or T1 symptoms in C3-6 laminoplasty compared to C3-7 laminoplasty⁵⁾. PSSC has been identified as a cause of radiculopathy after laminoplasty^{4,6)}. Uematsu et al. reported that the incidence of

radiculopathy after laminoplasty was significantly higher on both the opened and hinged sides when the bony gutter was cut in the lateral side of the medial aspect of the zygapophyseal joint, and recommended maintaining the angle of the lamina between 25° and 60°^{o9}; however, that study did not clarify the association between the location of the bony gutter and PSSC. The present study clarifies the correlation between PSSC and the PBG and AOL. We found that patients with postoperative radiculopathy had a PSSC greater than 3.0 mm and an AOL greater than 60° at C5 and C6. Selecting a more medial PBG and decreasing the angle of the opened lamina may prevent excessive PSSC. Three-dimensional printed models should assist with the analysis and development of operative techniques or intraoperative navigation to achieve the appropriate PBG and AOL.

This study had the following limitations. First, we did not evaluate the cervical sagittal alignment with plain X rays. Cervical sagittal alignment can influence the post-laminoplasty PSSC. Second, we did not evaluate preexisting foraminal stenosis. Imagama et al. reported that the C5 intervertebral foramen was significantly narrower and the anterior protrusion of the C5 superior articular process was significantly larger in patients who developed C5 palsy after cervical laminoplasty⁷. Third, this study included both CSM and OPLL patients. Especially, the OPLL type and the occupation rate of cervical canal with OPLL might affect AOL and PSSC. Fourth, we did not use intraoperative navigation technology.

Despite these limitations, our study demonstrates the benefits of 3-D print modeling in assisting the surgical technique in cervical laminoplasty. In the present study, 3-D models printed from patient data helped surgeons improve the accuracy of the PBG. However, maximizing the spinal canal increased the PSSC and subsequent radiculopathy.

Conflicts of Interest: The authors declare that there are no relevant conflicts of interest.

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Author Contributions: All authors participated in the study design. GK wrote and prepared the manuscript. All authors reviewed and approved the article.

Informed Consent: All subjects provided informed consent to participate in this study.

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