

Prospective Cohort Study

Percutaneous Endoscopic Robot-Assisted Transforaminal Lumbar Interbody Fusion (PE RA-TLIF) for Lumbar Spondylolisthesis: A Technical Note and Two Years Clinical Results

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Background: Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) and percutaneous endoscopic TLIF (PE-TLIF) have been widely used in spine surgery. The use of a robot-guided technique provided several advantages; however, few studies have investigated the clinical outcomes of robot-assisted PE-TLIF (PE RA-TLIF).

Objective: The aim of this prospective cohort study was to compare the clinical outcomes of PE RA-TLIF with MIS-TLIF for the treatment of lumbar 4-5 (L4-5) spondylolisthesis.

Study Design: Prospective cohort study.

Setting: Qilu Hospital of Shandong University.

Methods: Fifty-eight cases diagnosed with L4-5 spinal stenosis with instability and Meyerding grade I spondylolisthesis (degenerative spondylolisthesis or isthmic spondylolisthesis) were included in this study. Twenty-six patients (group A) were treated with PE RA-TLIF, and the others (group B) underwent MIS-TLIF. The surgical procedures for PE RA-TLIF included the percutaneous implantation of pedicle screws (PS) under robot guidance, percutaneous fully endoscopic transforaminal decompression, and interbody fusion. The Japanese Orthopedic Association (JOA) score, the visual analog scale (VAS) for low back pain (LBP), the VAS for leg pain/numbness, and the Oswestry disability index (ODI) were used as follow-up clinical outcomes, and the lumbar interbody fusion rate was evaluated by CT. All statistical analyses were performed with SPSS 22.0, and the results were presented as mean \pm standard deviation (SD).

Results: There were 4 cases of spinal stenosis with instability, 17 cases of degenerative spondylolisthesis, and 5 cases of isthmic spondylolisthesis in group A. For group B, there were 6 cases of spinal stenosis with instability, 19 cases of degenerative spondylolisthesis, and 7 cases of isthmic spondylolisthesis. The preoperative scores for the JOA, ODI, VAS for LBP, and VAS for leg pain were not statistically comparable between the 2 groups ($P > 0.05$). The incision length for decompression and interbody fusion, estimated blood loss (EBL), and 1-day and 3-day incision pain were significantly higher in group B than in group A ($P < 0.05$). The mean operative time was longer in group A than in group B ($P < 0.05$). The operation time of the first 10 cases (251 ± 24 min) was much longer than that of the last 16 cases (200 ± 17 min) in group A. The misplacement rate of percutaneous pedicle screw placement was higher in group B ($P < 0.05$). No infections of incisions and interbody or nerve root or dural injuries were found in either group A or B. No differences were found between the 2 groups in the JOA scores, ODI, leg pain VAS score, or lumbar interbody fusion rate at the 2-year follow-up. The VAS for back pain was better in group A than in group B ($P < 0.05$).

Limitations: The PE RA-TLIF procedure is technically challenging and has a steep learning curve, and the study was not strictly randomized.

Conclusion: PE RA-TLIF is a safe and effective procedure that can significantly improve the accuracy of pedicle screw placement, reduce surgical trauma, and facilitate rapid postoperative recovery. However, this technique has a steep and long learning curve and requires long-term follow-ups.

Key words: Lumbar, degenerative disease, minimally invasive, TLIF, robot-assisted, endoscopic surgery

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Harms and Rolinger et al first reported the use of transforaminal lumbar interbody fusion (TLIF) in 1982 (1). Foley et al (2) first reported the use of minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), a modification of TLIF, to reduce the occurrence of intraoperative paraspinous muscle injury. Compared with open spinal procedures, MIS-TLIF provided less blood loss, less initial postoperative pain, less analgesic medication use, early rehabilitation, and shorter hospitalizations (3,4). A percutaneous endoscopic minimally invasive TLIF procedure has been reported for lumbar diseases with better clinical results, which can minimize access trauma and hasten the recovery process after the intervention (5). The differences between these techniques include the following: 1.) different anesthesia methods (local analgesia with intravenous sedation [6-10], epidural analgesia [8,11] or general anesthesia [8,12]); 2.) different interbody implants used in TLIF (auto- and allograft bone [13], expandable cages [8,11,13,14], narrow surface cages [15], B-twin implants [14,16], deployable mesh implants [17], or routine rigid PEEK/titanium cages [13,18,19]); 3.) different endoscopic systems used in decompression and interbody fusion procedures (such as microendoscopy [15], inextensible endoscopic tubes [20], arthroscopy [UBE technique; (21,22)], full endoscopy with 8 mm working channels [6,8-12,14], or full-endoscopy with a larger beveled working cannula [13.7 mm of outer diameter, 10.2 mm of inner diameter (6,7)]); 4.) fixation methods (no posterior fixation [16], percutaneous pedicle screws fixation [8,12,18], or facet screws [14,23]); and 5.) different guide methods for pedicle screws insertion (fluoroscopy or navigation [11]).

Until now, the free-hand fluoroscopy-guided method (FH) has remained the principal method for pedicle screw implantation (24). Intraoperative computed tomography (CT) and 3D C-arm systems were used in spine surgery for navigation assistance (25,26). With navigation systems, the accuracy of PS placement has improved significantly compared with that of FH techniques or C-arm fluoroscopic guidance (27). Moreover, they can be used for navigation, even when anatomical landmarks are not exposed (28). The first robotic guidance system was described in 2004 with many advantages, including increased accuracy, a shortened surgical time, and less radiation exposure for both the patients and surgeons (29,30-32). However, few studies have investigated the clinical outcomes of percutaneous fully endoscopic TLIF with the assistance of robots.

In this study, we aimed to report the detailed surgical procedure of robot-assisted percutaneous fully endoscopic minimally invasive transforaminal lumbar interbody fusion (PE RA-TLIF) and assess the safety and 2-year clinical results of PE RA-TLIF for L4-5 lumbar spondylolisthesis or spinal stenosis with instability in comparison with MIS-TLIF.

METHODS

Inclusion and Exclusion Criteria

Inclusion criteria were as follows: 1) Low back pain with unilateral lower extremity symptoms and signs consistent with the clinical manifestations of lumbar spondylolisthesis or spinal stenosis; 2) L4-5 isthmic spondylolisthesis (Meyerding grade I), spinal stenosis with instability, Meyerding grade I degenerative spondylolisthesis associated with instability (slip distance > 5 mm or range of motion > 10° on flexion and extension radiographs) and needed to undergo interbody fusion and pedicle fixation without decompression; 3) There were no significant effects after 3 to 6 months conservative treatment.

Exclusion criteria were as follows: 1) Patients with a history of lumbar surgery; 2) Pure lumbar disc herniation without bony spinal canal stenosis; 3) Patients with any other neurological lesions or diseases that might affect precise pre- and post-operative clinical assessments.

Characteristics of the Patients

The Institutional Review Board (IRB) of Qilu hospital approved this study (IRB approval number: KYLL-2018-120), and patient consent was obtained for trial participation. Fifty-eight consecutive cases were included in this study and were divided into 2 groups with simple randomization. Group A included 26 patients (11 women and 15 men with an average age of 57.2 years) diagnosed with L4-5 spinal stenosis with instability (4 cases) and Meyerding grade I spondylolisthesis (17 cases of degenerative spondylolisthesis and 5 cases of isthmic spondylolisthesis) who were treated with percutaneous endoscopic transforaminal lumbar interbody fusion (PE RA-TLIF). For group B, 32 patients (14 men, 18 women with a mean age of 56.1 years) underwent L4-5 minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF). The diagnoses were L4-5 spinal stenosis with instability (6 cases) and Meyerding grade I spondylolisthesis (19 cases of degenerative spondylolisthesis and 7 cases of isthmic spondylolisthesis) (Table 1).

Table 1. PE RA-TLIF versus MIS-TLIF in terms of baseline and preoperative characteristics ($x \pm s$).

| | | PE RA-TLIF (group A) | MIS-TLIF (group B) | P value |
|--|--------------------------------|-------------------------|-----------------------|----------|
| Total | 58 | 26 | 32 | |
| Gender | | | | P = 0.29 |
| Male | 29 | 15 | 14 | |
| Female | 29 | 11 | 18 | |
| Mean age (years old) | | 57.2 ± 13.5 | 56.1 ± 12.1 | P = 0.12 |
| Diagnosis | | | | |
| L4-5 spinal stenosis with instability | 10 | 4 | 6 | P = 0.09 |
| L4-5 Meyerding grade I spondylolisthesis | Degenerative spondylolisthesis | 36 | 17 | |
| | Isthmic spondylolisthesis | 12 | 5 | |
| Mean follow-up time (months) | 17.9 ± 8.1 | 17.1 ± 8.5 | 18.6 ± 7.6 | P = 0.06 |

Surgical Procedures

The PE RA-TLIF (group A) and MIS-TLIF (group B) procedures performed at L4-5 on the left side are briefly described below with examples.

The patients were under general anesthesia and positioned in the prone position on a radiolucent table. The somatosensory-evoked potentials, electromyography signals, and free-run electromyography signals were monitored throughout the procedure using a nerve monitoring system.

1. The PE RA-TLIF procedure was performed as follows (Fig. 1):

1) The percutaneous pedicle screws were implanted with assistance from TiRobot (TINAVI Medical Technologies Co. Ltd.), a spinous process-mounted miniature device. Three-dimensional images were acquired using a C-arm scanner (Siemens Medical Solutions). Registration was performed via automatic recognition by the calibrator. The surgeons planned the screw trajectories, including the optimal positioning and dimensions of the implants in the axial, coronal, and sagittal views, with the TiRobot. The robot then steered toward the selected trajectory and indicated the entry point and direction of the pedicle screw trajectory. The surgeons drilled the guide pin through the guiding tube into the bilateral L4 and 5 pedicles percutaneously (Fig. 2).

2) The target point of the percutaneous endoscopic TLIF procedure in this study was the lateral rim of the superior articular process (SAP) in the posteroanterior view and the superior margin of the inferior vertebral body (L5) in the sagittal view, and the TiRobot was used to mark the optimal position

of the incision. Then, a 1.5 cm incision was made (as the longitudinal incision is usually adjacent to the L5 K-wire, the incision was also used for L5 pedicle screw insertion), and the Endo-sugi/plus posterior suite (Joimax GmbH, Germany) was used for the PE-TLIF procedure (the outer diameter of the endoscope and visual trepan were 7.3 mm and 8.5 mm, respectively). An 18-gauge spinal needle was firmly docked on the lateral rim of the SAP and was then replaced by a guidewire, over which a tapered obturator was advanced to the SAP surface. The working cannula was advanced over the dilator, and the Endo-sugi/plus working cannula (inner diameter > 8.5 mm and outer diameter < 10 mm) was introduced over the obturator and placed securely onto the facet joint. The guidewire and obturator were withdrawn, and a working-channel endoscope was advanced to the foraminal structures with the help of the robot (Figs. 3). Preoperative imaging showed that most of the patients had central spinal stenosis, and thus facetectomy with partial laminectomy were performed for decompression. The facet, unilateral lamina, ligamentum flavum in the foraminal zone, and foraminal ligament were then removed gradually by the trepan, endoscopic burr, and/or Kerrison rongeurs to expose the L4/5 disc under endoscopic view, leaving the interlaminar part of the ligamentum flavum untouched (Fig. 4).

3) The guidewire and obturator were reinserted, and a channel specifically designed for interbody fusion was introduced over the obturator and moved into the interbody space for the interbody fusion procedure. The channel was a 3/4 rectangle-shaped channel (designed by Dr. Zhou Yue from the Second Affiliated Xinqiao Hospital of Army Medical Univer-

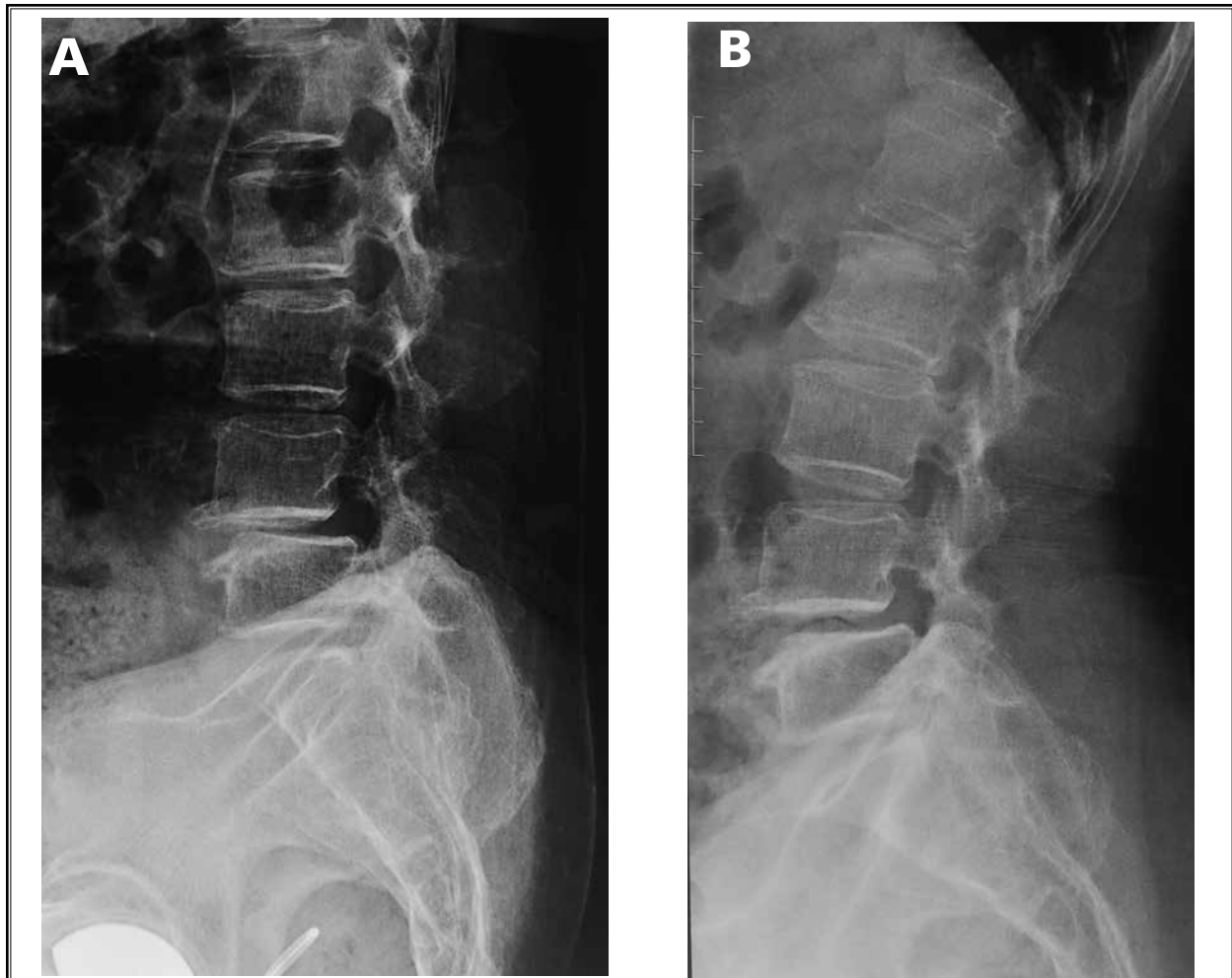


Fig 1. A) A 69-year-old woman with low back pain and left leg numbness was treated with robot-assisted, percutaneous, endoscopic, minimally invasive transforaminal lumbar interbody fusion. The preoperative x-rays showed instability at the L4-5 level. B) The preoperative x-rays showed instability at the L4-5 level.



Fig 2. Percutaneous pedicle screws were inserted with assistance from the TiRobot (TINAVI Medical Technologies Co. Ltd.).

sity), which also served as a nerve retractor to protect the dura and exiting and traversing nerve roots. The length, height, and width of the channel were 137 mm, 11 mm, and 9 mm, respectively (Fig. 5). Discectomy and endplate preparation were then performed through the nerve retractor with bipolar cautery, pituitary rongeurs, and curettes. The fusion bed preparation was endoscopically verified for cortical bone bleeding surfaces without endplate destruction (Fig. 6). After cartilage endplate removal, the contralateral and anterior disc space were packed with a morselized bone graft (obtained from the removed facet) and an autologous bone graft. An 8-mm-wide narrow-surface fusion cage made of polyetheretherketone (PEEK) (Double Medical Technology Inc., Xiamen, China) with

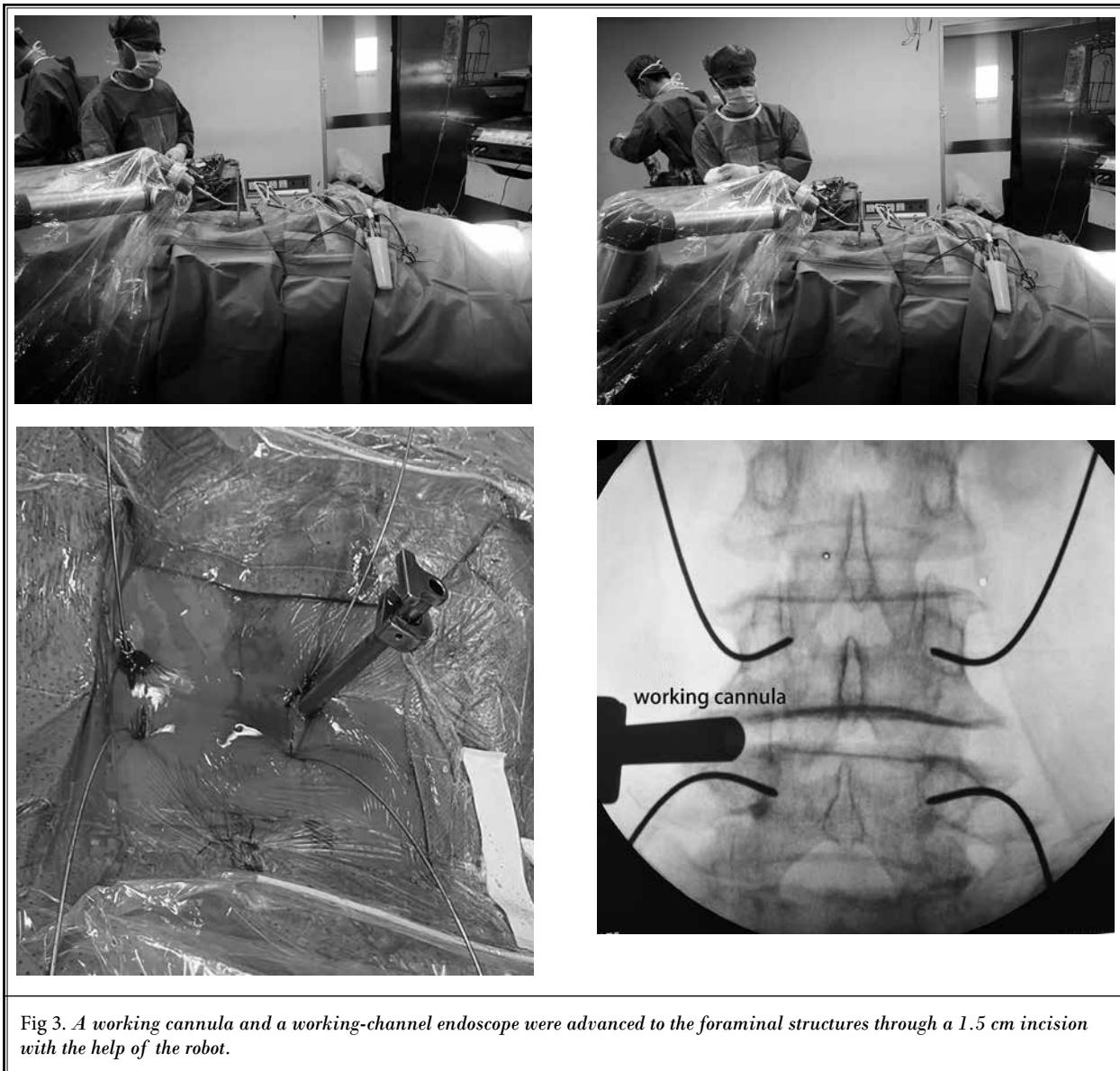


Fig 3. A working cannula and a working-channel endoscope were advanced to the foraminal structures through a 1.5 cm incision with the help of the robot.

different heights corresponding to the targeted intervertebral space was inserted from the left side, filled with autograft (Figs. 7,8).

4) After the interbody fusion procedure, the nerve retractor was replaced again by a working tube, and then the interlaminar part of the hypertrophic ligamentum flavum was removed for decompression (Fig. 9).

5) The cannulated pedicle screws were inserted with K-wires, and the screw-rod system was locked. Finally, the incisions were closed, and no postoperative drains were used.

2. The MIS-TLIF procedure was performed as follows:

With fluoroscopic guidance, Jamshidi needles were inserted into the bilateral L4 and L5 pedicles with the free-hand technique, and 4 K-wires were inserted into the bilateral L4 and L5 pedicles. A skin incision (approximately 2.5 cm long) between K-wires on the left side was made, the paraspinous muscles were bluntly separated by the dilators, and the minimally invasive retractor with appropriate size was docked on the facet joint complex. Facetctomy, discectomy, endplate preparation, interbody fusion with autologous, al-

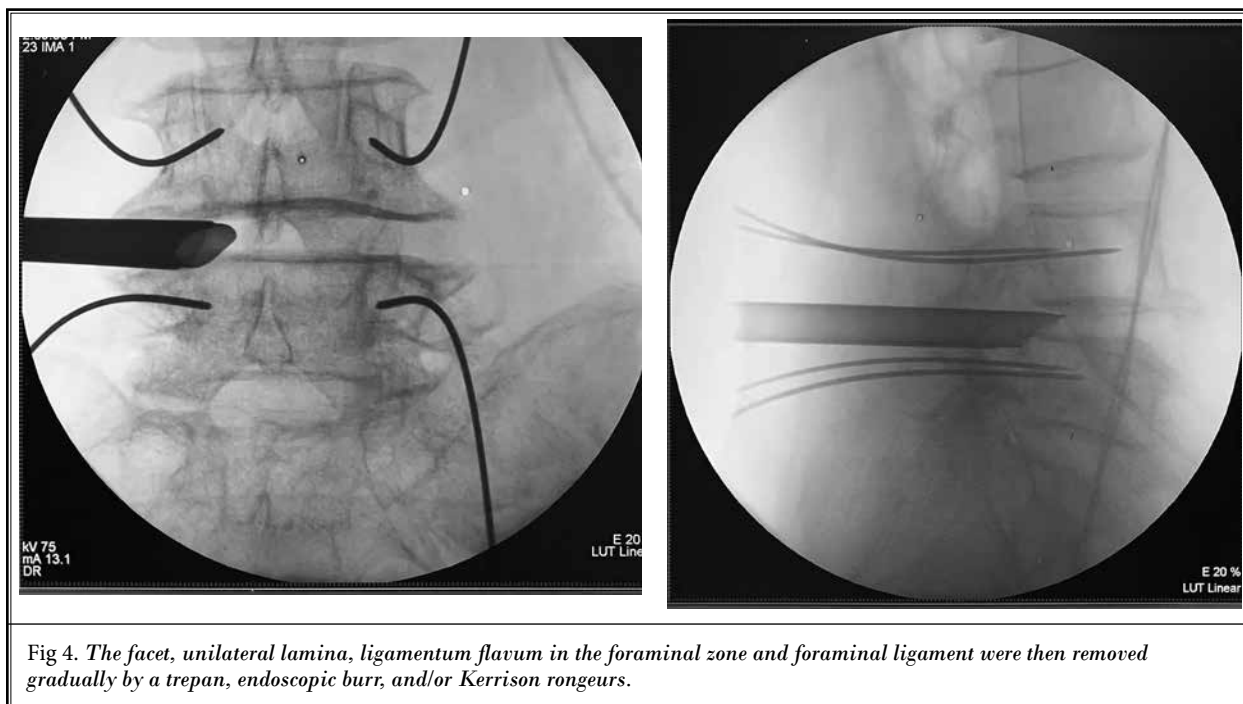


Fig 4. The facet, unilateral lamina, ligamentum flavum in the foraminal zone and foraminal ligament were then removed gradually by a trepan, endoscopic burr, and/or Kerrison rongeurs.

lograft bone graft and a single polyetheretherketone (PEEK) cage, and spinal canal decompression were performed in sequence. Finally, the cannulated pedicle screws were inserted with K-wires, and the set screws were then placed and tightened (Fig. 3).

Clinical Outcome Measures

The JOA score for LBP, the VAS for LBP, leg pain/numbness, and incision pain (0 indicated no pain/numbness and 10 represented the worst pain/numbness) and ODI were recorded for the clinical evaluation (for patients with bilateral leg symptoms, the more severe side was evaluated) (33). The recovery rate was calculated as follows: $(\text{follow-up score} - \text{preoperative score}) / (29 - \text{preoperative score}) \times 100\%$. These scores were collected before surgery, and at 1 day, 3 days, and 2 years postoperatively. At the 1-year follow-up, all subjects were conducted with CT scans to acquire Brantigan score (0-4 points) for evaluating the level of success of intervertebral fusion (34) and the accuracy of PS placement. Patients with scores of ≥ 3 were considered fused. The perforation was assessed using the following screw misplacement grading systems (35,26): Grade 0, no pedicle perforation; Grade 1, 0-2 mm; Grade 2, 2-4 mm; and Grade 3, greater than 4 mm. Grades 1 and 2 were considered clinically acceptable. Each parameter was measured 3

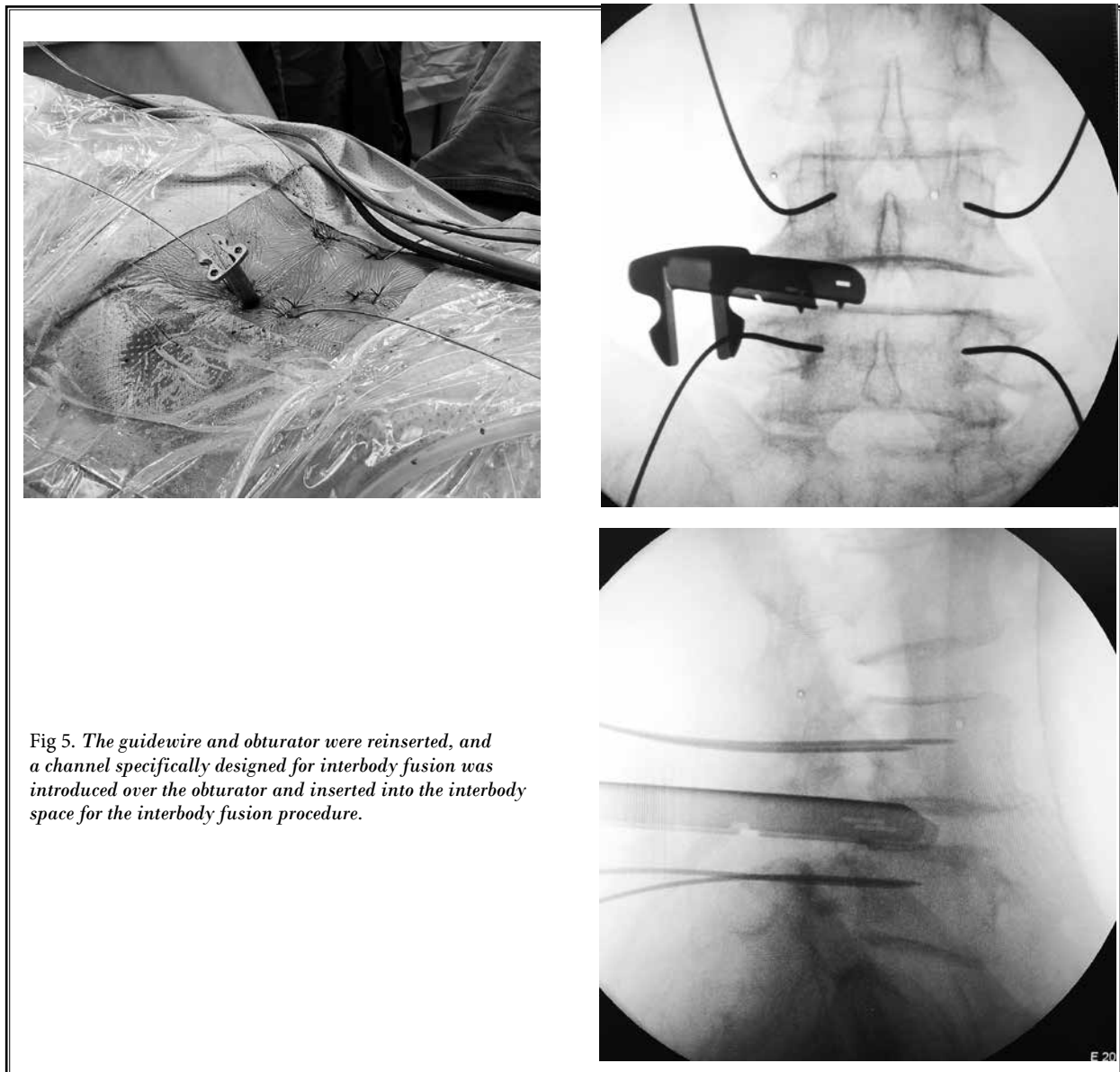
times by 2 experienced spine surgeons, and the average value was recorded. The groups were blinded to the measurements.

Statistical Analysis

SPSS version 22.0 software (IBM Corporation, Armonk, NY, USA) was used for statistical analysis. All the results were presented as mean \pm SD. Kolmogorov-Smirnov test was used for normality test. To assess statistical significance, unpaired t-tests and χ^2 -tests were performed. The significance level was set to be 0.05.

RESULTS

The preoperative scores for the JOA, ODI, VAS were not statistically comparable between the 2 groups ($P > 0.05$). The incision length for decompression and interbody fusion, estimated blood loss (EBL), and 1-day and 3-day incision pain were significantly worse in group B than in group A ($P < 0.05$). The mean operative time was longer in group A ($P < 0.05$). In this study, the operation time of the first 10 cases (251 ± 24 min) was much longer than that of the last 16 cases (200 ± 17 min). The accuracy rate of percutaneous pedicle screw placement was higher in group A than in group B ($P < 0.05$). No incisions or interbody infections, existing and traversing nerve root injuries,



dural injuries, or cerebrospinal fluid leaks were found in the 2 groups.

In this study, there was only 1 (0.9%) case of percutaneous pedicle screw (PPS) penetration in group A (grade 1) and 8 cases in group B (6.3%, grade 1: 6 cases; grade 2: 2 cases). No neurological deficits related to misplaced PPSs were observed during the follow-up in either group. The accuracy rate of PPS placement was higher in group A than in group B ($P < 0.05$) (Fig. 10).

The mean follow-up period was 26.9 ± 2.1 months. At the 2-year follow-up, no differences were found between the 2 groups in the JOA, ODI, and leg pain VAS

scores or lumbar interbody fusion rate. The VAS score for back pain was better in group A than in group B ($P < 0.05$) (Table 2). There were no cases of pedicle screw or rod breakage or cage migration during the follow-up.

DISCUSSION

The Accuracy of Robot-Assisted Percutaneous Pedicle Screw Insertion

Studies in the literature have reported that the misplacement rate of open thoracic and lumbar pedicle screws is as high as 42%, while that of PPS was



Fig 6. Endplate preparation was then performed through the channel with bipolar cautery, pituitary rongeurs, and curettes.

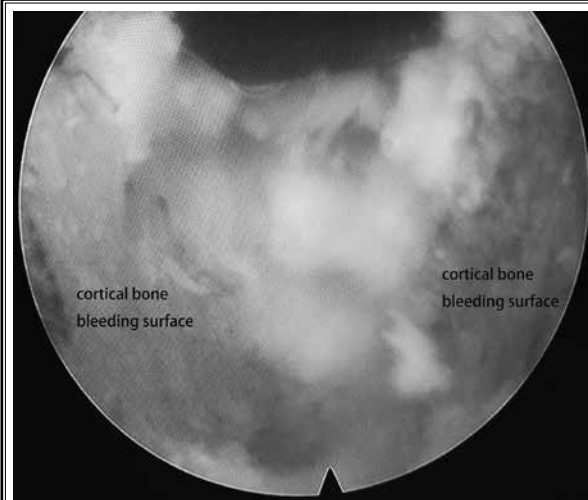


Fig 7. The fusion bed preparation was endoscopically verified for cortical bone bleeding surfaces without endplate destruction and the cage size was measured.



6.6% only (35). Oh et al (36) compared the accuracy of 558 open pedicle screws (OPS) with 498 PPSs using CT. The accuracy rates of OPS (13.4%) and PPS (14.3%) were not significantly different. A relatively higher

incidence of lateral penetration was observed in the OPS group (66.7% vs 43.7%), whereas there were more medial, superior, and inferior penetrations in the PPS group.

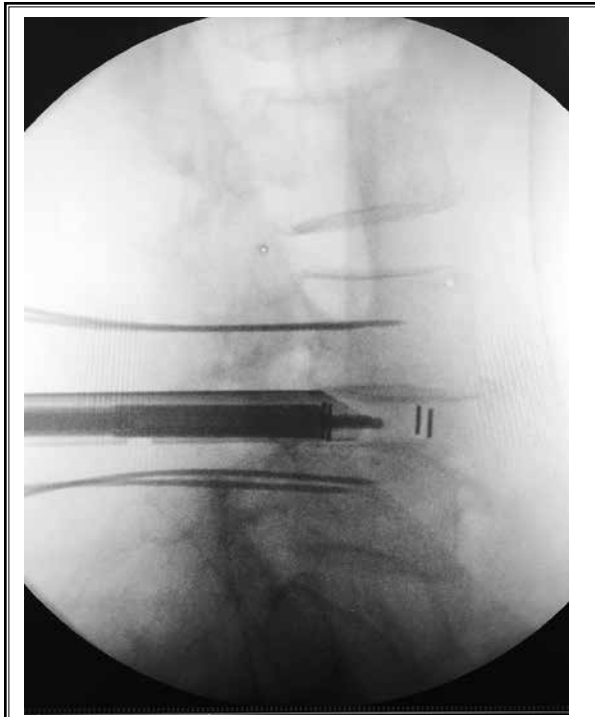


Fig 8. The contralateral and anterior disc spaces were packed with a morselized bone graft, and a narrow-surface PEEK cage with appropriate size was inserted.

The TiRobot device has a robotic arm combined with an intraoperative 3D navigation system. After preoperative planning of the desired screw trajectories, the surgeon manually drills holes and inserts the screws (32). Han reported the use of a total of 1116 pedicle screws in 234 patients, and the percentage of clinically acceptable screws was much higher in the robot-assisted group (98.7%) than in the freehand group (93.5%). Less surgeon's radiation exposure and also mean deviation was reported in the screws with robot-assisted technique. Osman reported that in 1 patient (1.6%), medial penetration of an S1 screw occurred with S1 nerve root irritation (37), and this complication required revision during the same period of hospital admission. According to our results, PPS insertion with robot guidance is a safe technique with minor complications. In this study, there was only 1 (0.9%) case of grade 1 PPS in group A, which was much better than the number of occurrences in group B (6.5%).

Moreover, fluoroscopic guidance is required in endoscopic TLIF. Excessive radiation exposure may increase the risk of health problems for the patients and the surgical team (38). When TiRobot guidance is used,

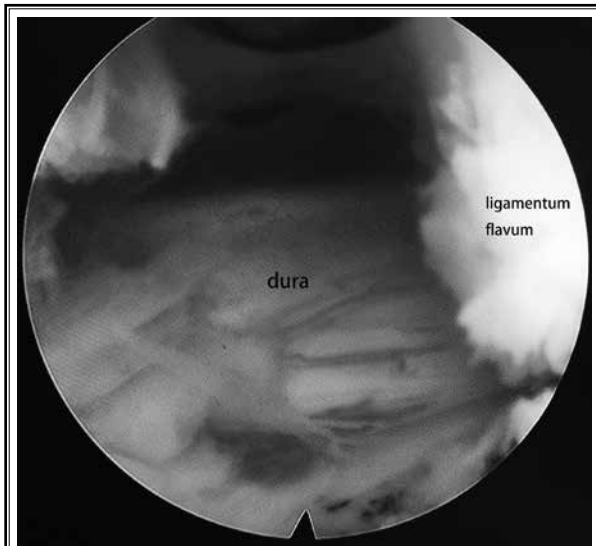


Fig 9. After the interbody fusion procedure, the nerve retractor was replaced again by a working tube, and then the interlaminal part of the hypertrophic ligamentum flavum was removed for decompression.

it can also help determine the optimal incision starting target point for facetectomy and interbody fusion procedures.

The Clinical Results of PE RA-TLIF

The safety and efficiency of PE-TLIF have improved considerably (6). Compared with open TLIF, fully endoscopic posterior interbody fusion is associated with less blood loss, shorter hospital stays, and fewer complications. The radiation exposure was 100 turns of C-arm guidance for each patient. In this case study, the incision length, estimated blood loss (EBL), and 1-day and 3-day incision pain were better in the PE RA-TLIF group than in the MIS-TLIF group. No incisions or interbody infections, existing and traversing nerve root injuries, dural injuries, or cerebrospinal fluid leaks were observed in the PE RA-TLIF group. There were also no cases of pedicle screw or rod breakage or cage migration during the follow-up.

The Complications of PE-TLIF and Modification of the Technique in this Study

The PE-TLIF-related complication rate ranges from 0-38.6%. In this study, no cases of dura tears, CSF leakage, infections, instrumentation-related complications, or neurologic injuries occurred in groups A or B. To avoid PE-TLIF-related complications, a few methods were used in this study.

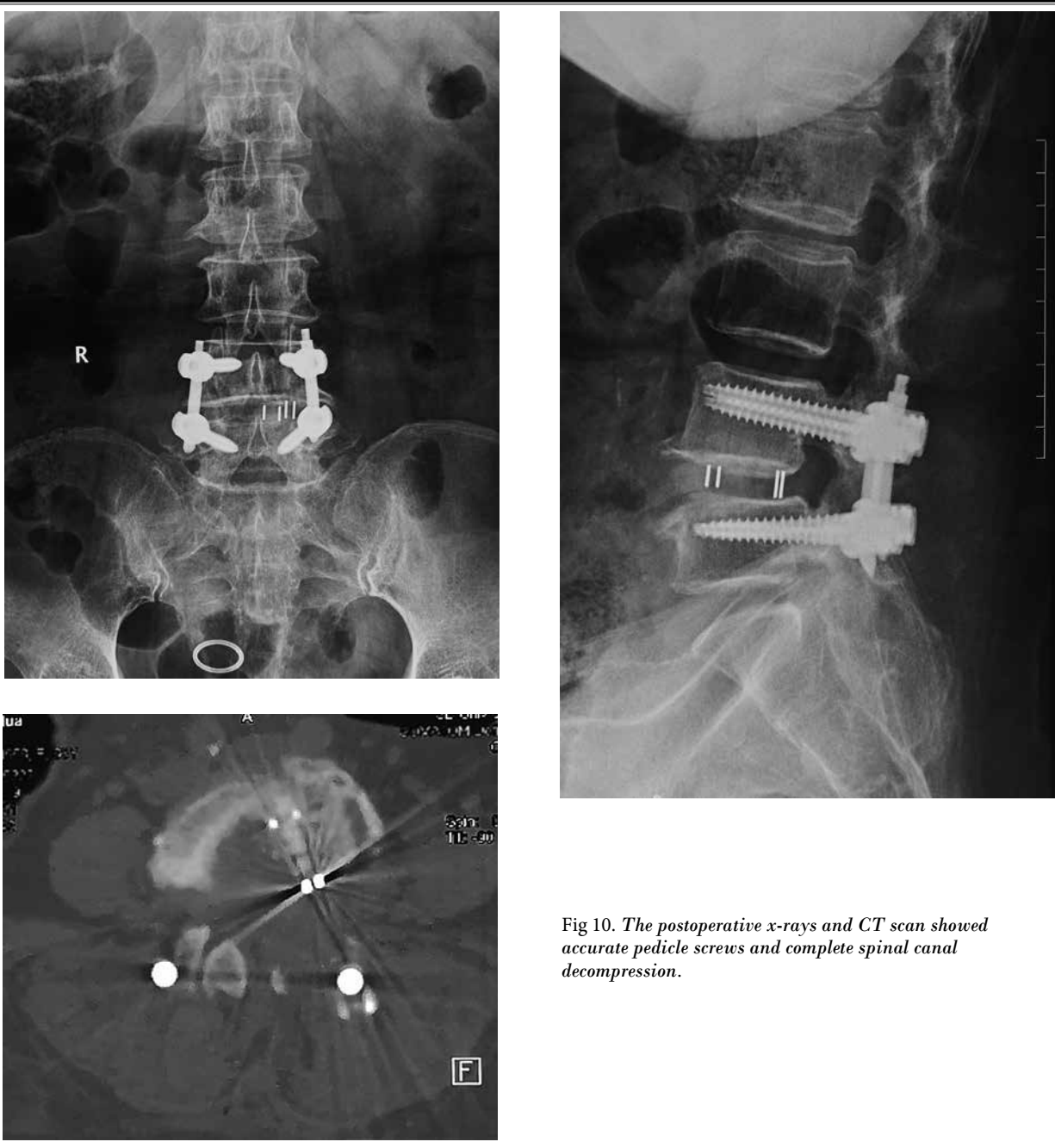


Fig 10. The postoperative x-rays and CT scan showed accurate pedicle screws and complete spinal canal decompression.

1. The Safety of PE-TLIF with General Anesthesia

In this study, general anesthesia was used. The main advantage of general anesthesia is significantly improved pain control; however, there are a few precautions that should be taken for surgical safety during the PE-TLIF procedure as in this study. First, the whole procedure was performed under direct endoscopic view,

neuromonitoring, and temporary preservation of the interlaminar part of the ligamentum flavum for dura and nerve root protection in the interbody fusion procedure. Second, the nerve retractor was inserted before the interbody fusion procedure to protect the exiting and traversing nerve roots. Third, facetectomy and spinal canal decompression were mainly performed using

the visual trepan, which significantly improved patient safety compared with the routine endoscopic trepan.

2. The Modification and Safety of Surgical Procedures

1) Working triangle and the safe zone for PE-TLIF.

Hardenbrook (39) measured the dimensions of the working triangle and the safe zone. The working triangle is the triangle located between the exiting and traversing nerve roots above the superior margin of the inferior pedicle. The safe zone is the trapezoid bound by the widths of the superior and inferior pedicles between the exiting and traversing nerve roots. The mean surface area for the working triangle was 1.83 cm², and the mean surface area of the safe zone was 1.19 cm². Moreover, at the medial border of the pedicle extending superiorly, there were no nerve structures within 1.19 cm at any level. By utilizing the superior border of the pedicle, the disc space can be accessed within this safe zone. In this study, the surgeons planned the initial position of the endoscope for facetectomy, and the robot then steered toward the skin entry point for facetectomy. According to Hardenbrook's study (39), there was enough working space for the facetectomy procedure with an 8 mm endoscope which was used to remove the facet and unilateral lamina gradually in the safe zone to expose the L4/5 disc under endoscopic view, leaving the interlaminar part of the ligamentum flavum temporary untouched to protect the dura and traversing nerve root. The interlaminar part of the ligamentum flavum was removed for decompression after the interbody fusion procedure was performed.

2) Temporary ligamentum flavum preservation to facilitate the protection of the nerve root and dura.

Different from the literature, the interbody fusion procedure was performed before the decompression procedure (laminectomy, removal of the interlaminar part of the ligamentum flavum, etc.) in this study. The advantage of this modification is that the interlaminar part of the ligamentum flavum can serve as a natural barrier to protect the traversing nerve root and dura and effectively avoid or reduce the risk of the traversing nerve root and dura injuries during the interbody fusion procedure. During the interbody fusion, after facetectomy and removal of the ligamentum flavum in the foraminal zone, there is enough space for interbody fusion while leaving the interlaminar part untouched, which can effectively protect the travers-

Table 2. Comparison of clinical outcomes between PE RA-TLIF and MIS-TLIF ($x \pm s$).

| | PE-TLIF (group A) | MIS-TLIF (group B) | P value |
|---|----------------------|-----------------------|-----------|
| Preoperative data | | | |
| JOA score | 14.2 ± 1.7 | 13.8 ± 2.0 | P = 0.49 |
| VAS of LBP | 6.7 ± 2.4 | 7.1 ± 1.5 | P = 0.10 |
| VAS of Leg pain | 5.4 ± 1.1 | 5.6 ± 0.7 | P = 0.82 |
| VAS of Leg numbness | 6.9 ± 1.4 | 6.6 ± 0.3 | P = 0.53 |
| ODI | 79 ± 19 | 81 ± 11 | P = 0.21 |
| Incision Length for decompression and fusion (cm) | 1.4 ± 0.3 | 2.5 ± 0.9 | P = 0.01* |
| Operative time (min) | 208 ± 15.2 | 161 ± 7.9 | P = 0.02* |
| Estimate blood loss (ml) | 25 ± 10 | 100 ± 20 | P = 0.01* |
| VAS of Incision pain | | | |
| Postoperative day 1 | 1.1 ± 0.5 | 2.1 ± 0.3 | P = 0.01* |
| Postoperative day 3 | 0.3 ± 0.2 | 1.3 ± 0.6 | P = 0.04* |
| Misplacement rate of PPS | 0.9% | 6.3% | P = 0.00* |
| 2 year Follow-up | | | |
| JOA score | 25.1±1.4 | 24.5±2.1 | P = 0.60 |
| JOA recovery rate (%) | 67.6±5.1 | 64.0±1.9 | P = 0.11 |
| VAS of LBP | 1.3±0.4 | 2.1±0.1 | P = 0.04* |
| VAS of Leg pain | 1.1±0.5 | 1.3±0.3 | P = 0.41 |
| VAS of Leg numbness | 1.8±0.5 | 1.5±0.3 | P = 0.41 |
| ODI | 17±5 | 21±8 | P = 0.09 |
| Interbody fusion rate (%) | 87.3 | 91.8 | P = 0.53 |

JOA, the Japanese Orthopaedic Association; VAS, visual analog scale; ODI, the Oswestry Disability Index.

ing nerve root and dura. After an interbody fusion was done, the interlaminar part of ligamentum flavum was finally removed for complete spinal canal decompression. In this study, no existing and traversing nerve root injuries, dural injuries, or cerebrospinal fluid leaks were found in the PE RA-TLIF group.

3) Special channel designed for an interbody fusion procedure.

The channel used for interbody fusion was a 3/4 rectangular shape, and it also served as a nerve retractor to protect the dura and exiting and traversing nerve roots. The length, height, and width of the channel was 137 mm, 11 mm, and 9 mm, respectively. According to Hardenbrook's study (39), the channel we used can be safely inserted into the interbody space through the safe

zone surface area. The design of the channel can also protect the exiting and traversing nerve root and dura effectively during interbody fusion procedure. In this study, no exiting and traversing nerve root injuries, dural injuries, or cerebrospinal fluid leaks related to the channel insertion were observed in the PE RA-TLIF group.

The width of the interbody cage used in this study was 8 mm, which was sufficient for cage insertion through the channel. As the channel was a 3/4 rectangle shape, the height of the chosen cage was not limited by the retractor. He et al (15) reported that the application of a narrow-surface fusion cage in endoscopic MIS-TLIF for the treatment of lumbar degenerative disease is feasible and effective. In this study, we used the same type of cage. Consistent with He's results, our follow-up results showed that the interbody fusion rate in group A was similar to that in group B (Fig. 11).



Fig 11. The 2-year follow-up CT scan showed satisfactory interbody fusion.

The Limitations of the PE-TLIF Technique and this Study

There are a few limitations of this technique and the study. First, PE RA-TLIF is still a new and complex procedure with limited indications. In this study, only Meyerding grade I L4-5 spondylolisthesis or spinal stenosis with instability was treated by PE-TLIF. The patients had unilateral symptoms only, without severe central spinal stenosis. Second, the PE-TLIF procedure is technically challenging and has a steep learning curve. In this study, the operation time of the first 10 cases was much higher than that of the remaining 16 cases. The surgeons should choose relatively easier cases, such as cases of lumbar instability without obvious spinal stenosis or positive nerve root sedimentation sign (the sedimentation of lumbar nerve roots to the dorsal part of the dural sac on supine MRI scans), for the initial cases. Moreover, the subjects in each group appeared to have similar characteristics; there could be selection bias involved. Therefore, further research for the clinical efficacy of robot-assisted PE-TLIF on severe cases of LBP symptoms is needed.

CONCLUSION

We compared the clinical outcomes of robot-assisted PE-TLIF with MIS-TLIF for the treatment of L4-5 spondylolisthesis, and PE RA-TLIF was associated with lower operation time, VAS of incision pain and LBP, and misplacement rate of PPS. Our results suggested that PE RA-TLIF is a safe and effective procedure that can significantly improve the accuracy of pedicle screw placement, reduce surgical trauma, and facilitate rapid postoperative recovery. However, this technique has a steep and long learning curve and requires long-term follow-ups so that the clinical results can be compared with those of traditional MIS TLIF.

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