


Radiographic and clinical evaluation of single-level lateral interbody fusion in patients with severe stenosis analyzed using cluster analysis

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Abstract

This study was a retrospective review of patients treated in a single institution. We performed a cluster analysis of the degree of preoperative stenosis to investigate the effect of indirect neural decompression in single-level lateral lumbar interbody fusion (LLIF). Surgery is generally indicated for patients with severe stenosis. On the other hand, severe lumbar spinal stenosis is a relative contraindication to LLIF and is excluded in most studies. If LLIF, which is less invasive to treatment, can be applied to severe stenosis patients, it may help treatment. Cluster analysis classified 80 patients into 3 groups based on preoperative central canal area (CCA), preoperative canal diameter (CD), and preoperative Schizas grade: group 1 with severe stenosis (n=43); group 2 with moderate stenosis (n=27); and group 3 with mild stenosis (n=10). Preoperative and immediately postoperative CCA and CD in magnetic resonance imaging were compared between groups. Disc angle (DA) and anterior, posterior, and average disc heights (AvDH) (anterior disc height, posterior disc height, average disc height AvDH) were measured using standing lateral plain radiographs. For clinical analysis, a numeric rating scale was used to evaluate clinical outcomes. DA, anterior disc height, posterior disc height, and AvDH increased significantly after the operation in all groups, but the average changes in these factors did not differ. Mean midsagittal CD and axial CCA on MRI magnetic resonance imaging increased significantly in all groups, but as with DA and DH, the changes in axial CCA and midsagittal CD did not differ between groups. The numeric rating scale score did not differ between groups at any time. The cluster analysis results suggested that postoperative changes in indirect neural decompression for severe stenosis after LLIF similar for moderate and mild stenosis and that pain did not differ according to the severity of stenosis after surgery.

Abbreviations: ADH = anterior disc height, AvDH = average disc height, CCA = central canal area, CD = canal diameter, DA = disc angle, IDF = indirect decompression failure, LLIF = lateral lumbar interbody fusion, MRI = magnetic resonance imaging, NRS = numeric rating scale, PDH = posterior disc height, XLIF = extreme lateral lumbar interbody fusion.

Keywords: cluster analysis, indirect decompression, lateral lumbar interbody fusion, lumbar degenerative disease, radiographical outcomes

1. Introduction

Of the types of lateral lumbar interbody fusion (LLIF) operations in current use, extreme lateral lumbar interbody fusion (XLIF)

and oblique lateral lumbar interbody fusion (OLIF) are minimally invasive spine operations. They have become the choice of many spine surgeons in recent years.^[1] In the LLIF operation, a large lateral cage is placed at the edge of the vertebral body hard cortex to create a strong anchoring force, and the ligament effect allows the disc height to be restored without the need for direct decompression of the foramen and spinal canal.^[2] Therefore, LLIF causes less damage to the posterior supporting elements than traditional open decompression surgery and can help to correct spinal misalignments, such as those of intervertebral foramen and disc height. LLIF is especially suitable for correcting spinal misalignment in elderly patients with spinal deformities and decompressing the spinal canal in patients who cannot tolerate extensive surgery.^[3]

However, as an indirect decompression technique, LLIF does not involve removing the discs, osteophytes, or flavum protruding into the spinal canal, and its decompression effect is not as complete as it is with traditional posterior direct decompression surgery. Although LLIF has been reported to achieve similar clinical results as posterior fusion, previous studies have shown that the improvements in the central canal area (CCA) and canal diameter (CD) of the thecal sac are significantly smaller after LLIF than after posterior fusion.^[4–7] A systematic review of neural decompression after LLIF reported a CCA expansion of 25.4% after surgery.^[8] The factors that can be used to predict the success of indirect decompression are currently being investigated.

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However, no conclusions have been reached.^[9–12] The actual clinical and radiographic results of LLIF for lumbar spinal stenosis remain unclear because most previous studies have excluded patients with severe stenosis.

Surgery is generally indicated for patients with severe stenosis. However, previously, patients with severe facet joint hypertrophy and predominantly posterior compression were thought to be unsuitable candidates for LLIF. To reduce the invasiveness, it is reasonable to perform LLIF for these patients instead of traditional open surgery, although additional posterior decompression is sometimes needed. However, Elowitz et al^[13] reported that patients with a slight increase in spinal canal area after LLIF also had improved clinical outcome scores. Against this background, we reasoned that applying less invasive LLIF may benefit the treatment of patients with severe stenosis.

The purpose of this study was to evaluate the effects of indirect neural decompression in patients with severe lumbar spinal stenosis. In this study, preoperative stenosis was classified and compared using cluster analysis of the preoperative CCA, preoperative CD, and preoperative Schizas grade.

The radiographic and clinical outcomes of single-level LLIF for a series of patients classified according to the severity of stenosis were evaluated retrospectively.

2. Materials and methods

The study protocol was reviewed and approved by the Committee on Ethics and the Institutional Review Board of Tokai University School of Medicine, the House Clinical Study Committee, and the Profit Reciprocity Committee (20R-351). Because this study was retrospective, the requirement for informed consent was waived.

2.1. Included patients

This study was a retrospective review of patients treated in a single institution. Patients were treated from January 2016 to October 2020. The inclusion criterion included patients who underwent LLIF (XLIF or oblique lateral lumbar interbody fusion) procedures for degenerative lumbar stenosis or adjacent disc disease with instability at single spinal levels. Patients with significant lumbar scoliosis, grade 2 spondylolisthesis, or lumbar fracture were excluded from this study. The lumbar vertebral body's coronal Cobb angle between the L1 vertebra upper edge and L5 vertebra lower edge was evaluated. The average scoliosis was $6.4^\circ \pm 5.8^\circ$, and patients with scoliosis $>30^\circ$ were excluded. All patients were diagnosed based on a detailed history, neurological and radiographic examination, myelograms, computed tomography scans after myelography, and/or magnetic resonance imaging (MRI). The location of stenosis was recorded by the operating neurosurgeon based on an evaluation of preoperative imaging studies.

A total of 80 patients were included, and their demographic data are presented in Table 1. The patients included 48 men and 32 females with a mean age of 71.6 years (range, 25–89 years). The distribution of the treated levels was as follows: 1 cage at L1 to L2, 5 cages at L2 to L3, 16 cages at L3 to L4, and 58 cages at L4 to L5. The average operating time was 96.9 min, and the average estimated blood loss was 54.1 mL. The average hospital stay was 16.3 days. Cluster analysis was used to classify the 80 patients into 3 groups based on the preoperative CCA, CD, and modified Schizas lumbar stenosis classification.^[14,15]

Table 1

Demographic information.

Characteristic	Patients (n=80)
Age (yr)	71.6 (10.1)
Females	32 (40.0%)
Height (cm)	158.4 (9.2)
Body weight (kg)	61.0 (12.5)
BMI (kg/m ²)	24.2 (3.9)
Levels treated, n (%)	
L1–L2	1 (1.2)
L2–L3	5 (6.3)
L3–L4	16 (20.0)
L4–L5	58 (72.5)
Average OR time (min)	96.9 (29.8)
Average Blood loss (mL)	54.1 (61.4)
Average Length of stay (d)	16.3 (5.2)

Data presented as mean (SD) or number of patients (%).

2.2. Surgical techniques

The LLIF procedure was performed as described previously.^[2,16,17] The patient was positioned in a lateral decubitus position, and the midpoint of the disc of interest was identified using fluoroscopy. A retractor was used to locate and expose the target intervertebral disc area. Once the lateral disc was accessed, the standard surgical techniques of LLIF were used. The discectomy was undertaken first through an ipsilateral annulus incision, Cobb elevator release of the contralateral annulus, and then careful clearance of cartilaginous tissue from the endplates using curettes and rasps. The nerve roots were not directly visualized. The cage height and lateral dimension were determined intraoperatively according to the dimensions of the index level. Posterior fixation was performed in a single-stage approach using percutaneous pedicle screws, and posterior decompression was not performed in any of the patients. As another surgical procedure, intraoperative three-dimensional navigation was also used for the LLIF procedure (navigation-assisted LLIF) and/or posterior fixation.^[18]

2.3. Radiological assessment

Standing lateral plain radiographs and MRI were obtained for all patients preoperatively and postoperatively (Figure S1, Supplemental Digital Content, <http://links.lww.com/MD2/A682>).

Postoperative evaluation of the midsagittal CD and axial CCA of the thecal sac was performed within 2 weeks immediately after surgery. We used the Schizas et al^[15] lumbar stenosis classification for morphological classification of central stenosis, and this study modified the Grade A subclass (Fig. 1).^[14] In this classification, the severity of stenosis is assessed on a scale of grade A to D based on the cerebrospinal fluid/rootlet ratio on T2-weighted axial images of MRI. Grade A stenosis is the mildest and is defined as all cerebrospinal fluid inside the thecal sac. In grade B stenosis, the rootlets occupy the whole of the thecal sac but can still be individualized. In grade C, no rootlets can be recognized, but epidural fat can be visualized posteriorly. In grade D, in addition to no rootlets being recognizable, there is no epidural fat posteriorly.

Each alignment was evaluated on a standing lateral plain radiograph preoperatively and 2 to 3 months after surgery. The main measurement index was calculated for the relevant surgical

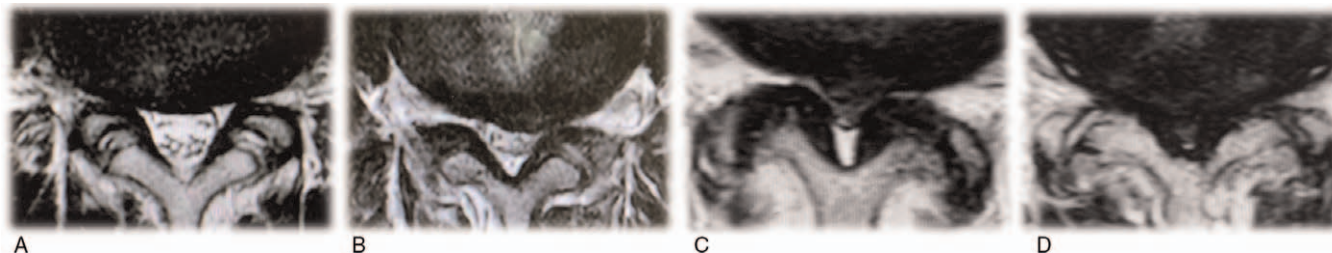


Figure 1. Modified Schizas classification.^[14] (A) The cerebrospinal fluid (CSF) is clear, and rootlets are unevenly situated. (B) Each of the rootlets is distinguishable, but the entire dural sac is occupied. (C) Both the rootlets and CSF are not distinguishable. (D) The epidural fatty layer is also not distinguishable.

level and included the disc angle (DA) and anterior, posterior, and average disc height (AvDH) [anterior disc height (ADH), posterior disc height (PDH), and AvDH, respectively] on standing lateral plain radiographs.

The interbody cage position was also assessed on sagittal T2-weighted MRI and was based on the midpoint locality relative to the inferior endplate’s midpoint, as described previously.^[3] The distance between the anterior vertebral border of the inferior endplate and the cage’s center was measured and normalized to the inferior endplate’s anteroposterior width. The cage’s center was defined as the midpoint between its anterior and posterior radio markers. If the cage position was <50%, the cage was considered to be positioned anteriorly.

2.4. Clinical assessment

The clinical evaluations were recorded and included the patients’ age, sex, operated segment, operation time, intraoperative bleeding, and length of hospitalization stay. We also collected information on transient psoas weakness and thigh pain at discharge.

The pain intensity was assessed using a numeric rating scale (NRS),^[19] and NRS scores were obtained for low back pain (LBP; NRS_{LBP}), leg pain (LP; NRS_{LP}), and leg numbness (LN; NRS_{LN}). The NRS is rated on an 11-point scale, where 0 indicates no pain and 10 indicates the worst pain or “pain as bad as it could be”.

2.5. Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics software (version 23.0; IBM Corp., Armonk, NY). All values are expressed as the mean ± standard deviation. The type 1 error was set at 5% for all statistical analyses, and *P* < .05 was significant. We first conducted a series of hierarchical cluster analyses on the base package (hierarchical cluster analyses; ward’s method) in the IBM SPSS Statistics software to identify 3 clusters. Next, we used the Kolmogorov–Smirnov test to test all continuous variables for a normal distribution. We investigated the relationship between the 3 clusters using one-way analysis of variance for continuous variables and the Kruskal–Wallis test.

3. Results

3.1. Patient characteristics

The cluster analysis identified the following groups: severe stenosis in group 1 included 43 patients, moderate stenosis in group 2 included 27 patients, and mild stenosis in group 3 included 10 patients (Fig. 2). The preoperative axial CCA and

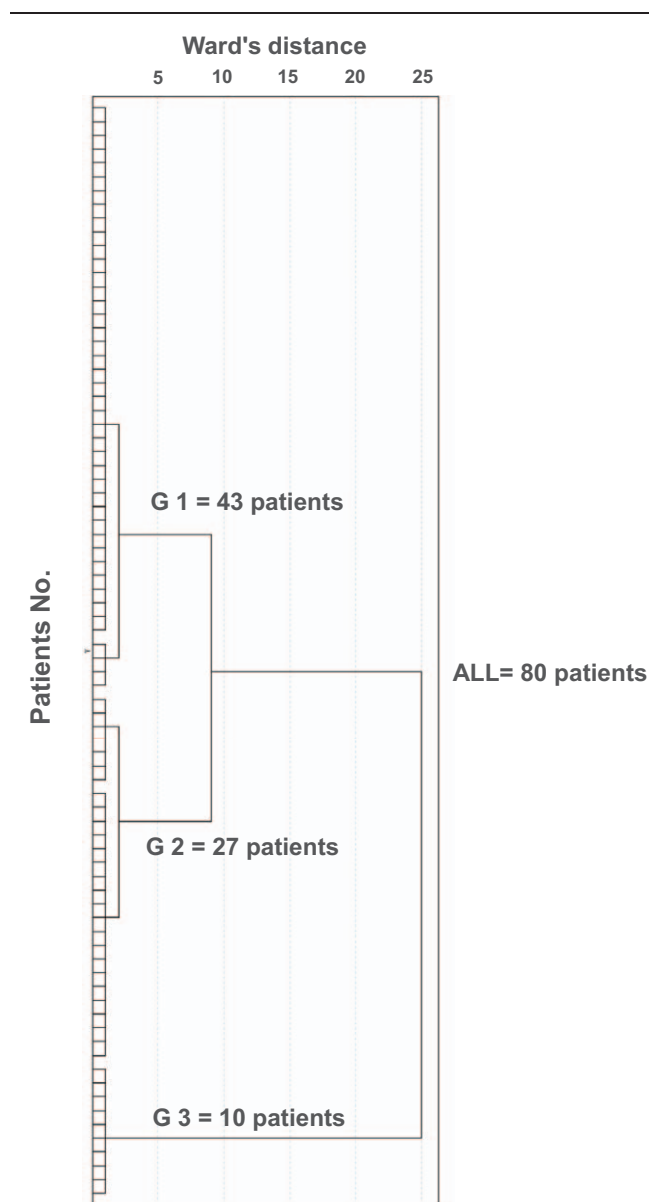


Figure 2. Hierarchical cluster analysis with dendrogram showing the relative distances between 80 patients for the preoperative axial CCA, preoperative midsagittal CD, and modified Schizas classification. Three clusters were identified: group 1 (G1) included 43 patients, group 2 (G2) included 27 patients, and group 3 (G3) included 10 patients. CCA, central canal area; CD, canal diameter.

Table 2
Comparison of three groups.

Characteristic	Group 1	Group 2	Group 3	P-value [†]
No of patients	43	27	10	
Preope-Axial CCA (mm ²)	34.5 (9.2)	63.6 (12.5)	115.0 (10.2)	<.001*
Preope- Midsagittal CD (mm)	5.1 (1.9)	6.2 (1.6)	7.8 (1.9)	<.001*
Preope-Schizas grade				
A	0	0	4	<.001*
B	0	5	5	
C	31	19	1	
D	12	3	0	
Age (yr)	71.5 (8.7)	71.9 (11.2)	71.6 (13.4)	.987
Females	12 (28.6%)	14 (51.9%)	6 (60.0%)	.055
Height (cm)	159.7 (9.1)	157.2 (9.6)	156.3 (8.1)	.404
Body weight (kg)	62.7 (12.3)	61.0 (11.8)	53.7 (14.0)	.126
BMI (kg/m ²)	24.5 (4.2)	24.5 (3.3)	21.8 (3.8)	.117
Levels treated				
L1–L2	1	0	0	.926
L2–L3	2	3	0	
L3–L4	9	4	3	
L4–L5	31	20	7	
Approach of LLIF				
LLIF	27	21	5	.228
NALIF	16	6	5	
Average OR time (min)	93.8 (31.5)	100.4 (29.3)	100.6 (23.9)	.615
Average blood loss (mL)	46.9 (59.8)	54.2 (36.4)	84.8 (106.3)	.112
Average Length of stay (d)	16.4 (5.8)	16.6 (4.4)	15.0 (4.2)	.704
No. of transient psoas weakness	5 (11.6%)	2 (7.4%)	1 (10.0%)	.538
No. of thigh pain	10 (23.2%)	6 (22.2%)	1 (10.0%)	0.639

Data presented as mean (SD) or number of patients (%).

CCA = central canal area, CD = canal diameter.

* Statistically significant.

† Comparison among groups.

midsagittal CD values for groups 1, 2, and 3 were 34.5 mm² and 5.1 mm, 63.6 mm² and 6.2 mm, and 115.0 mm² and 7.8 mm, respectively. Among the 80 segments included in this study, the Schizas classification showed grade A for 4 segments (5.0%), grade B for 10 segments (12.5%), grade C for 51 segments (63.8%), and grade D for 15 segments (18.8%).

3.2. Comparison of demographic characteristics between groups

Age ($P=.987$), sex ($P=.055$), body height ($P=.404$), body weight ($P=.126$), and body mass index ($P=.117$) did not differ significantly between the 3 groups. The treatment level ($P=.926$), operative procedure ($P=.228$), operation time ($P=.615$), estimated blood loss ($P=.112$), and length of hospital stay ($P=.704$) also did not differ significantly between the 3 groups. Transient psoas weakness and thigh pain were reported at rates of 10.0% (8/80 patients) and 21.3% (17/80), respectively, but these did not differ significantly between the 3 groups ($P=.538$ and $P=.639$, respectively) (Table 2). Two patients underwent reoperation after the LLIF. One patient had a postoperative wound infection, and the other patient required decompression because of relapse of symptoms associated with cage subsidence.

3.3. Comparison of radiographic outcomes between groups

Table 3 shows the results of the radiological comparisons for each group from before to after the operation. The radiological

parameters DA, ADH, PDH, AvDH, midsagittal CD, and axial CCA all increased significantly after surgery (Table 3). However, the average changes in these factors did not differ significantly between groups. These findings suggest that LLIF significantly increased the DA, ADH, PDH, and AvDH after surgery regardless of preoperative stenosis.

Both the preoperative and postoperative midsagittal CD and axial CCA differed significantly between groups. Mean midsagittal CD and axial CCA on MRI also significantly increased from before to after the operation in all groups. However, as with DA and DH, the axial CCA changes ($P=.575$) and mid-sagittal CD ($P=.211$) did not differ significantly between groups. For patients classified using the Schizas system, of the 12 patients with grade D in group 1, 6 improved by at least 1 grade immediately after the surgery. In addition, 16 of 31 patients with preoperative grade C improved to grade B. Of the 15 patients with grade D, 7 (7/15, 46.7%) improved by at least 1 grade immediately after surgery (Fig. 3).

These findings suggest that LLIF produced similar increases in thecal sac areas 2 weeks after the operation regardless of the degree of preoperative stenosis and that LLIF caused improvement of at least 1 grade or more in half of the patients with grade D (Fig. 4).

Next, we compared cage variables and cage positions (Table 4). Cage height ($P=0.349$), cage angle ($P=.791$), and cage position ($P=.558$) did not differ significantly between the 3 groups, but cage length differed significantly between groups ($P<.05$). There was a significant difference between groups 1 and 2 ($P<.05$).

Table 3
Comparison of radiologic data among the three groups.

Characteristic	Group 1	Group 2	Group 3	All	P-value [‡]
DA (°)					
Preop	3.7 (4.8)	3.4 (4.2)	2.5 (7.9)	3.5 (5.0)	.814
Postop	5.7 (3.9)	6.6 (3.7)	5.7 (5.3)	6.1 (4.0)	.666
Changes	2.0 (4.0)	3.0 (3.8)	2.9 (4.6)	2.5 (4.0)	.580
P-value [†]	<.01*	<.001*	<.01*	<.001*	
ADH (mm)					
Preop	9.5 (3.9)	7.9 (4.1)	6.2 (4.7)	8.5 (4.2)	.053
Postop	14.0 (2.8)	13.5 (2.3)	12.7 (4.4)	13.7 (2.9)	.450
Changes	4.4 (4.2)	5.5 (3.4)	5.8 (3.6)	5.0 (3.8)	.411
P-value [†]	<.001*	<.001*	<.001*	<.001*	
PDH (mm)					
Preop	5.8 (2.5)	4.3 (2.5)	4.0 (2.4)	5.0 (2.6)	.021*
Postop	8.9 (2.1)	8.6 (2.3)	8.5 (2.3)	8.7 (2.2)	.873
Changes	3.2 (2.1)	4.2 (1.6)	4.1 (2.2)	3.7 (2.0)	.114
P-value [†]	<.001*	<.001*	<.01*	<.001*	
AvDH (mm)					
Preop	7.8 (2.8)	6.3 (2.8)	5.7 (2.7)	7.0 (2.9)	.041*
Postop	11.5 (1.9)	11.1 (2.0)	10.6 (2.8)	11.2 (2.1)	.521
Changes	3.8 (2.7)	4.9 (2.2)	5.0 (2.7)	4.3 (2.6)	.195
P-value [†]	<.001*	<.001*	<.01*	<.001*	
Midsagittal CD (mm)					
Preop	5.1 (1.9)	6.2 (1.6)	7.8 (1.9)	5.8 (2.0)	<.001*
Immediate postop	7.3 (1.6)	9.0 (2.0)	11.1 (1.7)	8.4 (2.2)	<.001*
Changes	2.2 (2.0)	2.9 (1.9)	3.3 (2.4)	2.6 (2.0)	.211
P-value [†]	<.001*	<.001*	<.01*	<.001*	
Axial CCA (mm ²)					
Preop	34.5 (9.2)	63.6 (12.5)	115.0 (10.2)	54.4 (28.6)	<.001*
Immediate postop	58.2 (18.6)	91.2 (29.9)	133.4 (25.3)	78.7 (34.8)	<.001*
Changes	23.7 (16.6)	27.5 (29.6)	18.4 (23.2)	24.4 (22.5)	.575
P-value [†]	<.001*	<.001*	<.05*	<.001*	

ADH = anterior disc height, AvDH = average disc height, CCA = central canal area, CD = canal diameter, PDH = posterior disc height, SL = segmental lordosis.

* Statistically significant.

† Comparison with preop.

‡ Comparison among groups.

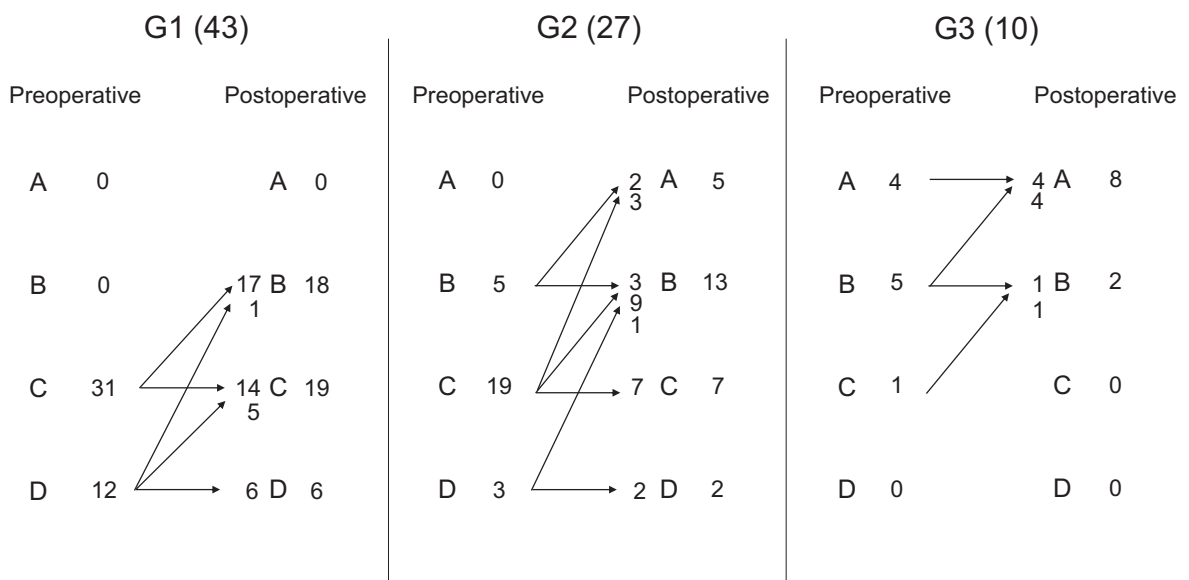


Figure 3. Changes in grade from before to immediately after the surgery, grouped according to the modified Schizas classification.

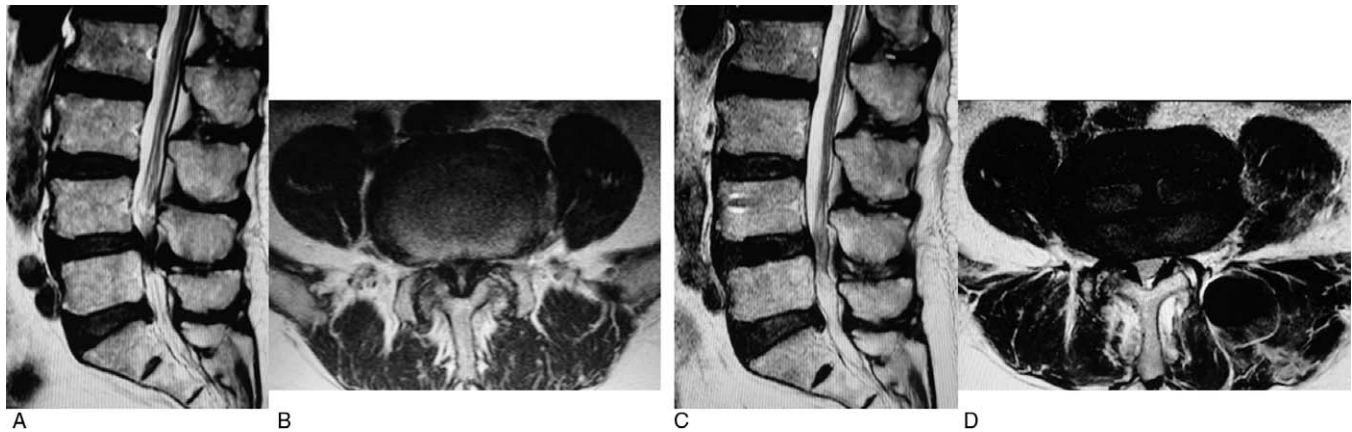


Figure 4. A 76-year-old man with Schizas grade D preoperatively at L4/5. His midsagittal CD and axial CCA improved to Schizas grade C after LLIF surgery. (A) Preoperative sagittal MRI image (B) Preoperative axial MRI image (C) Postoperative sagittal MRI image (D) Postoperative axial MRI image. CCA = central canal area, CD = canal diameter.

3.4. Comparison of pain intensity between groups

We quantified the clinical outcomes using the NRS score in 62 patients whose NRS could be evaluated preoperatively and about 1 year after surgery. As shown in Table 5, each NRS score improved significantly at the follow-up. NRS_{LBP} in the 62 patients decreased from 6.3 ± 2.6 to 2.7 ± 2.8 ($P < .001$). NRS_{LP} and NRS_{LN} decreased from 6.6 ± 2.9 to 2.0 ± 2.7 ($P < .001$) and

6.4 ± 3.1 to 2.6 ± 2.8 ($P < .001$), respectively. The NRS scores did not differ between groups at any time.

4. Discussion

In a systematic review, Lang et al^[8] reported that the mean CCA and CD of the thecal sac increased by 28.5 mm^2 (25%) and 2.4

Table 4

Cage information.

Characteristic No of patients	Group 1 43	Group 2 27	Group 3 10	P-value [†]
Cage length (mm) n (%)				
Mean (SD)	54.8 (3.3) (a)	52.2 (4.0) (b)	53.5 (4.1) (c)	.020*
40	0 (0)	0 (0)	0 (0)	a:b .015*
45	1 (2.3)	3 (11.1)	1 (10.0)	a:c .583
50	7 (16.3)	11 (40.7)	2 (20.0)	b:c .611
55	28 (65.1)	11 (40.7)	6 (60.0)	
60	7 (16.3)	2 (7.4)	1 (10.0)	
Cage height (mm) n (%)				
Mean (SD)	9.3 (0.8)	9.2 (0.8)	8.9 (0.6)	.349
8	6 (14.0)	4 (14.8)	2 (20.0)	
9	21 (48.8)	14 (51.9)	7 (70.0)	
10	14 (32.6)	8 (29.6)	1 (10.0)	
11	2 (4.7)	1 (3.7)	0 (0)	
12	0 (0)	0 (0)	0 (0)	
Cage width (mm) n (%)				
18	43 (100)	27 (100)	10 (100)	–
22	0 (0)	0 (0)	0 (0)	
Cage angle (°) n (%)				
Mean (SD)	9.8 (0.9)	9.9 (0.8)	10.0 (0)	.791
0	0 (0)	0 (0)	0 (0)	
6	2 (4.7)	1 (3.7)	0 (0)	
10	41 (95.3)	26 (96.3)	10 (100)	
Cage position (%) n (%)				
Mean (SD)	44.5 (11.1)	46.5 (9.4)	47.9 (11.8)	.558
Anterior (<50)	30 (69.8)	20 (74.1)	6 (60.0)	
Posterior (≥50)	13 (30.2)	7 (25.9)	4 (40.0)	

* Statistically significant.

† Comparison among groups.

Table 5
Pain intensity for each group.

	Preoperative	Postoperative	Change	P-value [‡]
NRS_{LBP}				
Group 1 n=35	6.1 (2.8)	2.4 (2.6)	-3.8 (3.7)	<.001*
Group 2 n=18	6.0 (2.8)	2.9 (3.0)	-3.1 (4.1)	<.01*
Group 3 n=9	7.4 (1.7)	3.8 (3.2)	-3.6 (3.5)	<.05*
ALL n=62	6.3 (2.6)	2.7 (2.8)	-3.6 (3.7)	<.001*
P-value [†]	.365	.373	.841	
NRS_{LP}				
Group 1 n=35	6.9 (2.6)	1.9 (2.7)	-5.0 (3.2)	<.001*
Group 2 n=18	6.2 (3.4)	1.6 (2.6)	-4.6 (3.4)	<.001*
Group 3 n=9	6.0 (3.3)	3.1 (2.8)	-2.9 (4.1)	<.05*
ALL n=62	6.6 (2.9)	2.0 (2.7)	-4.6 (3.4)	<.001*
P-value [†]	.578	.412	.293	
NRS_{LN}				
Group 1 n=35	6.4 (3.1)	2.3 (2.6)	-4.1 (3.6)	<.001*
Group 2 n=18	6.2 (3.1)	2.7 (3.1)	-3.5 (2.7)	<.001*
Group 3 n=9	6.8 (3.4)	3.4 (2.9)	-3.4 (4.8)	.069
ALL n=62	6.4 (3.1)	2.6 (2.8)	-3.8 (3.5)	<.001*
P-value [†]	.903	.579	.801	

* Statistically significant.

† Comparison among groups.

‡ Comparison with Preop.

mm (33%), respectively, after indirect decompression LLIF for central stenosis. One of the studies included in this review, by Oliviera et al,^[20] performed a post-XLIF radiological evaluation of 43 levels in 21 patients with lumbar stenosis accompanied by degenerative disc disease with degenerative spondylolisthesis grade I or II and/or degenerative scoliosis. They found that CD and CCA increased by 2.4 mm (33.1%) and 12.4 mm² (8.4%), respectively.^[20] Elowitz et al^[13] also found a 3.8 mm improvement in the CD of the thecal sac and an average increase of 83 mm² (143%) in the CCA after XLIF.

The effects of indirect neural decompression with LLIF on lumbar spinal stenosis have been discussed extensively in previous studies.^[5,8,13,20-22] Indirect decompression with LLIF allows the surgeon to control only the cage's size and position. We have previously reported that it is important to select a cage placement position in the middle of the intervertebral disc with a high cage height for indirect decompression.^[10] On the other hand, in some cases, additional decompression is required for indirect decompression. Indirect decompression failure (IDF) is generally defined as "persistent postoperative symptoms of nerve compression with or without a second direct decompression surgery to reach adequate symptom resolution." It is thought that the IDF associated with LLIF is about 9%.^[23] The factors likely to cause IDF include cage subsidence, low bone mineral density, ligament flavum hypertrophy, and osteophytes in the lateral recess and foraminal canal.^[8,11,20,24,25]

Severe central canal stenosis may also be a major risk factor. Nakashima et al^[26] reported that patients with preoperative lower limb paralysis and severe stenosis had a risk of perioperative neurological deterioration. Many patients who are refractory to conservative treatment and who undergo surgery may have severe stenosis. However, few reports have evaluated the effects of LLIF for severe stenosis, and this operation remains controversial. Therefore, it is important to analyze the effects of indirect neural decompression of LLIF on patients with moderate to severe stenosis.

This study used cluster analysis of the preoperative radiographic and clinical evaluation of patients classified according to the severity of spinal canal stenosis. Cluster analysis of groups classified according to the preoperative stenosis showed that the effects of indirect decompression immediately after LLIF surgery were similar for preoperative severe and moderate stenosis. The average changes in midsagittal CD and axial CCA in group 1 were 2.2±2.0mm and 23.8±16.8mm², which did not differ significantly from the changes in other groups. This finding suggests that the indirect decompression effect was not compromised in patients with severe spinal stenosis before the operation.

According to Fujibayashi et al,^[24] the more severe preoperative spinal canal stenosis, the more significant the improvement after neural decompression by LLIF compared with mild stenosis. Li et al^[27] reported that the radiographic decompression effect of

LLIF for Schizas grade D segments was similar to that for other grades. These findings and our analysis suggest that the improvement in the spinal canal after LLIF is not affected by the preoperative severity of spinal stenosis because patients with severe spinal stenosis had similar results as those with moderate or mild stenosis. Similarly, group 1 with severe stenosis showed no significant difference from the other groups regarding ADH, PDH, and DA changes after the LLIF. Therefore, we conclude that preoperative central canal stenosis does not significantly influence changes after LLIF with indirect neural decompression and spinal alignment.

However, the median sagittal CD and axial CCA change after LLIF did not differ between groups, but the median sagittal CD and axial CCA in group 1 was 7.3 ± 1.6 mm and 58.0 ± 18.7 mm². This value is significantly smaller than that for group 2 (9.0 ± 2.0 mm, 91.2 ± 29.9 mm²) and group 3 (11.1 ± 1.7 mm, 133.4 ± 25.3 mm²). Although the spinal canal is remodeled with time and further improvement is seen in many cases,^[14] it is possible that preoperatively severe spinal canal stenosis may prevent full morphological improvement over time.

In this series, 1 patient required additional decompression, but this reflected concern about the symptoms caused by the cage's subsidence. However, the NRS scores improved significantly at the final follow-up in all patients, and these scores did not differ significantly between the groups. Additional posterior decompression after LLIF is important to ensure adequate decompression in patients with severe lumbar spinal stenosis. However, even with indirect neural decompression by LLIF, enlargement of the thecal sac has been reported up to 6 months after surgery. In addition to the indirect decompression effect, the effect of spinal fusion on instability may reduce pain. Therefore, even in patients with severe spinal canal stenosis, it may be possible to expand the indications for this procedure provided the patient receives sufficient explanation.

This study has some limitations, such as its retrospective nature, limited follow-up, small sample size, and obvious variation in sample proportion between the 3 groups. Short follow-up periods can have a significant impact on results. In addition, we did not collect all of the clinical data, including the patient-reported outcomes about pain scores or quality of life, during the follow-up. Because this was a retrospective study, it was impossible to evaluate the radiographic and MRI data over time, and we evaluated the CCA and CD of the thecal sac only immediately after surgery. Therefore, MRI data and clinical evaluation could not be performed on all patients 1 year after the surgery. The time point of MRI data and patient-reported NRS were also mismatched. Finally, lumbar canal stenosis is a very complex structure. Factors affecting the canal's narrowing are hypertrophy of the ligaments, osteophytes, and a medial shift of the facet joints due to deterioration of bone quality. What makes the event more complex is the calcification of the ligaments or synovial cysts that develop into the canal or foramen and the lateral recess syndrome caused by the facet joints that migrate to the medial. In stenosis without calcification and accompanied by only soft tissues, even if the stenosis is severe, the patient may benefit, but if these tissues are calcified in the foramen or canal, LLIF may not give effective results.^[28] Further research is needed to determine whether the cause of canal stenosis is ligaments or osteophytes.

In conclusion, the indirect neural decompression effect of LLIF for severe stenosis was similar to that for mild or moderate

stenosis, and the rating of pain 1 year after surgery did not differ according to the severity of preoperative spinal canal stenosis.

Author contributions

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