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Transforaminal Lumbar Interbody Fusion for Lumbar Degenerative Disorders: Mini-open TLIF and Corrective TLIF

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Abstract

Minimally invasive transforaminal lumbar interbody fusion (TLIF) as a short fusion is widely accepted among the spine surgeons. However in the long fusion for degenerative kyphoscoliosis, corrective spinal fixation by an open method is thought to be frequently selected. Our objective is to study whether the mini-open TLIF and corrective TLIF contribute to the improvement of the spinal segmental and global alignment. We divided the patients who performed lumbar fixation surgery into three groups. Group 1 (G1) consisted of mini-open TLIF procedures without complication. Group 2 (G2) consisted of corrective TLIF without complication. Group 3 (G3) consisted of corrective TLIF with instrumentation-related complication postoperatively. In all groups, the lumbar lordosis (LL) highly correlated with developing surgical complications. LL significantly changed postoperatively in all groups, but was not corrected in the normal range in G3. There were statistically significant differences in preoperative and postoperative LL and mean difference between the pelvic incidence (PI) and LL between G3 and other groups. The most important thing not to cause the instrumentation-related failure is proper correction of the sagittal balance. In the cases with minimal sagittal imbalance with or without coronal imbalance, short fusion by mini-open TLIF or long fusion by corrective TLIF contributes to good clinical results if the lesion is short or easily correctable. However, if the patients have apparent sagittal imbalance with or without coronal imbalance, we should perform proper correction of the sagittal spinal alignment introducing various technologies.

Key words: corrective transforaminal lumbar interbody fusion, lumbar lordosis, minimally invasive transforaminal lumbar interbody fusion, pelvic incidence

Introduction

Minimally invasive spine surgery has been widely performed in the world. Among them, minimally invasive transforaminal lumbar interbody fusion (TLIF) with pedicle screw fixation as a short fusion is becoming increasingly popular, because of the less invasiveness for the patient and less instrument-related complications. The inter-body fusion such as posterior lumbar interbody fusion (PLIF),[1)] TLIF,[2,3)] anterior lumbar interbody fusion (ALIF),[4,5)] extremely lateral lumbar interbody fusion (XLIF),[6)] and so on should be performed in conjunction with pedicle screw fixation to perform the rigid fixation in whole circumference. Although mini-open XLIF[7)] or OLIF[8,9)] is recently reported even in the short fusion, TLIF method is superior in the point of one-port access and safety for the lumbar nerve root or lumbar plexus. However, if the long fusion is achieved by the traditional open method which is frequently done, perioperative bleeding, long operative time, and muscle damage become unfavorable.

We introduce our surgical procedures and clinical results for lumbar degenerative spondylolisthesis, instability, and kyphoscoliosis and review the literatures concerned with lumbar fixation for lumbar degenerative disorders.

Materials and Methods

There were 108 cases of lumbar degenerative spondylolisthesis, instability, and kyphoscoliosis for

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6 years since 2008. Following Research Ethics Board approval, a retrospective review was performed on 24 consecutive patients who underwent one- or two-segment instrumented fusions with minimal 24 months follow-up from 2008 to 2012 and 15 consecutive patients who underwent long-segment lumbar instrumented fusions exceeding three levels with minimal 18 months follow-up or until revision surgery from 2010 to 2012. All surgeries were performed by the author.

All patients were divided into three groups. Group 1 (G1) consisted of 24 patients who were performed mini-open TLIF procedures without complication. Group 2 (G2) consisted of 8 patients performed corrective TLIF without complication. Group 3 (G3) consisted of 7 patients performed corrective TLIF with instrumentation-related complication postoperatively.

I. Inclusion criteria

Inclusion criteria for mini-open TLIF consisted of patients with lumbar instability preserving lumbar lordosis (LL) who had a one- or two-intervertebral lesions with 5° or greater of focal kyphosis in flexion, 10° or greater of focal range of motion (ROM), more than 10% or 3 mm deterioration of spondylolisthesis in flexion-extension, and 10 mm or greater of lateral spondylolisthesis.

Inclusion criteria for corrective TLIF consisted of patients who had a minimum of three lumbar segments of posterior lumbar instrumented fusions for adult degenerative scoliosis or lumbar degenerative kyphosis combined with spondylolisthesis with proximal level of T10 or distal, distal level of L5 or distal.

In both groups, previous spinal operations adjacent, proximal, or distal to the fixed vertebrae were excluded. Patients were included if they had undergone a decompressive lumbar procedure. All constructs were pedicle screw and rod systems. TLIF with a single interbody fusion cage at each level was carried out in the segments.

TLIF with intervertebral cages was carried out in 1 segment in 21 cases and 2 segments in 3 cases in mini-open TLIF group, and 4 segments in 4 cases, 3 segments in 7 cases, 2 segments in 3 cases, and 1 segment in 1 case in corrective TLIF group.

II. Surgical methods for lumbar degenerative disorder

1. Mini-open TLIF (Figs. 1, 2)

Figure 1 provides a diagram of the mini-open TLIF procedure. The patient is prepared in the usual fashion and placed on a Jackson spine frame in the prone position. About 6 cm linear skin incision was made at open site (symptom site), 1 cm lateral to the midline. The paraspinous muscles are subperiosteally dissected from the spinous processes and laminae keeping the supraspinous and interspinous ligaments intact.

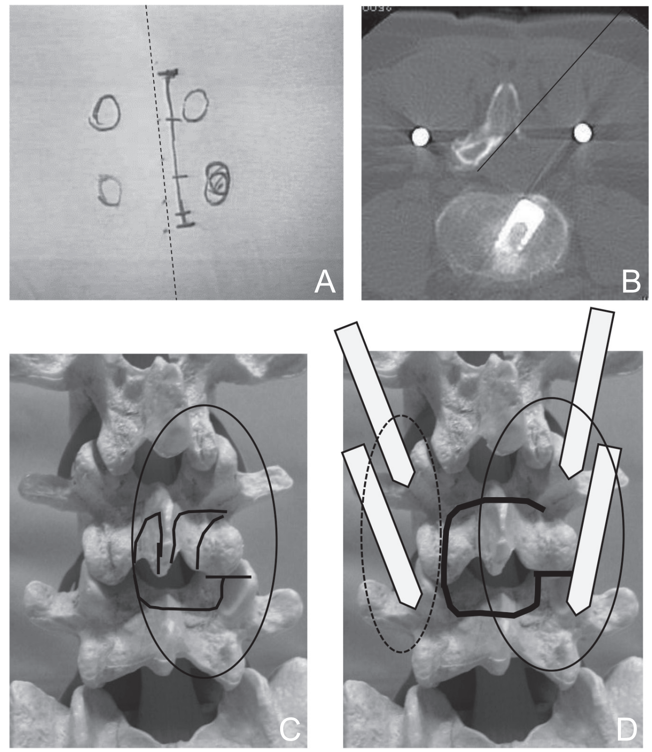

Fig. 1 Diagram of the mini-open TLIF procedure. About 6 cm linear skin incision was made 1 cm lateral to the midline (*broken line*) at open site. A: Hemilaminectomy and hemifacetectomy on the superior and inferior facets are performed at each level of the spinal segment to be fused. Decompression of the opposite site is simultaneously performed (*solid line*). The disc space is packed with local bone and TLIF cage with local bone is inserted from the open side. B: *Solid circle* shows an open side exposure. *Solid lines* depict the harvested bone fragments. C: Top loading pedicle screws are approximately placed in the open side and intramuscular side (*bold line*: laminectomy area, *solid circle*: an open side, *dotted circle*: intramuscular side, *arrows*: top loading screws) (D). TLIF: transforaminal lumbar interbody fusion.

Hemilaminectomy and hemifacetectomy of the superior and inferior facets are performed at each level of the spinal segment to be fused. Then decompression of the opposite site is simultaneously performed and epidural veins are electrocoagulated. These maneuvers provide access to the intervertebral disc space. Top loading pedicle screws are placed in the same operative field. Next, subcutaneous tissue is undermined and the lumbosacral

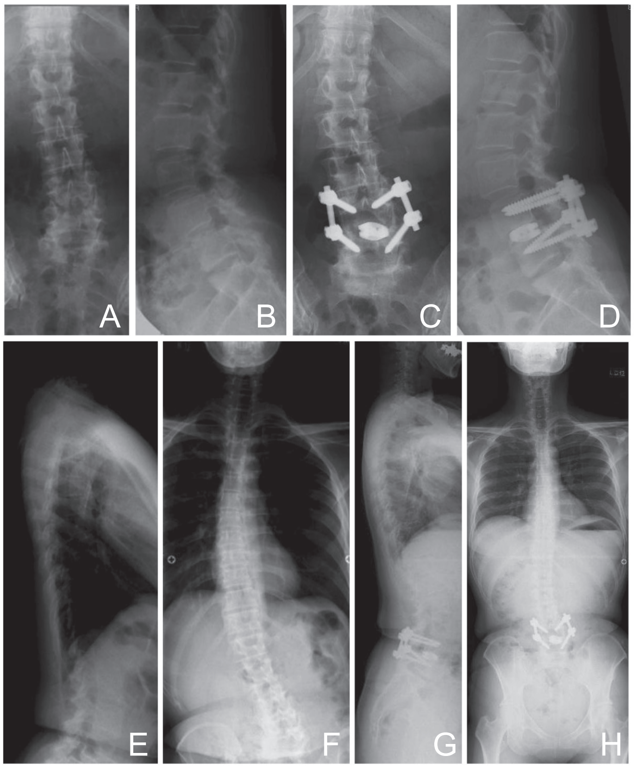

Fig. 2 Illustrative case of G1. Preoperative X-ray: lumbar spine (A-P: A, lateral: B) and total spine (lateral: E, A-P: F). Postoperative X-ray: lumbar spine (A-P: C, lateral: D) and total spine (lateral: G, A-P: H). Postoperative X-ray shows improvement of global spinal balance. A-P: antero-posterior, G1: group 1.

fascia is exposed and incised. Pedicle screws are inserted using the space between multifidus muscle and longissimus muscle. After the operative site is changed, the lower nerve root is protected by a retractor along the superomedial surface of the pedicle of the inferior vertebra. The upper nerve root hugs the inferomedial surface of the pedicle of the superior vertebra and can be directly visualized throughout the procedure. A scalpel is used to perform a posterolateral rectangular anulectomy. A nearly complete discectomy is performed using disc shavers, curets, and rongeurs, and the endplate decortication is performed. The disc space is packed with local bone and CAPSTONE®PEEK (Medtronic, Minneapolis, MN, USA) (19 cases) or titanium (5 cases) interbody spacer produced by Medtronic with local bone is obliquely inserted from the open side distracting the intervertebral space using inserted screws as the distractor until it is 3 mm to 4 mm below the posterior margin of the annulus. Rods, cut and contoured to the appropriate size and angle, are attached to the pedicle screws. Using the pedicle screws as the compressor to apply force,

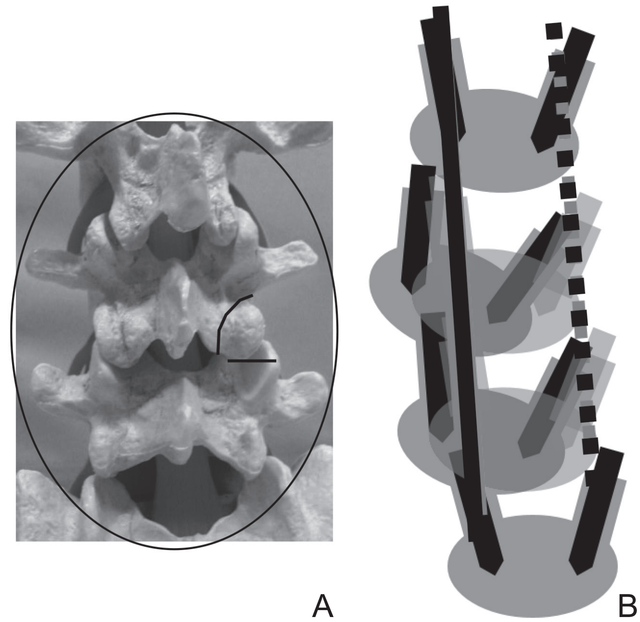

Fig. 3 Diagram of the corrective TLIF and correction of scoliosis. *Solid circle* indicates an operative field. Hemifacetectomy on inferior and superior facets and partial isthmic resection (*solid lines*) at concave side is performed. A: Drawing the screws to the rod which is pushed down is carried out on the concave side first and following on the convex side and the screws are tightened to the rod (B). TLIF: transforaminal lumbar interbody fusion.

TLIF cage is moderately compressed, and the screws are tightened to the rods. The wound is irrigated and closed, with care taken to restore the normal muscular envelope.

2. Corrective TLIF and correction of scoliosis (Figs. 3, 4)

Side lording screws are inserted as a traditional open method. After this maneuver, hemifacetectomy of inferior and superior facets and partial isthmic resection at concave side is performed. Then discectomy is performed using disc shavers, curets, and rongeurs, and the endplate decortication is performed. In some cases, multilevel Ponte osteotomies were used for reduction of kyphosis. The disc space is packed with local bone and CAPSTONE®PEEK interbody spacer with local bone is obliquely inserted from same side distracting the intervertebral space using inserted screws until it is 3 mm to 4 mm below the posterior margin of the annulus. Flat rods, which were cut and contoured to the appropriate size and angle, are attached to the pedicle screws to correct the scoliotic lumbar spine. Drawing the screws to the rod which is pushed down is carried out on the concave side first and following the convex side

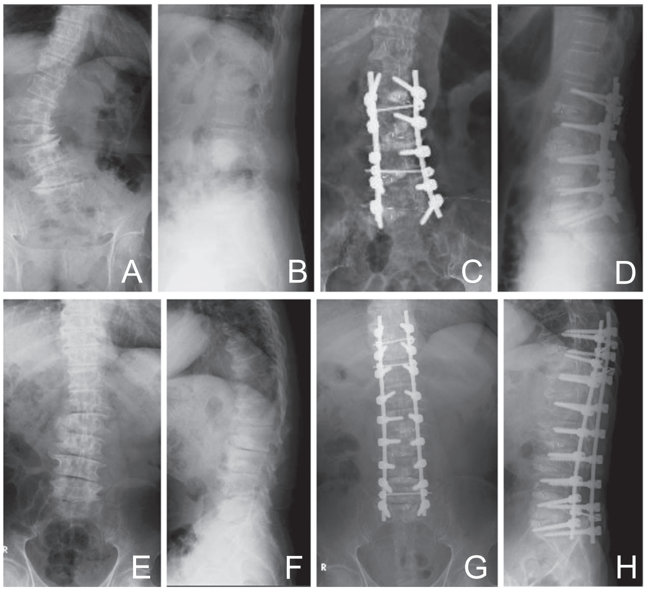

Fig. 4 Illustrative cases of G2 and G3. Preoperative X-ray (A-P: A, lateral: B) and postoperative X-ray (A-P: C, lateral: D) in G2. Preoperative X-ray (A-P: E, lateral: F) and postoperative X-ray (A-P: G, lateral: H) in G3. A-P: antero-posterior, G2: group 2, G3: group 3.

and the screws are tightened to the rods. Transverse links are settled passing the spinous processes and secured with bilateral rods. The wound is irrigated and closed, with care taken to restore the normal muscular envelope.

III. Study parameters

Clinical and radiographical data were collected by a spine surgeon who was not directly involved in the care or surgical treatment of the patients.

Their age, sex, and follow-up period were measured. A retrospective chart and radiographic review of all preoperative and postoperative imaging was performed by an independent reviewer who had nothing to do with either the initial surgery or aftercare of the patients. Patients were instructed to assume a free-standing posture, with elbows flexed and fingertips on the clavicles. Spinal measurements included LL (sagittal Cobb angle measured between the inferior endplate of T12 and the inferior endplate of L5), pelvic tilt (PT; angle between the vertical and the line through the midpoint of the sacral plate to axis of femoral heads), pelvic incidence (PI; angle between the perpendicular to the superior S1 endplate at its midpoint and the line connecting this point to the center of the femoral heads) and coronal Cobb angle in all groups, and segmental lordotic angle (sagittal angle between superior endplate and inferior endplate of affected vertebrae), vertebral height (length between midpoints of superior endplate and inferior endplate of affected vertebrae), and antero-posterior translation (length between posterior edges of affected vertebrae) in mini-open TLIF group (G1). The clinical outcome was assessed using the Japanese Orthopedic Association (JOA) score. All patients were followed for a minimum of 18 months or until revision surgery.

IV. Statistical analysis

Statistical analyses were performed using Student's *t*-test for continuous variables and clinical outcome was analyzed with linear correlation and regression analysis (Stat View; SAS Institute, Cary, North Carolina, USA). For all analyses, a p value < 0.05 was considered to be statistically significant. Values are expressed as mean ± standard error (SE).

Results

Some of the data, which was already reported by Nishimura et al. in this journal, were cited.[10]

I. Patient demographics (Table 1)

In mini-open TLIF group (G1), there were 4 men and 20 women, mean age was 64.1 ± 7.2 years and mean follow-up period was 27.7 ± 3.1 months. In corrective TLIF group, mean age of all patients was 71.8 ± 4.1 years. There were 1 man and 7 women whose mean age was 72.1 ± 3.8 years in G2 and 4 men and 3 women whose mean age was 71.4 ± 4.6 years in G3. The mean length of follow-up was 24.9 (18–36) months for G2 and 16.9 (5–40) months for G3. All patients who were not revised had a minimum follow-up of 18 months in G2 and 20 months in G3. There were no significant difference ($p > 0.05$) between G2 and G3 in mean age; however, significant differences ($p < 0.05$) between G1 and G2 and between G1 and G3 were present. There were no systemic complications in all groups. All 7 patients in G3 sustained screw cut-out (screw migration inside the vertebral body or out of the bone including screw back-out), screw loosening, or breakage of screws and vertebral compression fracture.

II. Clinical outcome

Mean preoperative JOA score was higher in mini-open TLIF group (G1: 17.5) than in corrective TLIF groups, which were similar in G2 and G3 (13.1 and 13.8, respectively). However, the difference of postoperative JOA score (24.1, 20.6, and 13.0 for G1, G2, and G3, respectively) was significantly different between G1 and G3, and between G2 and G3.

Table 1 Changes of spinal parameters in all groups

	G1 (mini-open TLIF)	G2	G3
M/F	4 men : 20 women	1 man : 7 women	4 men : 3 women
Mean age (y)	64.1 ± 7.2	72.1 ± 3.8	71.4 ± 4.6
Mean follow-up (M)	27.7 (24–60)	24.9 (18–36)	16.9 (5–40)
Mean JOA score (before op.)	17.5	13.1	13.8
Mean JOA score (after op.)	24.1	20.6	*13.0
Lumbar lordosis (before)	41.9 ± 2.7°	34.3 ± 4.0°	*19.0 ± 5.4°
Lumbar lordosis (after)	48.2 ± 2.4°	48.5 ± 3.0°	*25.1 ± 3.8°
Pelvic tilt (before)	25.7 ± 2.8°	26.3 ± 3.7°	30.1 ± 2.3°
Pelvic tilt (after)	25.5 ± 2.2°	26.3 ± 3.7°	25.3 ± 4.1°
Coronal Cobb angle (before)	17.1 ± 4.0°	30.5 ± 4.5°	22 ± 1.2°
Coronal Cobb angle (after)	11.4 ± 3.7°	6.8 ± 1.7°	7.3 ± 2.6°
PI	58.0 ± 4.5°	56.5 ± 2.1°	52.3 ± 4.9°
PI-LL (before)	16.3 ± 4.2°	22.5 ± 4.0°	*33.3 ± 2.7°
PI-LL (after)	9.6 ± 3.1°	9.8 ± 1.7°	*27.1 ± 3.6°

F: female, G1: group 1, G2: group 2, G3: group 3, JOA: Japanese Orthopedic Association, M: male, op.: operation, PI-LL: pelvic incidence-lumbar lordosis, TLIF: transforaminal lumbar interbody fusion, y: year, *: shows the significant difference ($p < 0.01$) among three groups. The LL highly correlated with developing surgical complications.

III. The change of spinal parameters

1. Mini-open TLIF (Table 2)

The preoperative lordotic angle and antero-posterior translation between affected vertebrae were approximately 8.5 ± 1.4° and 6.2 ± 0.8 mm, which significantly changed postoperatively to 10.0 ± 1.6° and 3.0 ± 0.5 mm. The vertebral height between affected vertebrae (67.4 ± 1.3 mm, 68.5 ± 1.1 mm) did not significantly change. LL tends to increase and thoracic kyphosis significantly increased at last follow-up (mean 27.7 months).

Table 2 Changes of spinal parameters in mini-open transforaminal lumbar interbody fusion

	Preoperation	Postoperation	p value
(between affected vertebrae)			
Lordotic angle (°)	8.5 ± 1.4	10.0 ± 1.6	$p < 0.01$
Vertebral height (mm)	67.4 ± 1.3	68.5 ± 1.1	n.s.
Antero-posterior translation (mm)	6.2 ± 0.8	3.0 ± 0.5	$p < 0.01$
(Spinal alignment)			
Lumbar lordosis (°)	41.9 ± 2.7	48.2 ± 2.4	$p = 0.11$
Thoracic kyphosis (°)	17.6 ± 1.7	23.1 ± 1.5	$p < 0.01$

Lordotic angle and antero-posterior translation between affected vertebrae significantly changed after the operation. Lumbar lordosis tends to increase and thoracic kyphosis significantly increased at last follow up (mean 27.7 months). n.s.: not significant.

2. Mini-open TLIF and corrective TLIF (all groups) (Table 1)

(a) LL (sagittal Cobb angle measured between the superior endplate of T12 and the superior endplate of S1) (Fig. 5)

The preoperative LL was approximately 41.9 ± 2.7° in G1, 34.3 ± 4.0° in G2, and 19 ± 5.4° in G3. The postoperative LL was 48.2 ± 2.4° in G1, 48.5 ± 3.0° in G2, and 25.1 ± 3.8° in G3. In all groups, postoperative LL significantly increased compared with preoperative one. There was significant difference among three groups. Postoperative LL was significantly different between G2 and G3, and also G1 and G3. The postoperative LL became near averaged normal LL (44 ± 12°)[11] in G1 and G2.

(b) PT (angle between the vertical and the line through the midpoint of the sacral plate to axis of femoral heads)

The preoperative pelvic tilt was approximately 25.7 ± 2.8° in G1, 26.3 ± 3.7° in G2, and 30.1 ± 2.3° in G3. The postoperative pelvic tilt was 25.5 ± 2.2° in G1, 26.3 ± 3.7° in G2, and 25.3 ± 4.1° in G3. Among all groups, there was no significant difference in PT before and after the surgery.

(c) Pelvic incidence (PI; angle between the perpendicular to the superior S1 endplate at its midpoint and the line connecting this point to the center of the femoral heads)

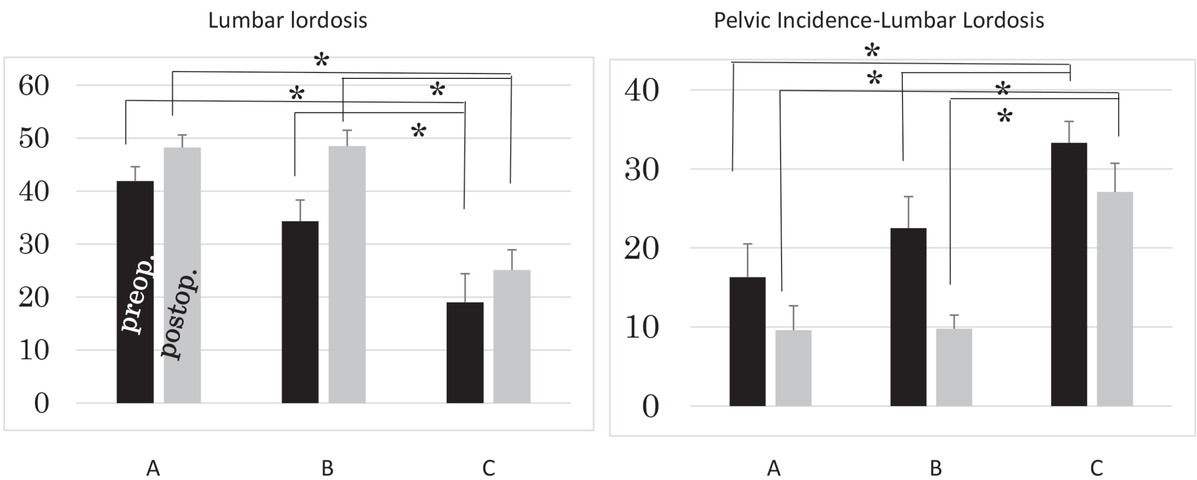

Fig. 5 Graphs of LL and PI-LL. LL was significantly corrected postoperatively in all groups, but did not correct in the normal range only in G3. * shows the statistically significant differences in preoperative and postoperative LL and mean difference between PI and LL between G3 and other groups. PI-LL: pelvic incidence-lumbar lordosis.

PI was 58.0 ± 4.5° in G1, 56.5 ± 2.1° in G2, and 52.3 ± 4.9° in G3. There were no significant differences among all groups.

(d) PI-LL (Table 1 and Fig. 5)

The preoperative PI-LL was approximately 16.3 ± 4.2° in G1, 22.5 ± 4.0° in G2, and 33.3 ± 2.7° in G3. The postoperative one was 9.6 ± 3.1° in G1, 9.8 ± 1.7° in G2, and 27.1 ± 3.6° in G3. In G1 and G2, postoperative PI-LL was significantly different from preoperative one and became an appropriate value.

(e) Coronal Cobb angle (Table 1)

The preoperative coronal Cobb angle was approximately 17.1 ± 4.0° in G1, 30.5 ± 4.5° in G2, and 22 ± 1.2° in G3. The postoperative angle was 11.4 ± 3.7°in G1, 6.8 ± 1.7° in G2, and 7.3 ± 2.6° in G3. In all groups, postoperative coronal Cobb angle was significantly different from preoperative angle. There was significant difference between G1 and G2 and between G1 and G3 in the coronal Cobb angle of before and after surgery. However the difference was not significant between G2 and G3, although the preoperative curve was significantly corrected after surgery in both groups.

IV. Spinal parameters related with surgical outcome

The LL highly correlated with developing surgical complications. Preoperative LL was 41.9 ± 2.7° in G1, 34.3 ± 4.0° in G2, and 19.0 ± 5.4° in G3 and the mean difference between PI and LL was 16.3 ± 4.2° in G1, 22.5 ± 4.0° in G2, and 33.3 ± 2.7° in G3. The initial postoperative LL was 48.2 ± 2.4° in G1, 48.5 ± 3.0° in G2, and 25.1 ± 3.8° and the postoperative mean difference between PI and LL was 9.6 ± 3.1° in G1, 9.8 ± 1.7° in G2, and 27.1 ± 3.6° in G3. LL was significantly corrected postoperatively in all groups, but did not correct in the normal range only in G3. There were statistically significant differences in preoperative and postoperative LL and mean difference between PI and LL between G3 and other groups.

Linear correlation and regression analysis showed that there was no correlation between the increase of JOA score and the correction of the coronal Cobb angle ($r = 0.381$, $p = 0.277$) in degenerative scoliosis patients. However, across the whole study population, we found a positive correlation between the increase of JOA and correction of LL ($r = 0.52$, $p < 0.05$).

Discussion

When the balance of the body axis is lost, deformation of the spinal column and the hip joint occurs.[12] Then it is easy to suffer from lifestyle-related diseases by declining the motor function.[13] Furthermore, hyper-kyphosis of the lumbar spine causes eating disorders by retraction of the gastrointestinal tract and respiratory failure due to compression of the diaphragm and also affects the prognosis.[14,15] However, nobody knows whether the correction of the spine is essentially necessary in all patients with spinal disorders.

In cases with instability of lumbar segments and without definite sagittal imbalance, short fusion by mini-open TLIF contributes to good clinical results. Our data in mini-open TLIF group indicates that increased LL causes increased thoracic kyphosis, which caused significant posterior shift of sagittal vertical axis (SVA: distance between the C7 plumb line and the posterior corner of the sacrum; 25.5 ± 4.4 mm to −0.4 ± 6.5 mm, data not shown) to younger standard value. If the patients have apparent sagittal imbalance with or without coronal imbalance, we should perform proper correction of the spinal alignment because failure of proper correction of the total spinal balance causes instrumentation-related complications. Our data also shows the most important thing not to cause the instrumentation-related failure is correction of the sagittal balance as previously reported.[5,16–21] The patients in G3 have more significant kyphotic deformity than other groups preoperatively (LL; 19 ± 5.4° in G3, 41.9 ± 2.5° in G1, and 34.3 ± 4.0° in G2). Intraoperatively, we failed to create adequate LL in harmony with PI in G3 (postoperative PI-LL: 9.6 ± 3.1° in G1, 9.8 ± 1.7° in G2, and 27.1 ± 3.6° in G3). PI is a morphological pelvic parameter that remains consistent during a patient's lifetime, with slight changes occurring during prepubertal development. Numerous studies have indicated that the pelvic morphology is an essential component of standing spinal alignment.[11,12,22] A ground rule of harmonious alignment consists of a LL proportional to PI and PI-LL becomes within 10°.[17] In our series, the low LL relative to PI accounts for the high instrumentation failure rate. If we perform the surgery considering spinal correction by fusion, treatment goal should be adapted to a given individual on the basis of their respective realignment needs. The relationship between the result of radiographic study and clinical outcome was analyzed with linear correlation and regression analysis. This showed that there was a positive correlation between the increase in JOA score and the increase in the LL angle ($r = 0.523$, $p < 0.05$),[10] which was consistent with earlier studies. However, no clear relationship between coronal Cobb angle and JOA scores ($r = 0.381$, $p = 0.277$) was detected. From these findings, the restoration of the LL angle should be much emphasized in the surgical procedure.

Our study indicates that short fusion by mini-open TLIF or long fusion by corrective TLIF contributes to good clinical results if the lesion is short or easily correctable in the cases with minimal sagittal imbalance and we should perform the spinal fixation getting the spinal balance to be adapted to a given individual on the basis of their respective realignment needs in the cases with prominent sagittal imbalance. However, we could not correct the sagittal alignment in the cases with more significant kyphotic deformity.

We think the main factor contributing the high instrumentation failure rate is surgical technique such as inadequate osteotomy, insufficient facetectomy, and use of single TLIF cage at each level with high reliance on local bone graft.

The flat rods we have used are convenient for the reduction of the degenerative kyphoscoliotic spine because we can apply the rods which were bended to make an adequate lordosis to the side lording screws. However, hyperplasia of the articular process could prevent the restoration of the LL angle for those patients with severe segment kyphosis.

Then posterior-only approach for long lumbar fusions would require the following techniques to achieve solid fusion leading to low complication rate[10]: (1) thorough release of the posterior and anterior structure, (2) removal of the contralateral side facet joints of the TLIF side if necessary, (3) settling two interbody cages in the anterior part of the intervertebral space to create the LL angle when the posterior column compression was conducted, (4) placement of wedge-shaped cages to produce better lordosis, (5) applying multi-segment TLIF technique by which the lordosis angle of the TLIF segment could be increased by 5°,[23] and (6) placing more amount of bone graft than harvested as local bone.

Minimally invasive spinal surgery

The goal of minimally invasive spinal surgery is to achieve the same objectives as the comparable open procedure via a less traumatic approach. Although lessening the approach-related morbidity is a primary aim of minimally invasive spine surgery, this must be accomplished without compromising the efficacy of the procedure. In other words, high fusion rates must be achieved, the amount of bleeding and postoperative pain must be reduced, and hospital stay also must be reduced by this procedure.[3,16] Some authors have reported high fusion rate and low complication rate in minimal access TLIF.[24]

Recently, minimally invasive XLIF[7,25] or OLIF[9] techniques are recognized as able to decompress the neural structures by intervertebral distraction, which cause the direct intervertebral foraminal widening and indirect spinal canal widening by stretching the yellow ligament.[26] However, no clear data about long-term efficacy of indirect decompression are present in the literature. At the moment, better choice of lumbar short segment fusion procedure is thought to be mini-open TLIF or PLIF with percutaneous pedicle screw insertion (PPS) and mini-open PLIF with cortical bone trajectory (CBT).[27] Using these techniques contributes to complete direct decompression of the cauda equina and roots and less invasiveness of paravertebral structures. On the other hand, there are several problems about corrective spinal surgery especially in long fusion. Correction of sagittal imbalance is most important as described above. However, traditional techniques used to correct sagittal imbalance include the shortening of posterior column as the Smith-Petersen osteotomy or the pedicle subtraction osteotomies and the vertebral column resection, they are associated with high intraoperative risk for bleeding and neurological damage, postoperative pain, and long hospital stay. Recently, minimally invasive anterior spinal fixation such as OLIF and XLIF is introduced. These techniques contribute to the reduction of blood loss and muscle damage and short hospital stay, but it is unclear whether they contribute to the correction of global misalignment and pain relief or not. Costanzo et al.[7] reported that the development and diffusion of these new minimally invasive anterior techniques reveal their ability to control and correct sagittal misalignment and provide reduced risks related to the anterior direct approaches as anesthetic complications, visceral damage, large vessels bleeding, and sexual dysfunctions and should permit an early patient mobilization. Acosta et al.[28] also showed the effect of correction of global spine using OLIF procedure, which significantly improved segmental, regional, and global coronal plane alignment and segmental sagittal Cobb angle in patients with degenerative lumbar disease, but did not improve regional LL or global sagittal alignment.

If minimally invasive anterior fusion procedures are effective for the correction of global spinal imbalance, further corrective fixation by PPS is ideal in the point of further less invasiveness. Recently, we perform the corrective surgery by OLIF with PPS. However, it is difficult to obtain the rigid fusion and to prevent the occurrence of more adjacent segmental lesion because of less fusion mass and lack of supplemental fixation using hooks and wire in PPS and also impossible to perform complete decompression.

Now we can use drugs to improve the bone density and quality such as bisphosphonate and parathyroid hormone (PTH). Brandon et al.[29] described that bisphosphonate therapy appeared to impede maturation of the fusion mass with an unclear effect on mechanical strength but only improved the radiographically defined fusion rate in the human study. However, intermittent PTH treatment may improve fusion rate.

Ohtori et al.[30] reported that incidence of pedicle screw loosening in the teriparatide group (7% to 13%: daily subcutaneous injection of 20 µg) was significantly lower than that in the risedronate (13% to 26%: daily oral administration 2.5 mg) or the control group (15% to 25%: without medication for osteoporosis) after lumbar spinal fusion surgery. In contrast, the extent of pedicle screw loosening in the risedronate group was not significantly different from that in the control group. Inoue et al.[31] has reported that teriparatide injections beginning at least 1 month prior to surgery were effective in increasing the insertional torque of pedicle screws during surgery in patients with postmenopausal osteoporosis. Teriparatide of daily subcutaneous injection of 20 µg also contributed to significant decreasing of the new vertebral fracture (3.1%) compared with placebo (14.5%) At 72 weeks, teriparatide administration significantly increased bone mineral density by 6.4 % at the lumbar spine compared with the placebo.[32]

If the patients have apparent sagittal imbalance with or without coronal imbalance, we should perform the spinal fixation getting the spinal balance to be adapted to a given individual on the basis of their respective realignment needs, because failure of the proper correction of the total spinal balance cause instrumentation-related complications. Minimally invasive surgical technologies for the treatment of degenerative conditions of the adult lumbar spine continue to improve. We must perform the lumbar fixation surgery using various techniques, using drugs like PTH, improved instrument design or material and sophisticated surgery based on our experiences.

Conclusion

Like other studies, this series is limited by the small numbers. Nevertheless, our conclusions related to sagittal imbalance and surgical procedure are significant findings. A multicenter setting based on this study's results may help further validate these findings and other findings in this study to provide surgeons with a better understanding in choosing appropriate surgical strategies for degenerative conditions of the adult spine. In the cases with minimal sagittal imbalance with or without coronal imbalance, short fusion by mini-open TLIF or long fusion by corrective TLIF contributes to good clinical results if the lesion is short or easily correctable. However, in the cases with prominent sagittal imbalance with or without coronal imbalance, we should perform the spinal fixation getting the spinal balance to be adapted to a given individual on the basis of their respective realignment needs. Minimally invasive surgery for the lumbar degenerative disorders should be performed introducing various technologies, using drugs like PTH, improved instrument material and design, and sophisticated surgery based on our experiences.

Conflicts of Interest Disclosure

All authors have no conflicts of interest with regard to the manuscript submitted. In addition, authors who are members of the Japan Neurosurgical Society (JNS) state that all authors have registered online Self-reported COI Disclosure Statement Forms through the website for JNS members.

References

1) Steffee AD, Sitkowski DJ: Posterior lumbar interbody fusion and plates. *Clin Orthop Relat Res* 227: 99–102, 1988
2) Harms JG, Jeszenszky D: Die posteriore, lumbale, interkorporelle Fusion in unilateraler transforaminaler Technik. *Oper Orthop Traumatol* 10: 90–102, 1998 (German)
3) Schwender JD, Holly LT, Rouben DP, Foley KT: Minimally invasive transforaminal lumbar interbody fusion (TLIF): technical feasibility and initial results. *J Spinal Disord Tech* 18(Suppl): S1–S6, 2005
4) Brau SA: Mini-open approach to the spine for anterior lumbar interbody fusion: description of the procedure, results and complications. *Spine J* 2: 216–223, 2002
5) Loguidice VA, Johnson RG, Guyer RD, Stith WJ, Ohnmeiss DD, Hochschuler SH, Rashbaum RF: Anterior lumbar interbody fusion. *Spine* 13: 366–369, 1988
6) Ozgur BM, Aryan HE, Pimenta L, Taylor WR: Extreme Lateral Interbody Fusion (XLIF): a novel surgical technique for anterior lumbar interbody fusion. *Spine J* 6: 435–443, 2006
7) Costanzo G, Zoccali C, Maykowski P, Walter CM, Skoch J, Baaj AA: The role of minimally invasive lateral lumbar interbody fusion in sagittal balance correction and spinal deformity. *Eur Spine J* 23(Suppl 6): 699–704, 2014
8) Mayer HM: A new microsurgical technique for minimally invasive anterior lumbar interbody fusion. *Spine* (*Phila Pa 1976*) 22: 691–699; discussion 700, 1997
9) Silvestre C, Mac-Thiong JM, Hilmi R, Roussouly P: Complications and Morbidities of Mini-open Anterior Retroperitoneal Lumbar Interbody Fusion: Oblique Lumbar Interbody Fusion in 179 Patients. *Asian Spine J* 6: 89–97, 2012
10) Nishimura Y, Hara M, Nakajima Y, Haimoto S, Yamamoto Y, Wakabayashi T: Outcomes and complications following posterior long lumbar fusions exceeding three levels. *Neurol Med Chir* (*Tokyo*) 54: 707–715, 2014
11) Bernhardt M, Bridwell KH: Segmental analysis of the sagittal plane alignment of the normal thoracic and lumbar spines and thoracolumbar junction. *Spine* (*Phila Pa 1976*) 14: 717–721, 1989
12) Ames CP, Smith JS, Scheer JK, Bess S, Bederman SS, Deviren V, Lafage V, Schwab F, Shaffrey CI: Impact of spinopelvic alignment on decision making in deformity surgery in adults: A review. *J Neurosurg Spine* 16: 547–564, 2012
13) Takahashi T, Ishida K, Hirose D, Nagano Y, Okumiya K, Nishinaga M, Matsubayashi K, Doi Y, Tani T, Yamamoto H: Trunk deformity is associated with a reduction in outdoor activities of daily living and life satisfaction in community-dwelling older people. *Osteoporos Int* 16: 273–279, 2005
14) Lee JS, Kim KW, Ha KY: The effect of vertebroplasty on pulmonary function in patients with osteoporotic compression fractures of the thoracic spine. *J Spinal Disord Tech* 24: E11–E15, 2011
15) Thiranont N, Netrawichien P: Transpedicular decancellation closed wedge vertebral osteotomy for treatment of fixed flexion deformity of spine in ankylosing spondylitis. *Spine* (*Phila Pa 1976*) 18: 2517–2522, 1993
16) Ames CP, Acosta FL, Chi J, Iyengar J, Muiru W, Acaroglu E, Puttlitz CM: Biomechanical comparison of posterior lumbar interbody fusion and transforaminal lumbar interbody fusion performed at 1 and 2 levels. *Spine* (*Phila Pa 1976*) 30: E562–E566, 2005
17) Lewis SJ, Abbas H, Chua S, Bacon S, Bronstein Y, Goldstein S, Magana S, Sullivan K, Dold AP, Bodrogi A: Upper instrumented vertebral fractures in long lumbar fusions: what are the associated risk factors? *Spine* (*Phila Pa 1976*) 37: 1407–1414, 2012
18) Glassman SD, Berven S, Bridwell K, Horton W, Dimar JR: Correlation of radiographic parameters and clinical symptoms in adult scoliosis. *Spine (Phila Pa 1976)* 30: 682–688, 2005
19) Jang JS, Lee SH, Kim JM, Min JH, Han KM, Maeng DH: Can patients with sagittally well-compensated lumbar degenerative kyphosis benefit from surgical treatment for intractable back pain? *Neurosurgery* 64: 115–121; discussion 121, 2009
20) Schwab F, Ungar B, Blondel B, Buchowski J, Coe J, Deinlein D, DeWald C, Mehdian H, Shaffrey C, Tribus C, Lafage V: Scoliosis Research Society-Schwab adult spinal deformity classification: a validation study. *Spine* (*Phila Pa 1976*) 37: 1077–1082, 2012
21) Schwab F, Patel A, Ungar B, Farcy JP, Lafage V: Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. *Spine* (*Phila Pa 1976*) 35: 2224–2231, 2010
22) Hasegawa K, Homma T: One-stage three-dimensional correction and fusion: a multilevel posterior lumbar interbody fusion procedure for degenerative lumbar kyphoscoliosis. Technical note. *J Neurosurg* 99(1 Suppl): 125–131, 2003
23) Li F, Chen Q, Chen W, Xu K, Wu Q: Posterior-only approach with selective segmental TLIF for degenerative lumbar scoliosis. *J Spinal Disord Tech* 24: 308–312, 2011

24) Wu RH, Fraser JF, Härtl R: Minimal access versus open transforaminal lumbar interbody fusion: meta-analysis of fusion rates. *Spine* (*Phila Pa 1976*) 35: 2273–2281, 2010
25) Youssef JA, McAfee PC, Patty CA, Raley E, DeBauche S, Shucosky E, Chotikul L: Minimally invasive surgery: lateral approach interbody fusion: results and review. *Spine* (*Phila Pa 1976*) 35: S302–S311, 2010
26) Oliveira L, Marchi L, Coutinho E, Pimenta: A radiographic assessment of the ability of the extreme lateral interbody fusion procedure to indirectly decompress the neural elements. *Spine* (*Phila Pa 1976*) 35(26 Suppl): S331–S337, 2010
27) Santoni BG, Hynes RA, McGilvray KC, Rodriguez-Canessa G, Lyons AS, Henson MA, Womack WJ, Puttlitz CM: Cortical bone trajectory for lumbar pedicle screws. *Spine J* 9: 366–373, 2009
28) Acosta FL, Liu J, Slimack N, Moller D, Fessler R, Koski T: Changes in coronal and sagittal plane alignment following minimally invasive direct lateral interbody fusion for the treatment of degenerative lumbar disease in adults: a radiographic study. *J Neurosurg Spine* 15: 92–96, 2011
29) Hirsch BP, Unnanuntana A, Cunningham ME, Lane JM: The effect of therapies for osteoporosis on spine fusion: a systematic review. *Spine J* 13: 190–199, 2013
30) Ohtori S, Inoue G, Orita S, Yamauchi K, Eguchi Y, Ochiai N, Kishida S, Kuniyoshi K, Aoki Y, Nakamura J, Ishikawa T, Miyagi M, Kamoda H, Suzuki M, Kubota G, Sakuma Y, Oikawa Y, Inage K, Sainoh T, Takaso M, Ozawa T, Takahashi K, Toyone T: Teriparatide accelerates lumbar posterolateral fusion in women with postmenopausal osteoporosis: prospective study. *Spine* (*Phila Pa 1976*) 37: E1464–E1468, 2012
31) Inoue G, Ueno M, Nakazawa T, Imura T, Saito W, Uchida K, Ohtori S, Toyone T, Takahira N, Takaso M: Teriparatide increases the insertional torque of pedicle screws during fusion surgery in patients with postmenopausal osteoporosis. *J Neurosurg Spine* 21: 425–431, 2014
32) Nakamura T, Sugimoto T, Nakano T, Kishimoto H, Ito M, Fukunaga M, Hagino H, Sone T, Yoshikawa H, Nishizawa Y, Fujita T, Shiraki M: Randomized Teriparatide [human parathyroid hormone (PTH) 1-34] Once-Weekly Efficacy Research (TOWER) trial for examining the reduction in new vertebral fractures in subjects with primary osteoporosis and high fracture risk. *J Clin Endocrinol Metab* 97: 3097–3106, 2012

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