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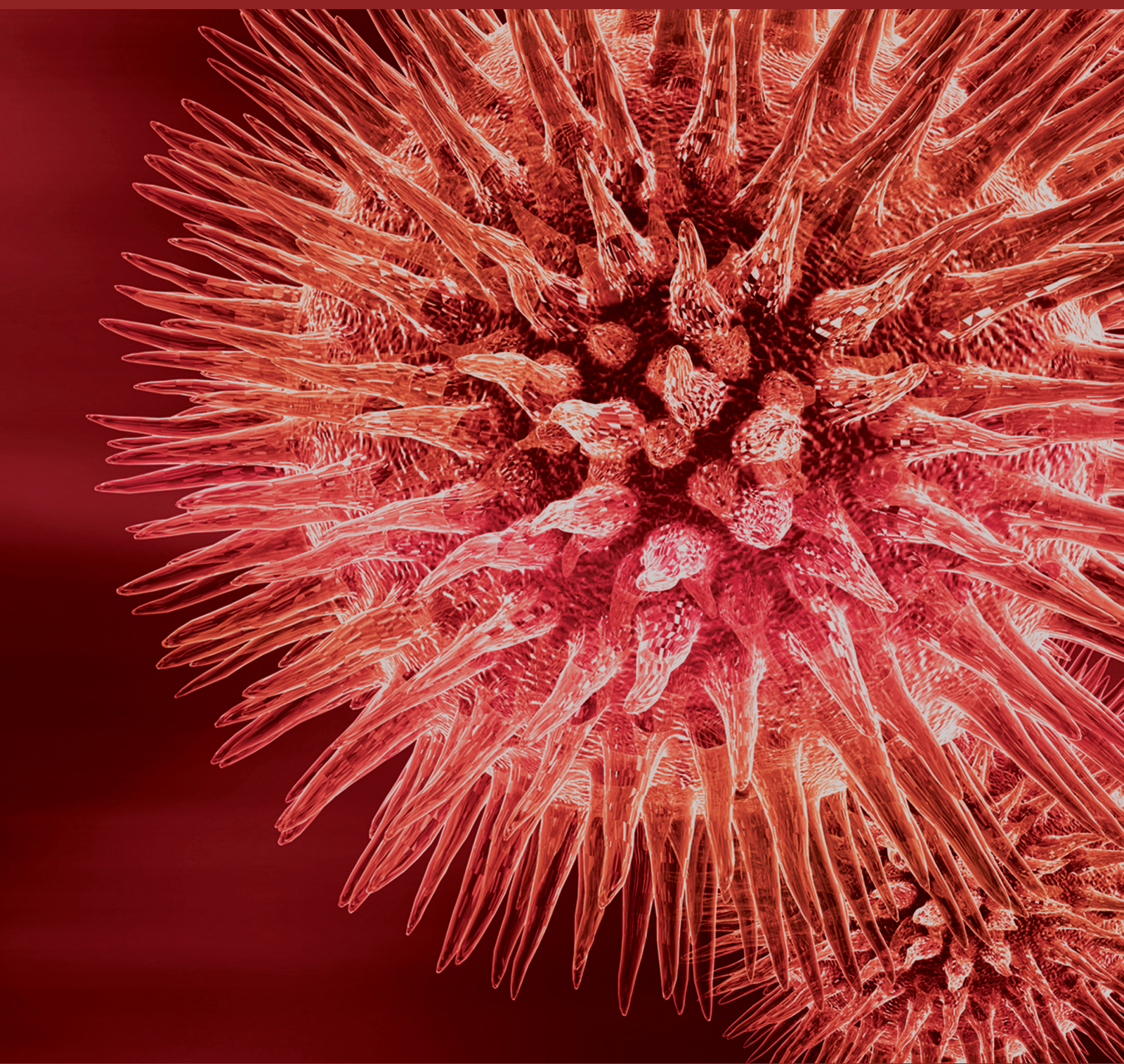
Minimally Invasive Spinal Surgery

Guest Editors: Jin-Sung Kim, Roger Härtl, and H. Michael Mayer



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Editorial
Minimally Invasive Spinal Surgery

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Minimally invasive approaches in spinal surgery are gaining popularity with some evidence in the literature supporting their value.

Significant progress in Minimally Invasive Spinal Surgery (MISS) has been seen in endoscopic spine surgery, minimally invasive fusion, and image-guided spinal surgery. It decreases the incidence of complications and approach-related morbidity and mortality associated with conventional open surgery.

Not only can MISS minimize injury to paraspinal back muscles, connective tissues, and joints but it can also decrease the amount of bleeding, infection, postoperative pain, and hospital stay.

Hence, there has been widespread adoption of MISS techniques, which can be beneficial for various kinds of spinal diseases. In this special issue on Minimally Invasive Spinal Surgery, we have selected high quality papers that highlight several of the benefits of MISS.

With the 7 papers in this issue we cover many of the challenging areas in MISS; three are dealing with image-guided spinal surgery, three are about minimally invasive lumbar interbody fusion including minimally invasive instrumentation for thoracolumbar fractures, one is on a minimally invasive decompressive technique, one is modified technique of laminoplasty, and one is about the novel use of an ultrasonic bone shaver in spine surgery.

H.-S. Kim and D.-H. Heo applied MISS for thoracolumbar fracture associated with Kummell's osteonecrosis and reported advantages of short segment percutaneous pedicle screw fixation with polymethylmethacrylate augmentation.

K.-T. Yeh et al. performed modified expansive open-door laminoplasty (MEOLP) for patients with multilevel cervical spondylotic myelopathy. They concluded that the MEOLP method was found to provide satisfactory medium-term results by preserving muscles and the nuchal ligament attached to the C7 spinous processes, minimizing injury of paraspinal extensor musculature, reducing facet joint violation, and ensuring adequate lamina.

H. M. Mayer and F. Heider also employed minimally invasive Slalom (microsurgical crossover) decompression for multilevel degenerative lumbar stenosis. They reported that minimally invasive decompressive surgery reduces intraoperative blood loss, soft tissue trauma, operative time, infection rates, and hospital stay.

P. Stavrinou et al. retrospectively reviewed 10 patients who underwent transtubular extraforaminal decompression of the L5 nerve root at the lumbosacral junction with navigation. They concluded that navigation is of particular advantage in cases of foraminal stenosis where it allows optimizing the approach angle and amount of bony resection required for successful decompression.

P. Nunley et al. reported neurological complications after lateral transpsoas approach to anterior interbody fusion with a novel flat blade spine-fixed retractor. Using a new retractor system, they observed an 11.1% neurologic complication rate in lateral lumbar interbody fusion procedures. There was resolution of symptoms for most patients by 12-month follow-up, with only 2% of patients with residual symptoms.

T. Kim et al. reported the excellent clinical outcome of intraoperative image-guided navigation. They emphasized

that spinal surgery based on O-arm navigation favors it as a good option for spinal instrumentation.

D. B. Hazer et al. reported technical tips of the application of ultrasonic bone shaver in spine surgery experience in 307 patients.

This special issue on Minimally Invasive Spinal Surgery provides valuable information including surgical "tips and pearls" on emerging MIS surgical techniques. Even though all articles were accepted after rigorous blinded reviews by experts in minimally invasive spinal surgical fields, we realize that the level of scientific evidence may be low in some areas. Therefore, we cordially invite the readers to read each article with an open and critical mind.

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Clinical Study

Percutaneous Pedicle Screw Fixation with Polymethylmethacrylate Augmentation for the Treatment of Thoracolumbar Intravertebral Pseudoarthrosis Associated with Kummell's Osteonecrosis

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Purpose. The purpose of our study is to evaluate the therapeutic efficacy of short-segment percutaneous pedicle screw fixation with polymethylmethacrylate (PMMA) augmentation for the treatment of osteoporotic thoracolumbar compression fracture with osteonecrosis. *Methods*. Osteoporotic thoracolumbar compression fractures with avascular necrosis were treated by short-segment PPF with PMMA augmentation. Eighteen were followed up for more than 2 years. The kyphotic angle, compression ratio, visual analog scale (VAS) score for back pain, and the Oswestry Disability Index (ODI) were analyzed. In addition, radiologic and clinical parameters of PPF group were compared with percutaneous vertebroplasty (PVP) group. *Results*. Vertebral height and kyphotic angle of the compressed vertebral bodies were significantly corrected after the operation ($P < 0.05$). Further, restored vertebral height was maintained during the 2 or more years of postoperative follow-up. Compared to the PVP group the postoperative compression ratio and kyphotic angle were significantly lower in the PPF group ($P < 0.05$). The postoperative ODI and VAS of the PVP group were significantly higher than the PPF ($P < 0.05$). *Conclusions*. According to our results, short-segment PPF with PMMA augmentation may be an effective minimally invasive treatment for osteoporosis in cases of osteoporotic vertebral compression fractures with Kummell's osteonecrosis.

1. Introduction

Occasionally, noninfected avascular osteonecrosis is detected in osteoporotic vertebral body compression fractures. Intravertebral avascular osteonecrosis presented fluid collection or the presence of conjunction with air cleft in compressed vertebral body. A necrotic cavity can develop intravertebral pseudoarthrosis and result in spinal instability. Percutaneous vertebroplasty or kyphoplasty using polymethylmethacrylate (PMMA) has been attempted to treat compression fractures with avascular necrosis [1–6]. Several studies have reported that vertebroplasty to treat an osteoporotic vertebral compression fracture with osteonecrosis is highly effective [1–5]. However, these studies reported short-term clinical and radiological results within 12 months. Long-term clinical and radiologic results of percutaneous vertebroplasty or kyphoplasty were poor [6, 7]. Percutaneous vertebroplasty may not be supportive enough for the long-term stabilization effect. Spinal fusion operations have been performed in Kummell's osteonecrosis; however, extensive fusion operations have morbidities and complications associated with surgical procedures and long surgical time. In our study, we have tried to perform short-segment pedicle screw fixation with PMMA augmentation after postural reduction. The purpose of this study was to assess, for at least 2 years, the radiologic and clinical outcomes of patients who underwent short-segment pedicle screw fixation with PMMA augmentation to treat osteoporotic vertebral compression fractures with intravertebral pseudoarthrosis comparing to patients who were treated by percutaneous vertebroplasty.

2. Materials and Methods

The current study was designed as a retrospective review of clinical and radiologic parameters. From October 2010 to March 2013, 21 patients who had osteoporotic compression fractures with avascular osteonecrosis were treated by short-segment percutaneous pedicle screw fixation (PPF) with PMMA augmentation in two hospitals in which the authors were affiliated. And 45 patients were treated by percutaneous vertebroplasty (PVP). We only included 49 patients who had a single-level osteoporotic vertebral compression fracture with avascular osteonecrosis and were able to be followed for more than 24 months.

Before the operation, we took dynamic X-ray films, measured bone mineral density, and performed magnetic resonance imaging (MRI) and computed tomography (CT) to define acute osteoporotic compression fractures with avascular osteonecrosis and intravertebral air cleft in all the patients. Intravertebral pseudoarthrosis or instability associated with Kummell's osteonecrosis was identified with dynamic X-ray: anterior vertebral height and kyphotic angulation are changed on lateral flexion and extension views. Vertebral plana and irreducible collapsed vertebrae with a small portion of the vacuum cleft were excluded. Also, we excluded the patients who had clinical histories of bone metabolic disorders, primary bone tumors, or malignancies including metastasis.

18 patients who were treated by PPF were assigned to "PPF group" and 31 patients who were treated by PVP were assigned to "PVP group."

We performed this investigation in accordance with our institutional guidelines, which comply with international laws and policies (∗∗∗∗ Hospital Institutional Review Board, #2014-03).

2.1. Surgical Procedures of Short-Segment Fixation with Augmentation [8]. First, all enrolled patients had received conservative management such as bed rest, analgesics, and brace wearing for at least 2 weeks after diagnosis of Kummell's osteonecrosis. Despite conservative management, patients presented intractable pain or progression of vertebral body compression and we planned surgical treatments. All the patients received postural reduction 24 hours before the operation. All surgical procedures were performed in the prone position under epidural or endotracheal anesthesia. PMMA was injected bilaterally via transpedicular trajectory just before insertion of the percutaneous pedicle screw under C-arm fluoroscopic guidance. Percutaneous pedicle screw insertion and PMMA augmentation was performed on the fractured vertebral body as well as 1 level above and below (Figure 1). If the patient had an L2 compression fracture with osteonecrosis, we inserted PMMA and percutaneous pedicle screws at L1, L2, and L3. Finally, two percutaneous rods and screw caps were applied. We did not perform additional posterolateral fusion procedures such as an autologous iliac bone graft or an allofusion material graft. If patients had neurologic deficit symptoms with thecal sac compression by retropulsed bony fragments and acute multilevel compression fractures, we did not perform these operative treatments.

2.2. Analysis of Clinical Parameters. We retrospectively reviewed the preoperative clinical parameters such as age, gender, bone mineral density, visual analog scale (VAS) score for back pain, and the Oswestry Disability Index (ODI). We checked the VAS score of back and ODI preoperatively and postoperatively at 7 days, 12 months, and 24 months or more (the final follow-up period). We compared the preoperative VAS scores and ODI with the immediate postoperative scores and also compared the immediate postoperative VAS scores and ODI with the VAS score and ODI at 12 months after the operation and at the final follow-up period after operations. We also reviewed operation time, bleeding amount, and complication related to anesthesia and operation procedures.

2.3. Analysis of Radiological Parameters. The presence of avascular osteonecrosis in the vertebral body was defined as the collection of intravertebral fluid or the presence of conjunction with air, as seen via MRI and CT scan. A CT scan finding of intravertebral vacuum phenomenon was defined as an area of air density in the fractured vertebral body. We reviewed radiological parameters, such as the compression ratio and kyphotic angle.

We reviewed serial follow-up plain radiographs immediately after the operation and postoperatively at 12 months and approximately 24 months (the final follow-up period). The anterior and posterior heights of the fractured vertebral body with avascular osteonecrosis were assessed in order to calculate the compression ratio (anterior/posterior height; AP ratio) before and after the operation. The kyphotic angle was measured using an angle between the lower endplate of the upper vertebral body and the lower endplate of the affected vertebral body.

The degree of compression progression of the cemented compressed vertebral bodies, which are the compression ratio and kyphotic angle difference between the immediate postoperative measurement and the final follow-up period measurements, was calculated for all of the patients. We compared each of the compression ratio and kyphotic differences. We also performed CT or MRI for the evaluation of bone healing in the fractured vertebral bodies during the final follow-up period.

2.4. Comparative Analysis with Percutaneous Vertebroplasty Group. Forty-five patients received percutaneous vertebroplasty with PMMA for the treatment of osteoporotic compression fracture with osteonecrosis. Among them, thirty-one patients were followed for more than 2 years. We compared radiological parameters such as kyphotic angle and compression ratio of PPF group with PVP group. We compared the mean differences in the compression ratios of the cemented vertebral bodies and mean kyphotic angles between the "PPF group" and the "PVP group."

Additionally, we compared clinical results such as ODI and VAS score of back of PPF group with PVP group.

2.5. Statistical Analysis. Statistical analysis was performed using the Mann-Whitney U test and the Wilcoxon rank sum test. The level of significance was set at 0.05. SPSS 12.0 for

Table 1: Characteristics of two groups.

Characteristics	PPF group	PVP group
Age (year)	69.5 ± 5.1	71.1 ± 3.9
Sex (M/F)	3/15	9/21
Bone mineral density (T-score)	−3.55 ± 0.59	−3.61 ± 0.57
Mean follow-up period (months)	24.8 ± 1.3	26.8 ± 2.1
Location of compression fracture	5 (T12); 9 (L1); 3 (L2); and 1 (L3)	3 (T11); 7 (T12); 15 (L1); 3 (L2); and 3 (L3)
Mean operation time	64.7 ± 15.4 minutes	
Volume of estimate blood loss	91.1 ± 15.4	
Complications related to operation	Screw fracture: 1 case Screw minor pulled out: 1 case	Severe recollapse of augmented vertebral body: 2 cases

Windows (SPSS, Chicago, IL, USA) was used for the statistical analysis.

3. Results

The mean age of PPF group was 69.5 ± 5.1 years (15 females and 3 males). The mean follow-up period was 24.8 ± 1.3 months (24–27 months). The treated levels were distributed from T12 to L3 with five in T12, nine in L1, three in L2, and one in L3. The mean T-score of the bone mineral density was −3.55 ± 0.59. The mean volume of estimated blood loss was 91.1 ± 27.6 mL, and the mean operation time was 64.7 ± 15.4 minutes (Table 1). The mean age of PVP group was 71.1 ± 3.9 (21 females and 9 males). The treated levels were distributed from T11 to L3. There were no differences between PPF group and PVP group (Table 1).

3.1. Compression Ratio and Kyphotic Angle Changes after Short-Segment Fixation with Augmentation. The vertebral height and kyphotic angle of the compressed vertebral bodies were significantly corrected from 0.35 ± 0.12 to 0.72 ± 0.08 and from 15.56 ± 3.69° to 7.90 ± 2.65° after operation in PPF group ($P < 0.05$). Although restored vertebral height was slightly decreased 1 year after the operation the compression ratio and kyphotic angle were well-maintained during the approximately 2 years of postoperative follow-up. The immediate postoperative mean compression ratio was 0.72 ± 0.08 and slightly decreased to 0.69 ± 0.07 at 1-year follow-up and 0.68 ± 0.07 at the 2-year follow-up (Figure 2(a)). The immediate postoperative mean kyphotic angle was 7.90 ± 2.65° and slightly increased to 9.28 ± 2.53° at the 1-year follow-up and 9.56 ± 2.64 at the 2-year follow-up (Figure 2(b)).

Bone healing of the compression fracture with osteonecrosis area was detected on finally followed CT or MRI images in all enrolled patients. Intravertebral fluid signal of MRI or intravertebral air density (vacuum phenomenon) of CT has completely disappeared (Figure 1(f)).

3.2. Comparative Analysis with Percutaneous Vertebroplasty Group. There were 31 patients in the vertebroplasty group and 18 patients in pedicle screw group. The mean difference between the compression ratios taken immediately postoperative and during the final follow-up period was 0.04 ± 0.03 in PPF group and 0.18 ± 0.08 in the PVP group.

Table 2: Comparison of mean difference in compression ratio and kyphotic angle.

	PPF group	PVP group
Number of patients	18	31
The mean difference of AP ratio*	0.04 ± 0.03	0.18 ± 0.08
The mean difference of kyphotic angle*	1.65 ± 1.22	6.06 ± 3.38
VAS at postoperative 24 months*	2.67 ± 1.03	3.71 ± 1.27
ODI at postoperative 24 months*	28.00 ± 5.47	37.77 ± 11.49

*$P < 0.05$.

The mean difference in compression ratios of the PVP group was significantly higher than that of the PPF group ($P < 0.05$, Table 2). The mean difference in measurements of the kyphotic angle taken immediately postoperative and during the final follow-up period was 1.65 ± 1.22° in the PPF group and 6.06 ± 3.38° in the PVP group. The mean difference of the kyphotic angle of the PVP group was significantly higher than that of PPF group ($P < 0.05$, Table 2). The postoperative compression ratio of the PPF group was significantly higher than the PVP group, and the kyphotic angle of the PPF group was significantly lower than PVP group (Figures 2(a) and 2(b)).

Preoperative ODI and VAS score were not significantly different in both groups. The mean preoperative VAS score was 9.00 ± 0.84 and 7 days post operation it was 3.11 ± 1.37, indicating that the mean VAS score decreased significantly after the initial operation ($P < 0.05$) in PPF group. VAS scores measured during the postoperative follow-up showed that the mean VAS scores were 2.17 ± 0.86 at 12-month follow-up and 2.67 ± 1.03 at the final follow-up appointment (Figure 3(a)) in PPF group. The mean ODI was 78.28 ± 3.85 preoperatively, 30.89 ± 5.87 at 1 day after the operation, 26.17 ± 6.53 at 12-month follow-up, and 28.00 ± 5.48 at the final follow-up appointment in PPF group. The mean ODI significantly decreased after the operation ($P < 0.05$, Figure 3(b)).

In PVP group, the mean preoperative VAS score was 8.90 ± 0.83 and 7 days after operation it was 2.06 ± 0.85, indicating that the mean VAS score decreased significantly after the initial operation ($P < 0.05$). Preoperative mean ODI was significantly decreased from 77.90 ± 1.83 to 29.19 ± 4.17 at 7 days after the operation in PVP group ($P < 0.05$, Figure 3(b)). The mean VAS score was increased from 2.06 ± 0.85 to 3.71 ± 1.27 at the final follow-up appointment in PVP

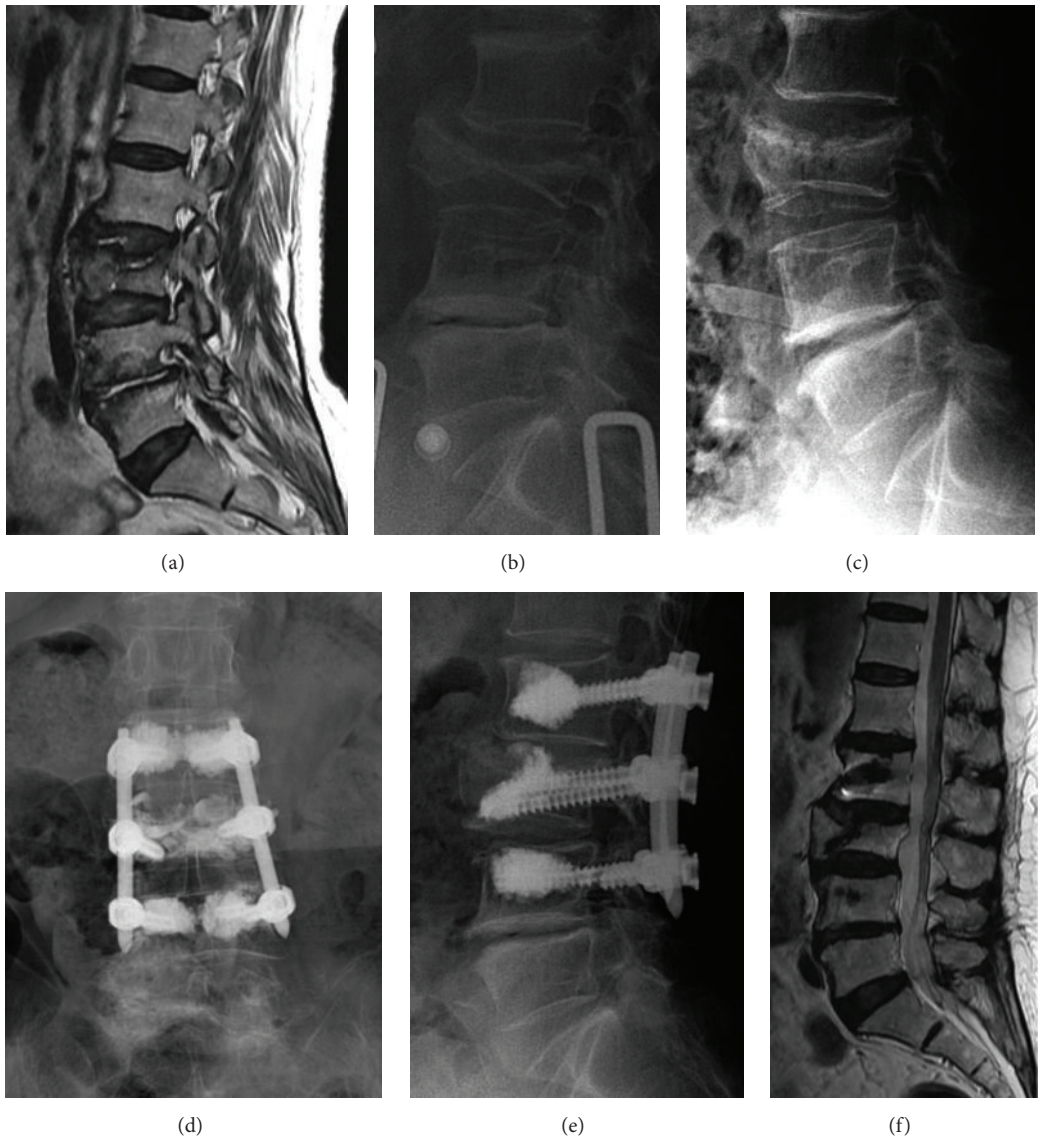

Figure 1: Preoperative MRI and X-ray show a L3 compression fracture with osteonecrosis ((a) and (b)). The compressed L3 body was reexpanded after postural reduction (c). The compressed vertebral body with osteonecrosis was well healed and still restored in spite of left L4 pedicle screw fracture at the 24-month follow-up ((d), (e), and (f)).

group. And the mean ODI was increased from 29.19 ± 4.17 to 37.77 ± 11.06 at the final follow-up appointment in PVP group. The postoperative ODI and VAS scores of the PVP were significantly higher than the PPF group at the final follow-up period (Figures 3(a) and 3(b), Table 2).

3.3. Comparative Analysis with Percutaneous Vertebroplasty Group. There were 31 patients in the vertebroplasty group and 18 patients in pedicle screw group. The mean difference between the compression ratios taken immediately after operation and during the final follow-up period was 0.04 ± 0.03 in PPF group and 0.18 ± 0.08 in the PVP group. The mean difference in compression ratios of the PVP group was significantly higher than that of the PPF group ($P < 0.05$, Table 2). The mean difference in measurements of the kyphotic angle taken immediately after operation and during the final follow-up period was 1.65 ± 1.22° in the PPF group and 6.06 ± 3.38° in the PVP group. The mean difference of the kyphotic angle of the PVP group was significantly higher than that of PPF group ($P < 0.05$, Table 2). The postoperative compression ratio of the PPF group was significantly higher than the PVP group, and the kyphotic angle of the PPF group was significantly lower than PVP group (Figures 2(a) and 2(b)).

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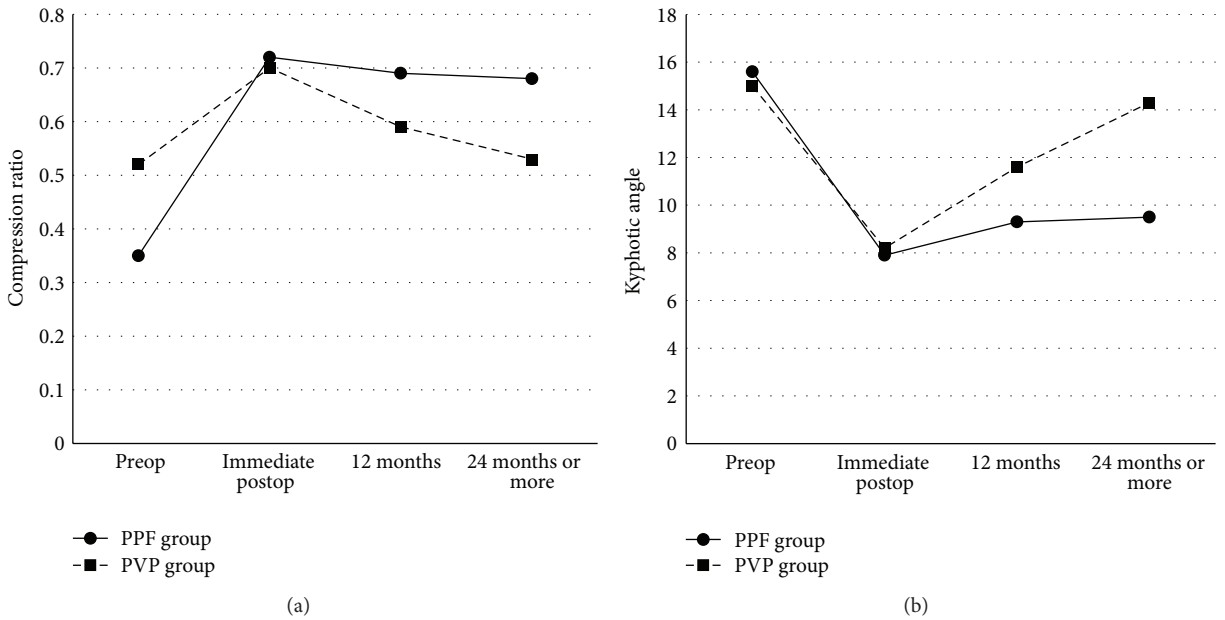

Figure 2: Serial changes in the compression ratio (a) and kyphotic angle (b). The PPF group maintained height of the compressed vertebral bodies after the operation compared to the PVP group.

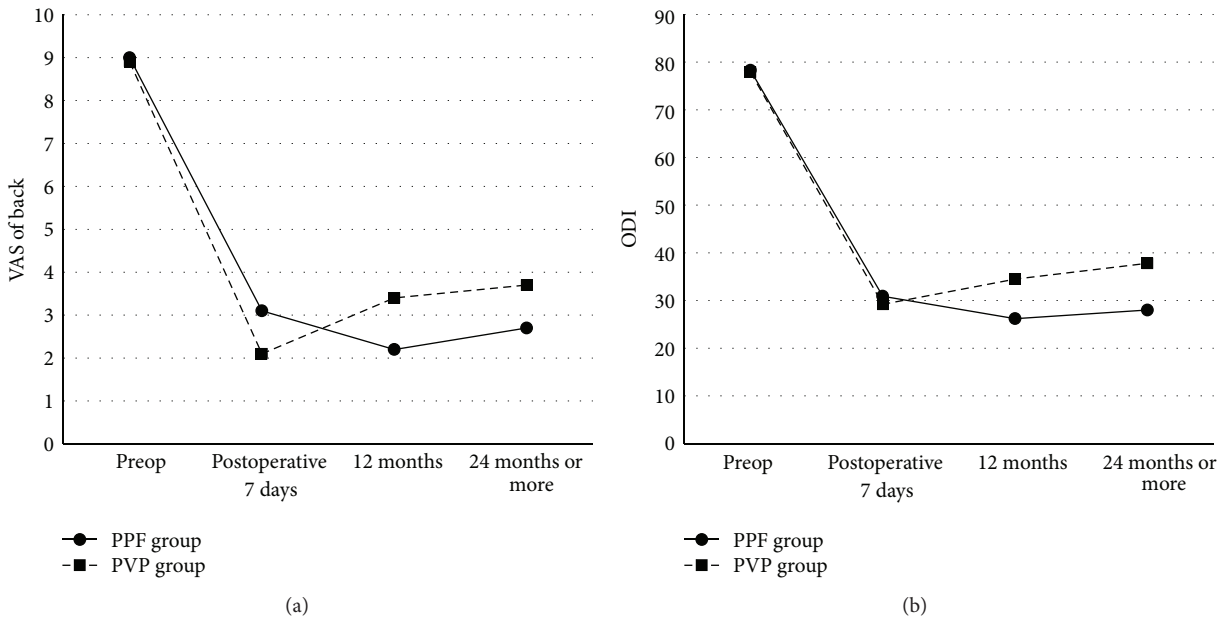

Figure 3: Serial changes in VAS (a) and the ODI (b). The ODI and VAS score of the PVP group are significantly higher than the PPF group at the final follow-up appointment (postoperative 24 months or more).

follow-up and 2.67 ± 1.03 at the final follow-up appointment (Figure 3(a)) in PPF group. The mean ODI was 78.28 ± 3.85 preoperatively, 30.89 ± 5.87 at 1 day after the operation, 26.17 ± 6.53 at 12-month follow-up, and 28.00 ± 5.48 at the final follow-up appointment in PPF group. The mean ODI significantly decreased after the operation ($P < 0.05$, Figure 3(b)).

In PVP group, the mean preoperative VAS score was 8.90 ± 0.83 and 7 days after operation it was 2.06 ± 0.85, indicating that the mean VAS score decreased significantly after the initial operation ($P < 0.05$). Preoperative mean ODI was significantly decreased from 77.90 ± 1.83 to 29.19 ± 4.17 at 7 days after the operation in PVP group ($P < 0.05$, Figure 3(b)). The mean VAS score was increased from 2.06 ± 0.85 to 3.71 ± 1.27 at the final follow-up appointment in PVP group. And the mean ODI was increased from 29.19 ± 4.17 to 37.77 ± 11.06 at the final follow-up appointment in PVP group. The postoperative ODI and VAS

scores of the PVP were significantly higher than the PPF group at the final follow-up period (Figures 3(a) and 3(b), Table 2).

In vertebroplasty group, two patients required aggressive decompression and fusion surgery due to recollapsed vertebral body and compression of the thecal sac. Two patients presented weakness in both legs. We performed anterior corpectomy for the recollapsed vertebral body and posterior pedicle screw fixation.

3.4. Complications Related Anesthesia and Operation. Postoperative atelectasis developed in 2 patients in the PPF group. Atelectasis was subclinical and improved immediately after ambulation. A screw fracture occurred in one patient; however, recollapse of the vertebral body did not develop, and healing of osteonecrosis was detected at the final follow-up MRI (Figure 2). In one patient, lower end pedicle screws were slightly pulled out 3 months after the operation. However, instrument failure was not aggravated until the final follow-up period. Minor stich abscess developed in one case. A new remote new vertebral compression fracture occurred in one patient. We did not experience any adjacent vertebral compression fractures or deep wound infections.

Severe recollapse of augmented vertebral bodies and spinal canal encroachment by bony fragment occurred in two patients of PVP group. Two patients required aggressive decompression and fusion surgery due to recollapsed vertebral body and compression of the thecal sac. However, there was no patient who needs additional surgical treatments in PPF group.

4. Discussion

Natural course of vertebral compression fractures avascular osteonecrosis named as intravertebral air cleft or pseudoarthrosis may be poor [9]. The height of the compressed vertebral bodies decreases and kyphosis is aggravated. Also, intravertebral instability has still remained above 70% [9]. Untreated intravertebral pseudoarthrosis can induce kyphotic deformity and disability. Several previous studies have reported that vertebroplasty or kyphoplasty with PMMA cement may be effective for the treatment of vertebral compression fracture with avascular osteonecrosis. Augmentation procedures with PMMA can improve refractory back pain and restore height of the compressed vertebral body height [3, 5]. However, cement augmentation procedures appear to be favorable treatments for intervertebral pseudoarthrosis only during the immediate postoperative phase and within one year [1, 3–5, 10]. At the long-term follow-up period, augmented vertebral body had recollapsed, and kyphosis had aggravated [6, 7]. Also, back pain and the ODI were aggravated during the long-term follow-up period. A recollapsed augmented vertebral body can compress neural tissue and induce neurologic deficit [6].

PMMA cannot be replaced by new bone; therefore, a foreign body reaction may occur. Fibrotic wall formation around a PMMA mass may induce micromotion and future instability [11, 12]. Sometimes, a radiolucent line named as "halo phenomenon" develops around the PMMA solid mass [13]. These phenomena may induce recollapse of the cemented vertebral body [6]. The PMMA mass has also spontaneously migrated to extravertebral lesions such as disc space or anterior vertebral space [14, 15]. Therefore, we tried additional PPF after PMMA augmentations. Vertebroplasty may not provide enough strength and stability in cases of compressed vertebrae with avascular necrosis. The most patients with intravertebral pseudoarthrosis are at an advanced age and have poor bone quality and medical illness histories; therefore, extensive fusion surgeries are hard to perform due to the length of time under anesthesia and surgical morbidities. Percutaneous pedicle screw fixation with PMMA augmentation can be performed under epidural anesthesia and has a short operation time. Furthermore, intraoperative blood loss is small, and a transfusion was not required in any of our cases. Therefore, these procedures may be compatible with older patients. However, if patients had nonreducible vertebra plana or small necrotic cavity without intravertebral pseudoarthrosis, we treated them with conservative management or vertebroplasty.

Geriatric patients have a higher incidence of complications or morbidity related to general anesthesia due to significant medical illness history. General or epidural anesthesia cannot be performed in old patients with serious medical diseases. Consequently, we performed percutaneous vertebroplasty instead. We also recommended strict activity restriction and advised the patients to wear rigid spinal orthosis for a longer period after vertebroplasty. Recently, parathyroid hormone therapy was administered to patients with intravertebral osteonecrosis.

We did not experience any major complications related to hardware failure. A screw fracture and slightly pulled-out screw developed in only two patients. Fortunately, the two patients did not develop kyphosis or recollapse of the cemented vertebral bodies, and bone healing of osteonecrosis occurred.

We suggested that osteoporotic vertebral compression fractures with osteonecrosis are a different pathologic condition compared to fractures without osteonecrosis. Therefore, vertebroplasty is a relative contraindication for Kummell's osteonecrosis. However, if the compression ratio is high and the area of the osteonecrosis is narrow, vertebroplasty may be a good treatment option.

The present study had several limitations. Our study design was not a randomized case control study but a retrospective review. In addition, we did not have a control group that underwent conservative treatments. Therefore, the results of our study cannot be generalized to all osteoporotic compression fractures with osteonecrosis. Additionally, we were only able to follow a total of 18 patients. In order to better establish the clinical and radiologic outcomes of this procedure, more patients should be studied over an extended follow-up period. Randomized case control trials should also be evaluated.

5. Conclusions

According to our results, short-segment percutaneous PPF with PMMA augmentation may be an effective minimally invasive treatment for osteoporosis in cases of osteoporotic vertebral compression fractures with osteonecrosis, which manifests as an intravertebral vacuum phenomenon, pseudoarthrosis, or intravertebral fluid collection during the two years or longer of patient follow-up. A short operation time, less bleeding, and no morbidity related to bone graft were maybe merit point of our treatment. However, for a more exact evaluation of the clinical and radiologic outcomes of the operation, a longer follow-up period is needed.

Competing Interests

Hyeun-Sung Kim and Dong-Hwa Heo declare that they have no conflict of interests.

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Research Article

The Midterm Surgical Outcome of Modified Expansive Open-Door Laminoplasty

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Laminoplasty is a standard technique for treating patients with multilevel cervical spondylotic myelopathy. Modified expansive open-door laminoplasty (MEOLP) preserves the unilateral paraspinal musculature and nuchal ligament and prevents facet joint violation. The purpose of this study was to elucidate the midterm surgical outcomes of this less invasive technique. We retrospectively recruited 65 consecutive patients who underwent MEOLP at our institution in 2011 with at least 4 years of follow-up. Clinical conditions were evaluated by examining neck disability index, Japanese Orthopaedic Association (JOA), Nurick scale, and axial neck pain visual analog scale scores. Sagittal alignment of the cervical spine was assessed using serial lateral static and dynamic radiographs. Clinical and radiographic outcomes revealed significant recovery at the first postoperative year and still exhibited gradual improvement 1–4 years after surgery. The mean JOA recovery rate was 82.3% and 85% range of motion was observed at the final follow-up. None of the patients experienced aggravated or severe neck pain 1 year after surgery or showed complications of temporary C5 nerve palsy and lamina reclosure by the final follow-up. As a less invasive method for reducing surgical dissection by using various modifications, MEOLP yielded satisfactory midterm outcomes.

1. Introduction

Cervical laminoplasty is a safe and effective surgical method for treating multilevel cervical spondylotic myelopathy (MCSM) [1]. One of the most commonly used methods of laminoplasty is expansive open-door laminoplasty (EOLP) [2]. The approach, developed by Hirabayashi et al., involves fixing the opened laminae by using suture material [3]. This method was found to yield a high incidence of lamina reclosure [4]. O'Brien et al. in 1996 reported a method of applying maxillofacial miniplates and screws to provide primary resistance against lamina reclosure [5]. Between 2005 and 2011, we conducted EOLP secured by using titanium miniplates and screws for treating MCSM and observed favorable surgical results [6]. However, several predominant complications of this method were still noted; approximately 42% of the treated patients exhibited moderate to severe postoperative axial neck pain, 35% experienced a loss of range of motion (ROM), and 4.7% displayed C5 nerve palsy. To reduce the incidence rates of these complications, we developed a modified EOLP (MEOLP), which we have used since 2011 and evaluated in a retrospective study [7]. Through reducing surgical dissection by preserving the unilateral paraspinal musculature [8], preserving the C7 spinous process [9], and creating more medial gutter for reducing facet joint violation, the frequency of persistent postoperative axial neck pain and loss of ROM significantly decreased. The average length of surgical wounds after MEOLP was significantly smaller than that after conventional EOLP, and neurological outcomes for the methods were similar. Although the short-term surgical outcomes were encouraging, three major concerns remained for MEOLP at midterm follow-up. As a less invasive method,

whether it can maintain adequate neurological recovery, less postoperative axial neck pain, and sufficient preserved ROM in a longer follow-up period must be clarified. Thus, the purpose of this study was to elucidate midterm (4 years) clinical and radiological results of patients with MCSM treated by MEOLP.

2. Material and Methods

This was a retrospective cohort study. The protocol was approved by the institutional review board of Hualien Tzu Chi Hospital, Buddhist Tzu Chi Medical Foundation, and fully informed consent was obtained from all participants (IRB103-189-B). All the patients enrolled in this study were diagnosed as having MCSM without local kyphosis of more than 15°, an anterior major lesion, or segmental instability and underwent MEOLP at Hualien Tzu Chi Hospital between March and December in 2011. Those who had a history of disorders that may have affected the baseline Japanese Orthopaedic Association (JOA) score [10], such as cerebral disorders, rheumatoid arthritis, joint disorders, and urological disorders, were excluded. The surgical procedure was a modification of unilateral open-door laminoplasty secured by using miniplates [5], which has been fully described previously [7]. Through unilateral paraspinal muscle dissection and cutting of spinous process, the bilateral laminae were approached. C7 partial laminectomy was performed at first and the border of spinal cord was exposed. We then created the bilateral gutters based on the diameter of exposed spinal cord. The gutters were often less than 0.8 cm lateral to the spinous process and just lateral to the border of spinal cord without visional exposure of the facet joints. Then C3–C6 laminae were separately elevated and fixed with titanium miniplates and screws. After checking the spinal cord free from compression, we closed the wound to finish this procedure. For the first 3 months after surgery, the patients wore hard collars and performed adequate neck extension exercise. All of them were followed up for at least 4 years. The follow-up rate of these patients was 100%.

All patients underwent follow-up examinations every 3 months for the first year after surgery and once per year thereafter. We collected the demographic data of the patients, namely, age, sex, body mass index, preexisting medical comorbidities, and smoking history. Clinical outcome data included neurological and functional status assessed by using the neck disability index (NDI) score [11], JOA score and recovery rate (100 × [final JOA score − preoperative JOA score]/[17 − preoperative JOA score]) [6], and visual analog scale (VAS) score for axial neck pain, which was defined as nuchal and/or scapular pain. Pain intensity was graded as severe (VAS 8–10), moderate (4–7), or mild (0–3), in accordance with a previous study [12]. Maximal flexion and neutral and maximal extension were examined by taking lateral radiographs of the cervical spine obtained before surgery and at regular intervals after surgery thereafter. Parameters of sagittal alignment of the cervical spine included cervical lordosis (CL) and cervical sagittal vertical axis (CSVA). CL was measured as the C2–C7 angle formed by two lines drawn parallel to the posterior margin of the vertebral body on a radiograph in the neutral position [13]. CSVA was measured as the distance between the vertical axes through the center of the C2 body and posterior border of the upper endplate of C7 [14]. The C2–C7 ROM of the cervical spine was calculated by subtracting the maximal flexion C2–C7 angle from the maximal extension C2–C7 angle [15].

Data are presented as the mean ± SD. An independent t-test was used to analyze the difference between the preoperative and postoperative scores. A P value less than 0.05 was considered statistically significant.

Table 1: Demographics (n = 65).

	Male	Female	Total
N	45	20	65
Age	60.47 ± 10.44	63.75 ± 10.66	61.48 ± 10.53
Body mass index			
Normal	21 (46.7%)	8 (40.0%)	29 (44.6%)
Underweight	0 (0.0%)	1 (5.0%)	1 (1.5%)
Overweight	20 (44.4%)	6 (30.0%)	26 (40.0%)
Obese	4 (8.9%)	5 (25.0%)	9 (13.8%)
Diabetes mellitus (%)	5 (11.1%)	7 (35.0%)	12 (18.5%)
Hypertension (%)	9 (20.0%)	8 (40.0%)	17 (26.2%)
Cardiovascular disease (%)	13 (28.9%)	5 (25.0%)	18 (27.7%)
Smoke (%)	16 (35.6%)	3 (15.0%)	19 (29.2%)
Functional score			
VAS	2.8 ± 1.9	3.0 ± 2.3	2.9 ± 2.0
NDI	30.6 ± 4.6	30.8 ± 4.8	30.7 ± 4.6
JOA score	11.3 ± 1.5	10.4 ± 1.6	11.0 ± 1.5
Nurick score	2.6 ± 0.9	2.9 ± 1.0	2.7 ± 0.9
Radiographic parameters			
CL (°)	13.0 ± 9.9	15.8 ± 8.6	13.9 ± 9.6
C2–7 SVA (mm)	22.3 ± 11.9	13.4 ± 9.4	19.6 ± 11.9
ROM (°)	34.7 ± 12.5	35.1 ± 13.4	34.9 ± 12.7

Data are presented as n (%) or mean ± standard deviation.

3. Results

Forty-five male and 20 female patients were enrolled in this study. The demographic data were presented in Table 1. More female patients than male patients had a history of diabetes mellitus. The female patients had a smaller mean preoperative CSVA and less favorable preoperative JOA score. The mean age of all patients at the time of surgery was 60.5 years, and the mean length of wound was 4.8 cm. The mean duration of follow-up was 48.5 months.

3.1. Axial Neck Pain. The mean VAS of preoperative axial neck pain was 2.9, and it decreased to 2.6 at 3 months after surgery (Table 2). The mean VAS of axial neck pain at 48 months after surgery was 1.3. Thirteen patients (20%) experienced moderate neck pain at the third postoperative month; the symptom completely decreased to mild pain at

Table 2: Preoperative and postoperative clinical and radiographic status ($n = 65$).

Item	Pre-op	Post-op			P value
		3 M	12 M	48 M	
Axial neck pain					
VAS	2.9 ± 2.0	2.6 ± 2.1	1.9 ± 1.6	1.3 ± 1.0	<0.001[*a]
Functional recovery					
NDI	30.7 ± 4.6	—	13.2 ± 2.2	11.5 ± 4.6	<0.001[*a]
JOA score	11.0 ± 1.5	—	15.6 ± 3.4	16.3 ± 1.4	<0.001[*a]
Nurick score	2.7 ± 0.9	—	1.2 ± 1.3	0.7 ± 1.0	<0.001[*a]
JOA recovery rate (%)				*82.3 ± 16.7*	
Radiographic change					
CL (°)	13.9 ± 9.6	11.3 ± 7.8	13.6 ± 8.3	13.6 ± 8.5	0.700[a]
CSVA (mm)	19.6 ± 11.9	23.1 ± 12.8	21.8 ± 13.2	22.3 ± 13.6	0.031[*a]
ROM (°)	34.9 ± 12.7	21.6 ± 8.6	29.0 ± 10.0	29.9 ± 10.7	<0.001[*a]

Data are presented as mean ± standard deviation.
[a]Post-op 48 M versus pre-op.
[*]P value < 0.05 was considered statistically significant after test.

1 year after the operation. None of the patients experienced aggravated or severe neck pain from 1 to 4 years after surgery.

3.2. Functional Score. The mean JOA score improved significantly from 11.0 before surgery to 15.6 at 1 year after surgery (Table 2). At the final follow-up, the mean score increased slightly to 16.3, representing a mean recovery rate of 82.3%. The mean NDI score decreased from 30.7 preoperatively to 11.5 at the 48-month follow-up. The mean Nurick score also improved from 2.7 preoperatively to 0.7 at 4 years after the operation. None of the 65 patients showed worsening of myelopathy after surgery.

3.3. Radiographic Parameters. The mean CL decreased but not significantly, declining from 13.9° preoperatively to 13.6° at 4 years after the operation. Figure 1 shows that CL decreased to the lowest point at the third postoperative month and recovered gradually afterward. The mean CSVA increased from 19.6 mm preoperatively to 22.3 mm at 4 years after the operation ($P < 0.05$). Mean C2–C7 ROM decreased from 34.9° before surgery to 29.9° at the 48-month follow-up ($P < 0.05$). Figure 2 shows that ROM decreased to the lowest point at the third postoperative month and gradually improved afterward. Approximately 85% ROM was preserved at 4 years after the operation. Progression of C6/7 degeneration was found in two patients (3.1%) at the final follow-up, and both patients had intermittent moderate neck pain with gradual onset of radiculopathy but near normal life quality.

3.4. Complications. One patient exhibited poor wound healing and received debridement and reclosure in the operation room. No patient had experienced temporary C5 nerve palsy or lamina reclosure at the final follow-up.

3.5. Case Report. A 47-year-old male teacher presented with bilateral hand clumsiness, numbness in four limbs, and impaired tandem gait. He was found to have preoperative

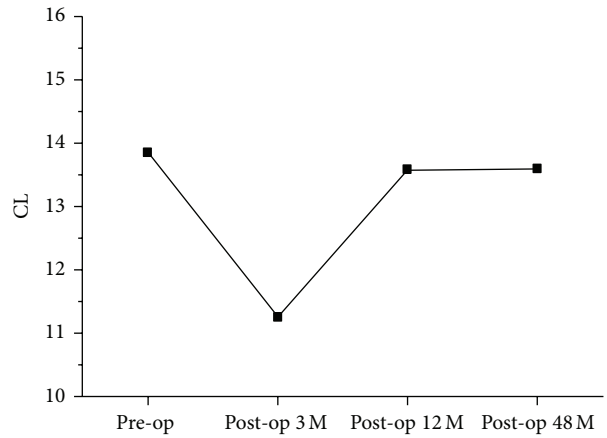


Figure 1: The change of C2–C7 lordotic angle (CL) from preoperative status to final follow-up at postoperative 4 years. The lowest point was at postoperative 3 months.

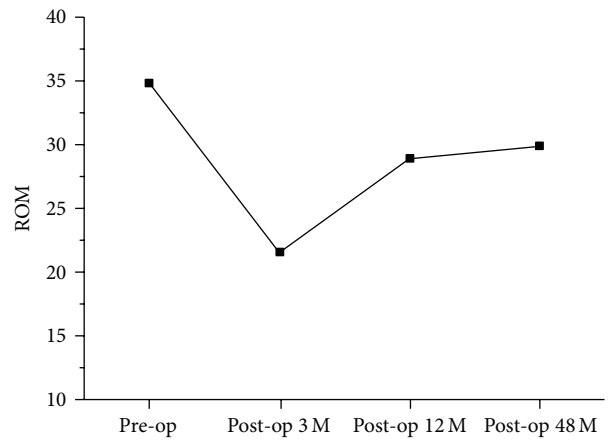


Figure 2: The change of C2–C7 range of motion (ROM) from preoperative status to final follow-up at postoperative 4 years. The lowest point was at postoperative 3 months.

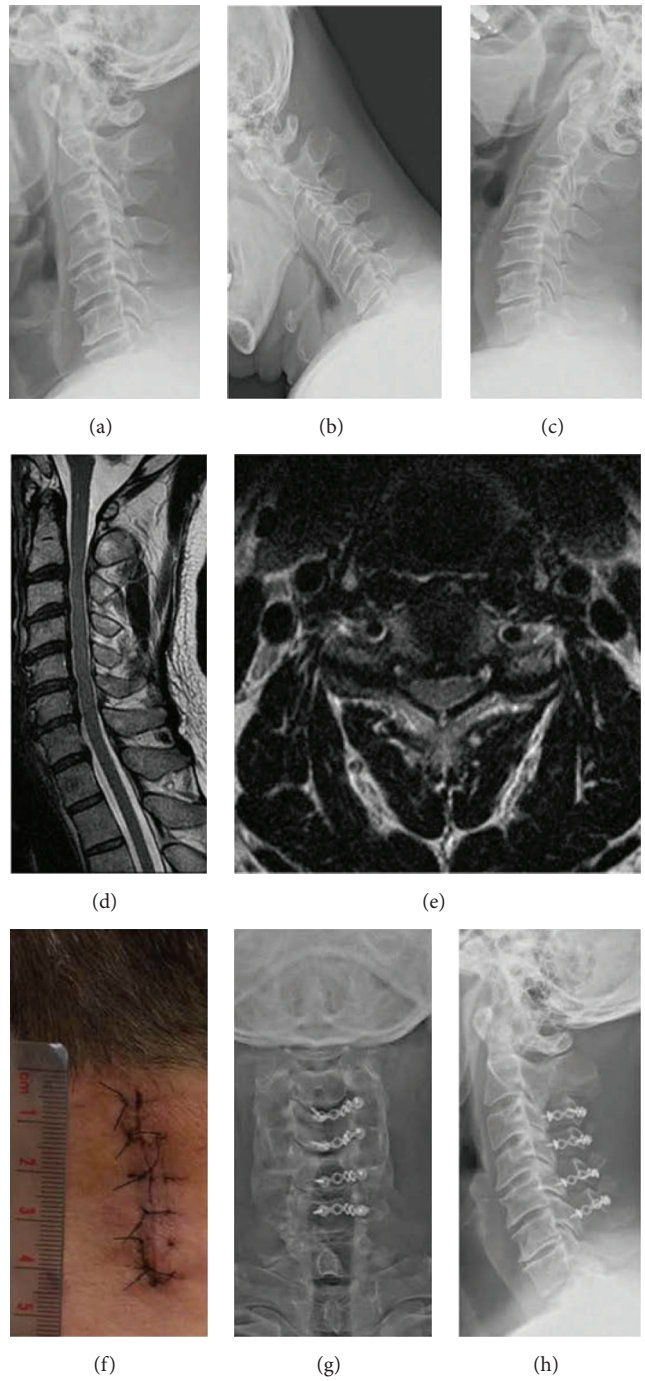
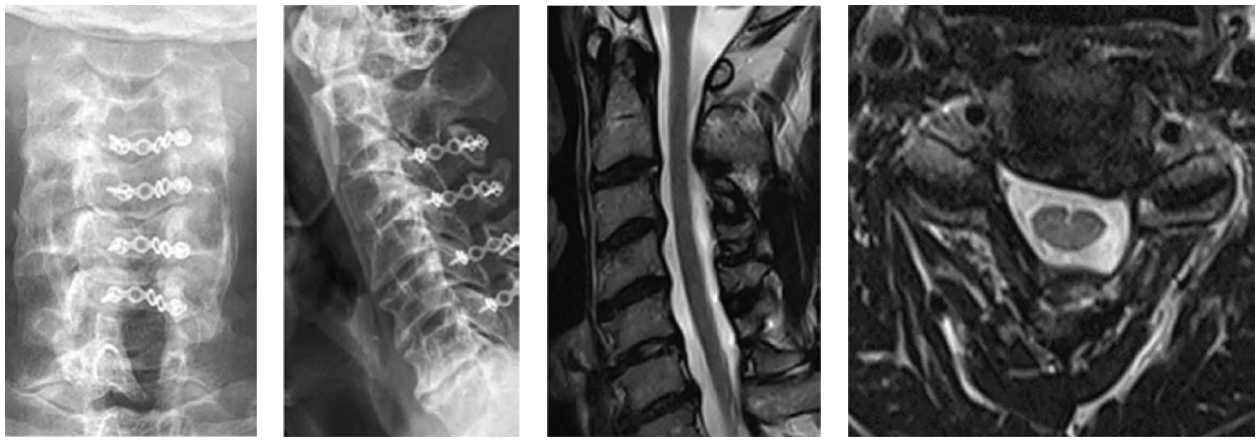


Figure 3: Preoperative X-ray in this case showed C3–C7 spondylosis (a) without segmental instability and local kyphotic deformity (b and c). T2 weighted MRI revealed C3–C7 stenosis at sagittal plane (d) and banana shape of the compressed spinal cord at axial plane (e). The surgical wound was about 4 cm (f). Postoperative plain films showed well alignment of C3–C6 laminoplasty and C7 partial laminectomy at anterior to posterior (g) and lateral (h) views at 1 month.

JOA score of 11, Nurick score of 2, and preoperative neck pain VAS of 3. Plain film revealed no instability or local kyphosis (Figures 3(a), 3(b), and 3(c)). His preoperative CL was 14° and preoperative ROM was 35°. Cervical MRI showed C3–C7 stenosis with substantial compression of the spinal cord but without any anterior main budging lesion over these segments (Figures 3(d) and 3(e)). We performed MEOLP on the patient (Figures 3(f), 3(g), and 3(h)). His neck pain VAS score was 2 at 3 months, which decreased to 0 at 6 months after operation. His postoperative JOA and Nurick scores were 17 and 0, respectively, at both 12 and 48 months after surgery. At 4 years after surgery, the patient exhibited a 100% JOA recovery rate, 10° CL, and 28° ROM (Figures 4(a), 4(b), and 4(c)), with 60% ROM preserved. A postoperative



(a) (b) (c) (d)

Figure 4: Postoperative X-ray at 4 years demonstrated well cervical curvature with C6-C7 disc space narrowing at anterior to posterior (a) and lateral (b) views. Post-op MRI revealed patent spinal cord without compression at sagittal plane (c) and axial plane (d).

MRI at 4 years after surgery revealed a patent spinal cord without compression (Figure 4(d)). The patient expressed high satisfaction with this operation and recovery.

4. Discussion

This study revealed favorable clinical and radiographic outcomes of MEOLP at 4 years postoperatively. We reduced the complication rates by minimizing surgical dissections of conventional EOLP [7]. Several less invasive methods, such as muscle preservation concepts of exposure of the cervical spinal laminae developed by Shiraishi [8], selective laminoplasty [16], C3–C6 laminoplasty [17], and cervical laminoplasty with C3 laminectomy [18], have been reported for preventing surgery-associated problems such as axial neck pain and loss of cervical lordosis by reducing damage to the paraspinal muscles and nuchal ligaments. Our MEOLP combines the advantages of these methods and has comparable neurologic recoveries and very less axial neck pain during the longer period of follow-up [16, 18, 19]. Compared to C3–C6 laminoplasty developed by Hosono et al., our method also restores better postoperative neck ROM and cervical lordosis at medium-term follow-up [17, 19].

The current results showed significant improvements in neck pain at 3 months, 1 year, and 4 years following surgery. None of the patients reported aggravated or severe neck pain after 1 year following surgery. Aggravated axial neck pain is one of the most common complications of EOLP, with a reported incidence of 30%–60% [20]. The main causes include the severe damage to the paraspinal muscle and nuchal ligament. One cadaveric study revealed that laminoplasty without the dissection of muscles attached to the C7 spinous process preserves the trapezius as well as the rhomboideus more effectively than do conventional methods [21]. Our MEOLP method reduces muscle damage by dissecting unilateral paraspinal muscle and sawing the spinous process to approach the other side of the laminae. The method also reduces injury to the nuchal ligament by preserving muscles attached to the C7 spinous process. Two patients reported intermittent moderate neck pain with left C7 radiculopathy at the final follow-up because of progressive C6/7 disc degenerative change. Both patients had preoperative C6/7 disc space narrowing without segmental instability or local kyphosis. Partial C7 laminectomy may aggravate this condition.

Favorable neurologic recovery and significant improvement of disability were noted in the patients at the final follow-up without deterioration. In addition, the patients did not exhibit C5 nerve palsy (a common short-term complication [22]) or lamina reclosure (a common medium- and long-term complication [23]). Laminoplasty decompresses the spinal cord through lamina elevation and secure fixation; an overly wide opening may cause facet joint violation and a higher incidence of C5 nerve traction injury [24]. Furthermore, an overly lateral approach may damage the posterior rami of the spinal nerves and cause paraspinal muscle atrophy and disability [25]. Our MEOLP method achieves lamina elevation by creating more medial bilateral gutters to approximately 7 mm from the spinous process. The distance was determined according to three findings: (1) the border of the spinal cord measured during partial C7 laminectomy, (2) the measurement of the extent of the spinal cord width in cadaveric study, and (3) the measurement of spinal cord diameters from the axial MRI view of C3–C7 in 200 patients. We found that the average distance between the facet joints was 24 mm but the average cord width was only 14 mm. The axial MRI and cadaveric research revealed that the facet joints were located so laterally from the lateral borders of the spinal cord that they were not necessary to be identified and approached while creating the gutters on the laminae. Based on the information from MRI study, cadaveric dissection, intraoperative findings, postoperative MRI work-up, and postoperative neurologic improvement, we could say that the modified EOLP could afford enough cord decompression.

Preservation of more than 80% ROM and restoration of cervical lordosis to near preoperative levels were noted at 48 months following MEOLP. This result may be attributable to repairing the semispinalis cervicis (SC) [26] and reducing facet joint violation [27]. Failure to repair the SC can cause substantial axial neck pain and loss of lordosis [28]. Preserving more musculature can not only reduce axial neck pain but also preserve and restore more neck ROM [29].

More than 80% JOA recovery rate was noted in this group of our patients who received modified laminoplasty technique. We strictly selected our patients by the indications of laminoplasty as multilevel cervical myelopathy without segmental instability, local kyphosis, or anterior major foci. We also convinced patients to receive the operation when the diagnosis of symptomatic myelopathy was confirmed so that the treatment was not delayed. The earlier the myelopathy is surgically treated, the more the neurologic functions recover. Then we followed up these patients closely and taught them to do neck extension exercise under hard collar protection aggressively. Although we had good neurologic recovery and functional outcomes in the medium-term follow-up, the long-term outcomes of the modified technique still need to be clarified under the influence of degenerative change of cervical spine.

The results of this study are limited because of the relatively small case number of MEOLP, the retrospective design, and the lack of a comparison group. In addition, longer term follow-up is required to evaluate the progressive degenerative disc change within the laminoplasty and adjacent segment [30] following MEOLP.

5. Conclusion

We conclude that our MEOLP method is an effective and less invasive surgical procedure for treating patients with MCSM. Furthermore, the method was found to provide satisfactory medium-term results by preserving muscles and the nuchal ligament attached to the C7 spinous processes, minimizing injury of paraspinal extensor musculature, reducing facet joint violation, and ensuring adequate lamina opening. This method provided favorable clinical outcomes with fewer complications resulting from avoiding unnecessary dissection.

Competing Interests

The authors declare that they have no competing interests.

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Clinical Study

"Slalom": Microsurgical Cross-Over Decompression for Multilevel Degenerative Lumbar Stenosis

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Objective. Selective, bilateral multisegmental microsurgical decompression of lumbar spinal canal stenosis through separate, alternating cross-over approaches. *Indications*. Two-segmental and multisegmental degenerative central and lateral lumbar spinal stenosis. *Contraindications*. None. *Surgical Technique.* Minimally invasive, muscle, and facet joint-sparing bilateral decompression of the lumbar spinal canal through 2 or more alternating microsurgical cross-over approaches from one side. *Results.* From December 2010 until December 2015 we operated on 202 patients with 2 or multisegmental stenosis (115 f; 87 m; average age 69.3 yrs, range 51–91 yrs). All patients were suffering from symptoms typical of a degenerative lumbar spinal stenosis. All patients complained about back pain; however the leg symptoms were dominant in all cases. Per decompressed segment, the average OR time was 36 min and the blood loss 45.7 cc. Patients were mobilized 6 hrs postop and hospitalization averaged 5.9 days. A total of 116/202 patients did not need submuscular drainage. 27/202 patients suffered from a complication (13.4%). Dural tears occurred in 3.5%, an epidural hematoma in 5.5%, a deep wound infection in 1.98%, and a temporary radiculopathy postop in 1.5%. Postop follow-up ranged from 12 to 24 months. There was a significant improvement of EQ 5 D, Oswestry Disability Index (ODI), VAS for Back and Leg Pain, and preoperative standing times and walking distances.

1. Introduction

Bilateral microsurgical so-called "cross-over decompression" through a unilateral approach has become a new minimally invasive surgical treatment option for degenerative lumbar spinal stenosis [1–7].

The main advantages of this technique are the diminished "access trauma" to the paravertebral muscles and to the facet joints. In particular the inferior facet contralateral to the approach side as well as its outer capsular surroundings can be preserved completely.

In cases of central spinal or foraminal stenosis associated with degenerative lumbar scoliosis decompression can be performed from the convex side, thus preserving the stability of the heavily loaded facet joint on the concave side [6].

These advantages usually get lost in cases with bi- or multisegmental pathologies which account for more than 50% of our own patient population in the last 17 years [3, 9, 10]. Longer skin incisions are necessary to reach 2 or more segments. The paravertebral muscles have to be retracted over a longer distance and the partial resection of the inferior and superior facets has to be performed at 2 or more segments on the same approach side. This produces higher unilateral collateral damage for muscles and joints which more or less counteracts the microsurgical philosophy of this approach.

The following paper describes a new surgical technique for selective multisegmental decompression through multiple microsurgical approaches with alternating approach sides ("Slalom" Technique).

2. Methods

2.1. Surgical Goal. The goal of this technique is to achieve multisegmental bilateral decompression through separate unilateral microsurgical approaches. The spinal canal is reached through approaches with alternating the sides (e.g.,

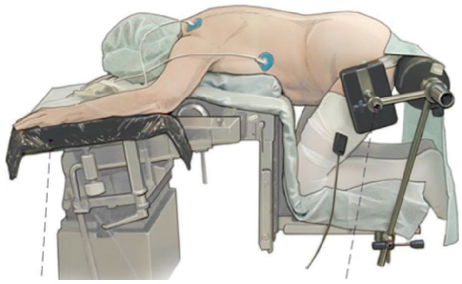
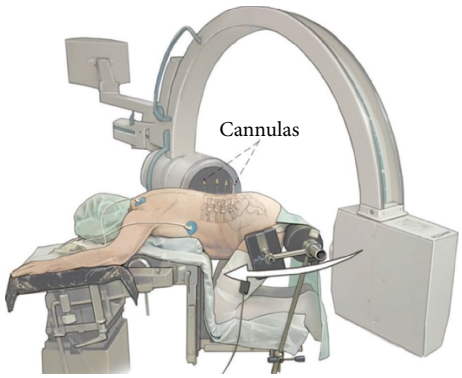
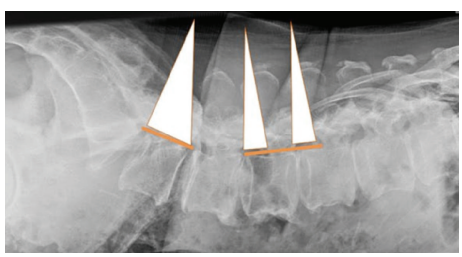


Figure 1: From [8], with permission. Positioning of the patient in knee-thorax position with no pressure on abdomen.



(a)

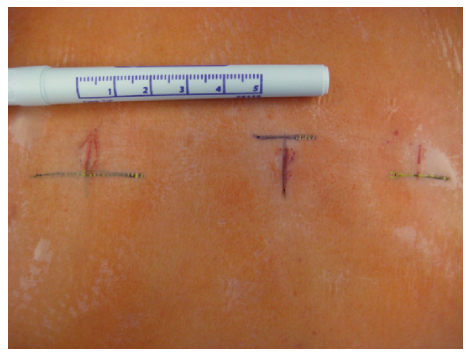


(b)

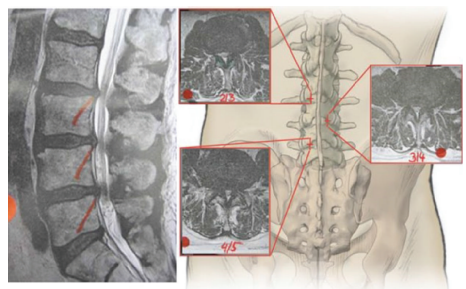
Figure 2: (a) From [8] with permission. Localization of the levels to be approached. Cannulas are inserted to mark the levels under fluoroscopic control. (b) From [8] with permission. Lateral X-ray with graphic marking of the approach corridors to the levels L3-4-5-S1. Due to the lordotic angle of the lumbosacral junction, the levels L4-5-1 can be approached through one small incision while the other two levels are approached through separate skin incisions ("Giant Slalom").

left-right-left). The rationale behind this is not only to decrease the amount of unilateral access damage but also to "balance" the trauma to the tissues on the way to the spinal canal (skin, muscles, facet joints, and lamina). Bilateral decompression of the central spinal canal and of the lateral recess is possible. If foraminal ("far lateral") decompression has to be achieved as well, the approach has to be chosen from the contralateral side.

2.2. Indications. Patents with central, lateral, and foraminal stenosis of 2 and more lumbar levels with typical clinical symptoms (neurogenic claudication, buttock, leg pain,



(a)



(b)

Figure 3: (a) From [8] with permission. Marking of the skin incisions to approach the levels L3-4-5-S1. (b) From [8] with permission. Graphic demonstration of a "Slalom" approach to stenotic levels L2-3 from the right side, L3-4 from the left, and L4-5 again from the right side.

heaviness in the legs w/wo radicular symptoms, and w/wo associated deformity (e.g., degenerative lumbar scoliosis and degenerative spondylolisthesis) were included. There were no general contraindications to this approach.

2.3. Surgical Technique. The patient is placed in a so-called knee-thorax position (Figure 1). He is kneeling on the surgical table with hips and knees flexed 90° and shoulders in 90° abduction and 90° external rotation (attention: avoid overextension of the shoulders). Elbow (N. ulnaris) and wrist joint (N. medianus) and the shins are positioned on gel pads to avoid pressure sores. The abdomen should "hang" freely to maximally lower the pressure in the epidural veins. Lateral supports are important to secure the patient while the OR table is tilted during the procedure (Figure 1).

The projection of the disc space on to the skin level is then marked under fluoroscopic control with cannulas (Figures 2(a)-2(b)). If there is a fixed lordosis sometimes 2 segments can be reached through one 20 mm skin incision. Figure 3 shows various skin incisions to 2-3-4-5 segments (Figures 3(a)-3(b)). Surgery is performed skin-to-skin with the help of a surgical microscope (Zeiss N 700, Zeiss, Oberkochen, Germany) with variable 400 mm focus length.

About 5 mm paramedian, the dorsolumbar fascia is opened and the paravertebral muscles are bluntly and gently retracted from the lamina and the interlaminar window. Care has to be taken not to incise bigger attachments of the muscles

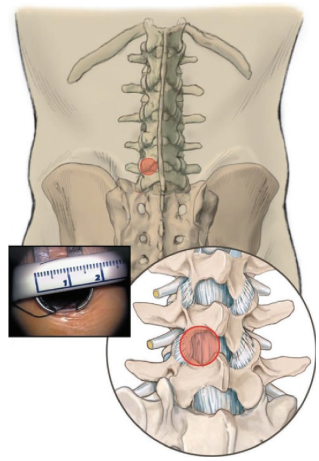


Figure 4: From [8] with permission. Graphic presentation of the interlaminar approach window with a minispeculum.

to the spinous process. Small attachments of the rotators are cut from the inferior lateral part of the superior lamina to expose the interlaminar window and the facet joint contour. A microspeculum (Piccolino, Medicon, Tuttlingen, Germany) is then inserted and the level of exposure is checked under fluoroscopic control (Figure 4).

The first step of decompression is to undercut the proximal lamina with a high speed burr to expose the attachment of the yellow ligament medially and cranially. Then the spinal canal is opened and the yellow ligament is removed starting in the midline and then towards lateral cranial and finally along the lateral recess to expose the thecal sac and the root until it leaves the spinal canal around the caudal pedicle (Figure 5(a)). The cranial rim of the caudal lamina is undercut 2-3 mm. Thus the ipsilateral decompression is complete (Figure 5(a)). Now the OR table is tilted to the contralateral side and the assistant who fixes and guides the speculum tilts it to the contralateral side (Figure 5(b)). The surgical microscope is adjusted to give an oblique view to the contralateral part of the spinal canal. The yellow ligament is removed and the proximal lamina is undercut as is the superior facet on the contralateral side. Thus the central part as well as the lateral part (lateral recess) is completely decompressed as well (Figure 5(b)). Hemostasis is achieved with repeated irrigation with saline solution or the use of Floseal (Floseal Baxter Deutschland GmbH, Unterschleissheim, Germany). The table is tilted into the neutral position, the speculum is removed, and the fascia and skin are closed with resorbable intracutaneous sutures. Submuscular drainage without vacuum is inserted if necessary. A postop MRi shows the amount of decompression and the lack of "collateral damage" (Figure 6). This procedure is then repeated in the other segments with alternating skin incisions (see Figure 3).

3. Results

From December 2010 until December 2015 we operated on 202 patients with 2-segmental or multisegmental stenosis (115 f; 87 m; average age 69.3 yrs, range 51–91 yrs). In 202 patients a total of 577 segments were decompressed through separate approaches (see patient data listed below). All patients were suffering from symptoms typical for a degenerative lumbar spinal stenosis. All patients complained about back pain; however the leg symptoms were dominant in all cases.

Patient data are as follows:

$N = 202$,

f : m (115 : 87),

age: average 69.3 yrs (range 51–91 yrs),

follow-up: 12–24 mos,

Operated segments are as follows:

2 segments ($n = 84$):

- L1-2-3 ($n = 8$),
- L2-3-4 ($n = 14$),
- L3-4-5 ($n = 32$),
- L4-5-1 ($n = 22$),
- T12-L1-2 ($n = 3$),
- L2-3 + L4-5 ($n = 2$),
- L1-2 + L3-4 ($n = 1$),
- L3-4 + L5-1 ($n = 2$),

3 segments ($n = 75$):

- L1-2-3-4 ($n = 16$),
- L2-3-4-5 ($n = 28$),
- L3-4-5-1 ($n = 24$),
- L1-2-3 + L5-1 ($n = 4$),
- L2-3-4 + L5-1 ($n = 3$),

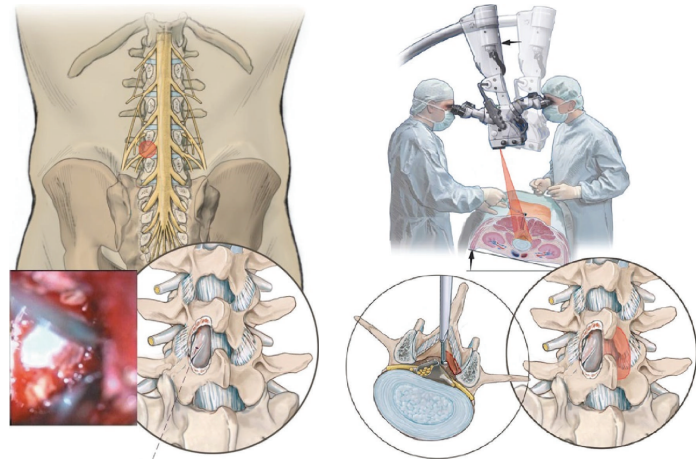
4 segments ($n = 31$):

- L1-2-3-4-5 ($n = 14$),
- L2-3-4-5-1 ($n = 11$),
- L1-2-3-4 + L5-1 ($n = 4$),
- T12-L1-2-3-4 ($n = 2$),

5 segments ($n = 12$):

- L1-2-3-4-5-1 ($n = 11$),
- T12-L1-2-3-4 + L5-1 ($n = 1$).

Per decompressed segment, the average OR time was 36 min, and the blood loss 45.7 cc. Patients were mobilized 6 hrs postoperatively and hospitalization averaged 5.9 days (which was mainly due to reimbursement regulations in Germany). A total of 116/202 patients did not need submuscular drainage. All patients received a soft lumbar brace (Lumbotrain®, Fa Bauerfeind, Germany) for 4 weeks postop. Postop follow-up ranges from 12 to 24 months. There was a marked improvement of EQ 5D and Oswestry Disability Index (ODI) (Figure 7(a)). The same is true for the VAS for Back and Leg Pain (Figure 7(b)). All patients reported a significant improvement of their preop standing times and walking distances. A total of 27/202 patients suffered from a complication (13.4%). Dural tears occurred in 3.5%, epidural hematoma in 5.5%, a deep wound infection in 1.98%, and a temporary radiculopathy postop in 1.5%.



(a) (b)

Figure 5: (a) From [8] with permission. Decompression of the ipsilateral side. (b) From [8] with permission. Decompression of the contralateral side.

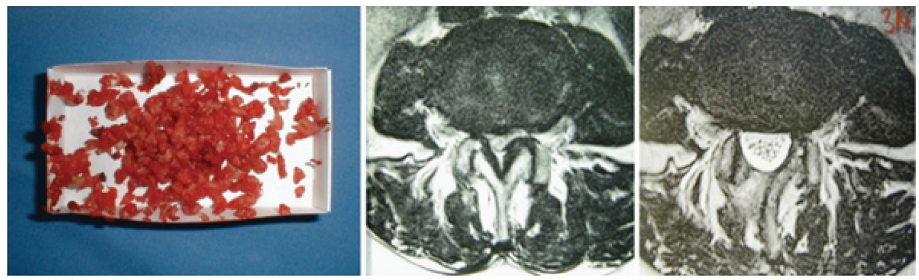


Figure 6: From [8] with permission. "Technical result" of decompression of one level (L3-4). Left: material that has been removed (yellow ligament, bone). Middle: MRI preoperatively; right: MRI postoperatively shows a complete decompression with preserved facet joint and minimum scar tissue formation in the muscles.

4. Discussion

Degenerative lumbar spinal stenosis is gaining increasing importance. Growing life expectancy with higher demands towards quality of life and better diagnostic options have made spinal stenosis the most frequent pathology seen in spine centers around the Western World.

Conventional laminectomy with removal of posterior bony and ligamentous structures has been the gold standard of surgical treatment for decades. Although postoperative development of segmental instability is a multifactorial problem, unnecessary damage to anatomic structures which stabilize the functional spinal unit has always been a problem with this technique [11–14]. Moreover, the fact that the spinal canal is exposed more than what would be necessary just for a decompression increases the contact surface between paravertebral muscles and the dura is one of the reasons for extensive scar tissue formation and epidural fibrosis following conventional laminectomy which may lead to tethering of the cauda equina and radicular symptoms [12, 15–18].

Microsurgical cross-over decompression through a unilateral approach significantly minimizes these problems [3, 4, 9, 10, 19]. The muscles are retracted only on one side and the area of the spinal canal which is exposed to the surrounding tissue remains small. This reduces the area of potential scar formation. Moreover, the integrity of the contralateral facet joint remains nearly completely intact.

In multisegmental stenosis however the sum of several unilateral interlaminar exposures leads to a more extensive unilateral muscle trauma. The removal of the medial part of the inferior facet in 2 or more levels on the same side may also lead to unilateral functional problems on the joint level. This gains even more importance in cases where spinal stenosis is associated with a degenerative deformity such as degenerative spondylolisthesis or de novo scoliosis. The "Slalom" Technique described in this paper leads to a more "balanced" collateral damage pattern thus keeping the full advantages of this minimal invasive approach.

Intraoperative blood loss was low, and submuscular drainage was necessary in only 42.5% of the cases. Minimal surgical trauma allows for early mobilization of the patient. Our success rates correspond well with those described for monosegmental approaches.

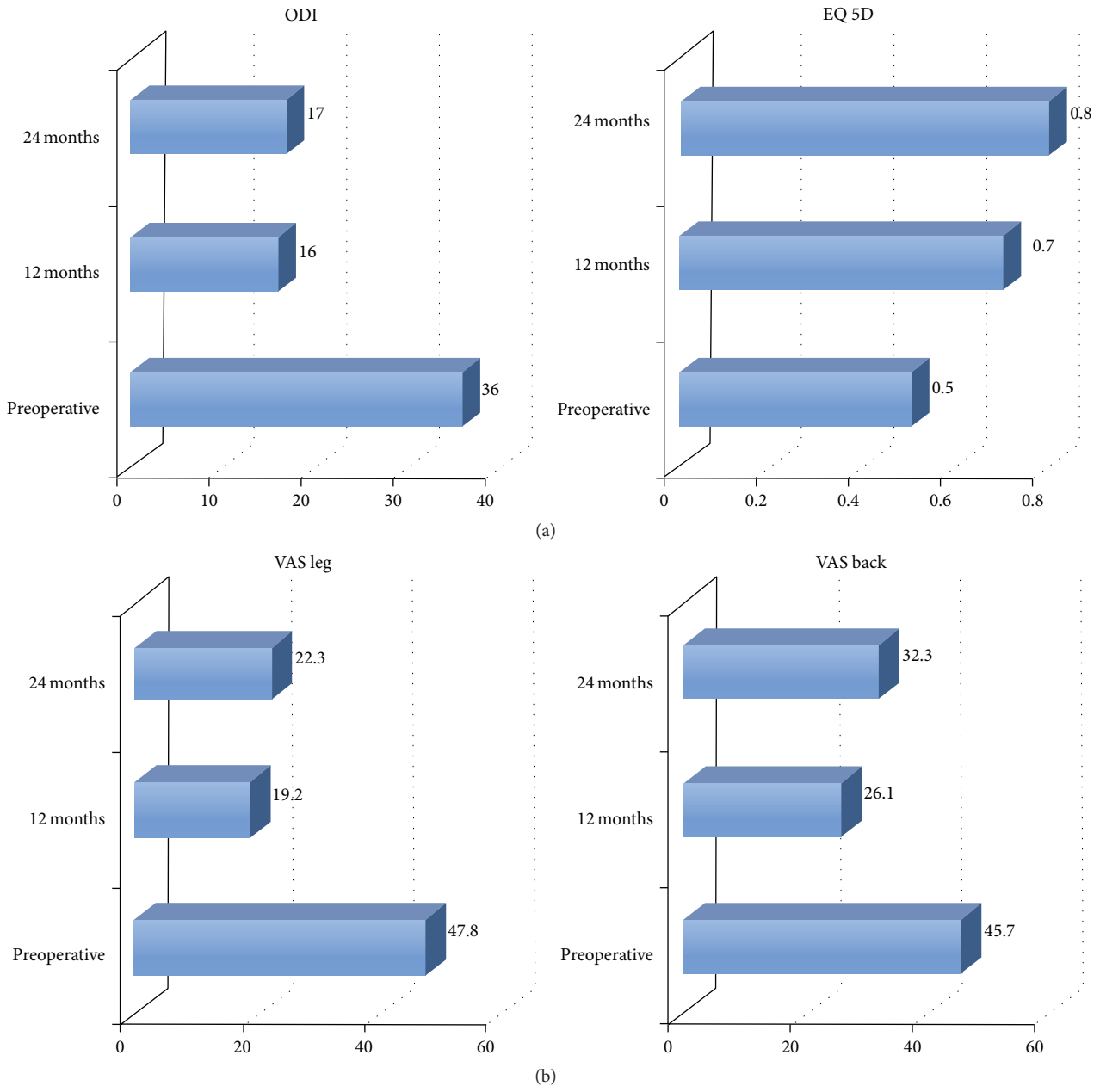


Figure 7: (a) EQ5 D and Oswestry Disability Index (ODI) preoperatively, as well as 12 and 24 mos postoperatively. (b) VAS for Leg and Back Pain preoperatively as well as 12 and 24 mos postoperatively.

The following limitations of the Slalom approach and of our short-term experience should not remain unmentioned.

In case a dural tear occurs intraoperatively on the ipsilateral approach side, repair is only possible with the use of dura clips and patches (e.g., TachoSil®, Takeda Ltd., UK). In case of larger defects the approach has to be enlarged to perform a proper suture. This is also true for contralateral dural tears which then would require a contralateral approach.

The lordotic curvature at the levels L4-5-S1 sometimes suggests a 2-segmental decompression through one small skin incision on the same side ("Giant Slalom"). However, since this can be associated with the unilateral violation of the 2 inferior facets (L4 and L5) as mentioned above, we only recommend it in cases with wide isthmus interarticularis in order to prevent fatigue fractures postoperatively.

Our postop follow-up ranges between 1 and 2 years which may be too short for proof or disproof of a surgically induced progression of a preexisting deformity.

Competing Interests

The authors declare that they have no competing interests.

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Research Article

Neurological Complications after Lateral Transpsoas Approach to Anterior Interbody Fusion with a Novel Flat-Blade Spine-Fixed Retractor

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Introduction. The lateral lumbar interbody fusion (LLIF) surgical approach has potential advantages over other approaches but is associated with some unique neurologic risks due to the proximity of the lumbosacral plexus. The present study analyzed complications following LLIF surgical approach using a novel single flat-blade retractor system. *Methods*. A retrospective data collection of patients receiving LLIF using a novel single flat-blade retractor system at two institutions in the US. Inclusion criteria were all patients receiving an LLIF procedure with the RAVINE® Lateral Access System (K2M, Inc., Leesburg, VA, USA). There was no restriction on preoperative diagnosis or number of levels treated. Approach-related neurologic complications were collected and analyzed postoperatively through a minimum of one year. *Results*. Analysis included 253 patients with one to four treated lateral levels. Immediate postoperative neurologic complications were present in 11.1% (28/253) of patients. At one-year follow-up the approach-related neurologic complications resolved in all except 5 patients (2.0%). *Conclusion*. We observed an 11.1% neurologic complication rate in LLIF procedures. There was resolution of symptoms for most patients by 12-month follow-up, with only 2% of patients with residual symptoms. This supports the hypothesis that the vast majority of approach-related neurologic symptoms are transient.

1. Introduction

Lumbar spinal fusion has historically been accomplished through open surgical procedures [1].

The first minimally invasive spine (MIS) procedure, chemonucleolysis, needle injected chemical chymopapain into the annulus of a herniated disc was in 1969 [2]. However, the first MIS fusion procedure was not until the introduction of the MIS stand-alone anterior lumbar interbody fusion (ALIF) in 1995 [1, 3]. ALIF with posterior fixation has become an accepted method of stabilizing and fusing the spine, but it is associated with significant complications and, in most cases, the need for an access surgeon to expose the spine [4–6].

The MIS lateral transpsoas approach of lateral lumbar interbody fusion (LLIF) was introduced in 1998, in an effort to reduce anterior approach-related complications [7]. The LLIF procedure utilizes a lateral, retroperitoneal, transpsoas approach coupled with neuromonitoring [7, 8]. LLIF has unique approach-related complications, such as transient nerve deficits, nerve injury with residual effects, and contralateral motor deficits [8–11]. To date, there is a growing body of literature reporting the complications associated with the LLIF surgical approach. However, there is a paucity of literature that analyzes the specific retractor system utilized for the approach. The present study analyzed complications following LLIF surgical approach using a novel single flat-blade retractor system.

2. Materials and Methods

With institutional review board approval, patients were retrospectively identified in chart review from two centers. Identified patients underwent MIS LLIF between October 2010 and August 2014. Inclusion in the study was restricted to patients receiving lateral lumbar interbody fusion using

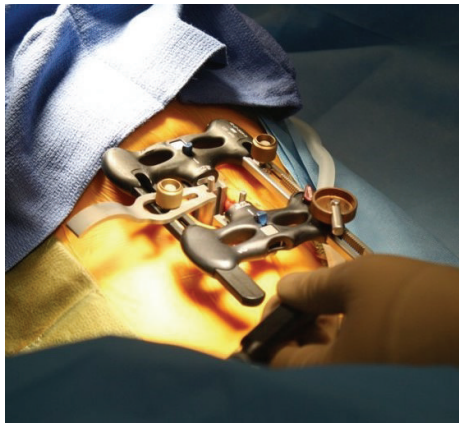

Figure 1: Intraoperative photograph of RAVINE.

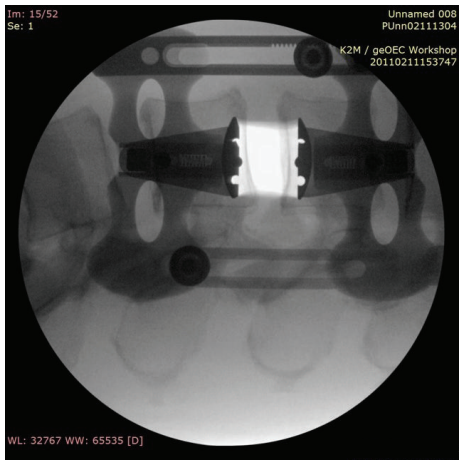

Figure 2: Intraoperative radiograph of RAVINE.

the RAVINE Lateral Access System, K2M, Inc., Leesburg, VA, USA (RAVINE), with minimum of one-year follow-up and complete data to evaluate approach-related neurologic complications at follow-up. Patient preoperative diagnosis was not restricted and included degenerative disc disease with/without spondylolisthesis and deformity cases.

RAVINE is used for a transpsoas approach with rigid fixation to the spine. The system uses dual flat blades with options for a third and fourth blade, instead of the standard tubular retractor. Radiographic intraoperative images and photos are included, Figures 1–3.

The surgeries were performed at two centers in the US between October 2010 and August 2014 by an orthopedic and a neurosurgeon, both fellowship trained spinal surgeons experienced in performing lateral access surgery. The lateral surgery was performed with the surgeon's choice of interbody cage while using RAVINE. The surgical procedure differed based on surgeon preference, and thus surgeries included LLIF with posterior fixation (rods and percutaneous screws) as well as stand-alone LLIF. The LLIFs with posterior fixation surgeries were completed as same-day procedures in some cases and staged over multiple days in other cases.

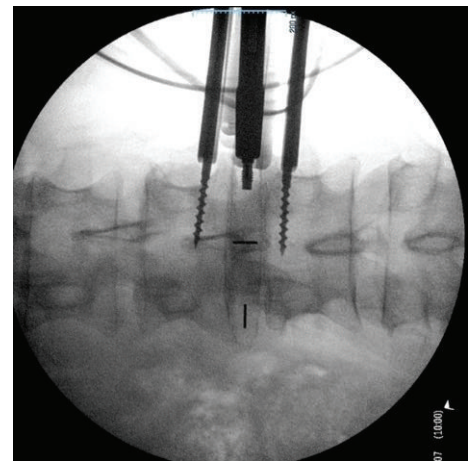

Figure 3: Intraoperative radiograph of PEEK Cage Insertion using RAVINE.

Table 1: Demographics.

Sex	Male: 78, female: 175
Age (years)	61 (range 28–86)
Height (in)	65.9 (range: 51–76)
Weight (lbs)	181.4 (range: 107–301)
BMI (kg/m^2)	29.3 (range: 19.0–43.9), not noted: 9
Current smoker	Yes: 47, no: 183, not noted: 23

All LLIF surgeries were performed with the guidance of neuromonitoring. The two surgeons in this study included the use of neuromonitoring per their standard protocol for lumbar LLIF cases. This included monitoring L2, L3 (rectus femoris), L3, L4 (vastus medialis), L4 (tibialis anterior), L5, S1 (peroneus longus), and S1, S2 (gastroc to gastrocnemius) for all cases. Baseline measures were obtained and stimulation was provided multiple times during the decompression and insertion of the lateral device. Following surgery, neurologic complications were collected and evaluated for relationship to the surgical approach at each postoperative visit.

Data were retrospectively collected and included demographics, operative details, and postoperative neurologic complications. Descriptive statistics were calculated for the demographic and operative data. All neurologic complications were analyzed for relationship to the surgical approach and resolution at final follow-up. SPSS Statistics 20 was used to run multinomial regression analysis of neurologic complications with surgical time, EBL, and specific levels treated.

3. Results

Retrospective data were collected and analyzed for 253 patients meeting the inclusion/exclusion criteria, with an average follow-up of 13.2 months at the final postoperative visit. The average age at time of surgery was 61 years and 31% of patients were male. Complete patient demographics are included in Table 1.

Table 2: Operative data.

Lateral and posterior same-day ($N = 210$)	
LOS (days)	2.36 (range: 1–10)
Surgery time (min)	150.0 ± 56.2 (range: 58.0–360.0)
EBL (cc)	87 (range: 10–700)
Lateral and posterior staged ($N = 17$)	
LOS (days)	7.41 (range: 3–15)
Surgery time (min)	453.2 ± 85.0 (range: 299.0–582.0)
EBL (cc)	262 (range: 50–1350)
Lateral stand-alone ($N = 26$)	
LOS (days)	3.88 (range: 1–13)
Surgery time (min)	122.2 ± 38.9 (range: 77.0–216.0)
EBL (cc)	55.2 (range: 15–300)

Surgical procedure differed based on surgeon preference including same-day LLIF with posterior fixation, staged LLIF with posterior fixation, and stand-alone LLIF, so operative data were analyzed separately for each surgical procedure. Hospital length of stay was similar between same-day LLIF with posterior fixation and stand-alone LLIF. The posterior portion of the staged LLIF procedure was performed one day after the lateral surgery, with the length of stay five days longer on average than same-day procedure. Surgery time and EBL were also noticeably longer than same-day and stand-alone procedures. Complete operative results are included in Table 2.

The inclusion/exclusion criteria included all patients treated with RAVINE and complete data to evaluate for any approach-related neurological complications; therefore, the lateral and posterior treated levels varied. The most treated lateral and posterior level was L4-L5 followed by L3-L4. All treated lateral and posterior levels are reported in Table 3.

Analysis of neurologic complications showed transient approach-related symptoms existing in 11.1% (28/253) of patients at the initial postoperative visit. Femoral cutaneous nerve neuropraxia was the most common symptom. By the last postoperative visit, neurologic symptoms remained in only 2.0% (5/253) of patients. The symptoms included foot drop, hypersensitivity in the left lateral thigh, left thigh numbness, left thigh tingling, and right thigh dysesthesia. The patient that experienced foot drop was a grade 3 spondylolisthesis prior to surgery and received same-day LLIF with posterior fixation at L4-L5. The patient with hypersensitivity in the left lateral thigh also received same-day LLIF with posterior fixation at L4-L5. Left thigh numbness was experienced after staged two-level LLIF at L3–L5 with posterior fixation from L3–S1. Tingling in the left thigh occurred after staged three-level LLIF at L2–L5 with posterior fixation from L2–S1. The last patient, with chronic right thigh dysesthesia, received a stand-alone three-level LLIF from L2–L5. Review of neuromonitoring of patients with complications did not reveal any relationship between intraoperative alarm and presence of complications. Multinomial regression analysis indicated that there was no statistically significant relationship between neurologic complications and surgery time, EBL, or levels treated.

4. Discussion

The LLIF surgical approach has potential advantages when compared to ALIF, TLIF, and PLIF but is associated with some unique risks. The proximity to the lumbosacral plexus increases the risk of neurologic complications, with the literature reporting a wide range of complications 0.7–23% [9, 12–16].

An early retrospective review of the direct lateral transpsoas approach of 58 patients at one-year follow-up showed that two (3.4%) patients experienced persistent motor deficit from L4 nerve injury [8]. Lykissas et al. hypothesized that neurologic deficits following LLIF surgery decrease over time and, in a review of 919 LLIF treated levels at 18 months, approach-related deficits were reduced to 3.2% of patients [17]. A prospective multicenter study of 107 patients also found that postoperative weakness appeared to be transient. Initially, 33.6% of patients had weakness, but symptoms resolved by six months in all patients except 7 (6.5%) [14]. Pumberger et al. found in 235 LLIF patients that motor deficits occurred in 2.9% of patients at 12-month follow-up [12].

A retrospective case series of 118 patients receiving one-level to four-level LLIF reported a postoperative complication rate of 36% that was reduced to 0.8% (one patient) at the final follow-up [18]. Data from an extreme lateral interbody fusion (XLIF) of 107 patients showed lower extremity weakness in 24% (36/107) of patients following surgery. Five (5%) patients had continued motor weakness at 12 months. However, by 24 months 4/5 deficits were only a single motor grade and one patient was lost to follow-up [19]. The current study results follow a similar trend with an immediate postoperative neurologic complication rate of 11.1% (28 patients) reduced to 2.0% (5 patients) at last follow-up.

Recent studies have attempted to isolate the risk factors for neurological deficits following LLIF surgery. Rodgers et al. did not find a correlation between the number of levels and neurologic deficits but did find a statistically significant relationship to surgery at the L4-L5 level [9]. However, other studies and our study did not reproduce this correlation [12]. The complications reported here occurred at L4-L5 for 2 patients, L2–L5 for two patients, and L3–L5 for one patient, but no correlation exists to surgery time, EBL, or levels treated.

A case series of 107 patients found that the number of levels operated was the strongest predictor of complications, with an additional correlation of hip flexor weakness to surgery time [14]. However, our study did not analyze the relationship between the number of levels operated, the specific levels operated, and the surgery time.

This study does have limitations, largely related to its retrospective design. A multicenter prospective study is currently enrolling to further study outcomes and complications following LLIF surgery with RAVINE.

5. Conclusion

Minimally invasive spine surgery is associated with risks, regardless of the approach. Although some reports in the

Table 3: Lateral and posterior levels treated.

	Lateral levels treated	Number of patients, lateral	Number of patients with neurological complication*
One	L1-L2	3	0
	L2-L3	19	0
	L3-L4	52	0
	L4-L5	85	2
	L5-S1	1	0
Two	T12–L2	1	0
	L1–L3	4	0
	L2–L4	17	0
	L3–L5	34	1
	L4–S1	3	0
Three	L1–L4	1	0
	L2–L5	25	2
	L3–S1	1	0
Four	L1–L5	1	0
	L2–S1	6	0

* At final postoperative visit (average follow-up of 13.2 months).

literature have found correlations of certain risk factors such as levels treated, number of levels treated, and surgery time, with postoperative neurologic complications, this study data did not support those reports. The LLIF procedure minimizes the risks of anterior approach such as damage to major blood vessels resulting in potentially catastrophic blood loss and retrograde ejaculation. However access through the psoas in LLIF has potential neurologic complications. Recent literature concludes that neurologic complications following LLIF surgery are predominantly transient. The LLIFs performed here, using RAVINE Lateral Access System, add to the body of literature that most neurologic complications are transient and resolve by 12-month follow-up.

Disclosure

Pierce Nunley received royalties from Osprey Medical, LDR, and K2M and institutional support for research study from K2M. He owns stock in Amedica, Safewire, Paradigm, and Spineology. He is a speaker and teacher at K2M and LDR, serves on the Scientific Advisory Board of K2M, and is a consultant at Vertiflex. Faheem Sandhu received royalties from K2M. Marcus Stone and Kelly Frank received institutional support for research study from K2M.

Competing Interests

The authors declare that they have no competing interests.

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Clinical Study

Minimally Invasive Spinal Surgery with Intraoperative Image-Guided Navigation

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We present our perioperative minimally invasive spine surgery technique using intraoperative computed tomography image-guided navigation for the treatment of various lumbar spine pathologies. We present an illustrative case of a patient undergoing minimally invasive percutaneous posterior spinal fusion assisted by the O-arm system with navigation. We discuss the literature and the advantages of the technique over fluoroscopic imaging methods: lower occupational radiation exposure for operative room personnel, reduced need for postoperative imaging, and decreased revision rates. Most importantly, we demonstrate that use of intraoperative cone beam CT image-guided navigation has been reported to increase accuracy.

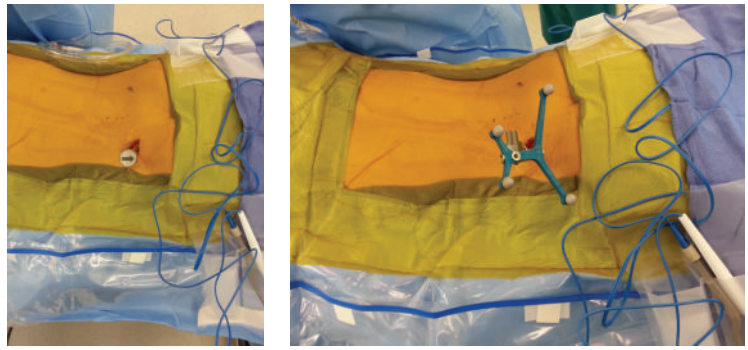
1. Introduction

Neurological sequelae may result from pedicle screw misplacement during spinal instrumentation and fusion, and inaccurate placement can be fairly frequent with conventional fluoroscopy [1–3]. Because of limited dissection and exposure during spine operations and especially with minimally invasive spine surgery (MISS) techniques, spine surgeons have heavily relied on intraoperative fluoroscopy for procedures such as pedicle screw insertion [4]. However, this has raised concerns over the level of radiation exposure for the all persons in the operating room.

The drawbacks associated with conventional intraoperative imaging methods have increased the interest in improving navigation methods in spine surgery, evolving tremendously over the last few years [5–12]. Use of 2-dimensional (2D) fluoroscopic navigation moderately decreased the number of improperly placed screws and introduction of preoperative CT scan imaging navigation techniques further reduced the percentage [13–15]. Such computer-based navigation technology has facilitated complex procedures in MISS, where visualization is limited. The use of 2D and 3D navigation systems during the last decade has made spine operations safer and less invasive [6, 16, 17]. Many authors have highlighted the use of image navigation for spinal operations as a way to decrease radiation exposure and operative time [18–20].

Most recently, introduction of the O-arm (Medtronic, Inc.) has allowed spine surgeons to perform minimally invasive procedures accurately, safely, and more efficiently [6]. The O-arm is a 3-dimensional (3D) imaging system that provides full 360° rotational capability that can interface with an external navigation system [21, 22]. While providing excellent imaging and navigation to guide an operation, the O-arm also permits the surgeon to obtain immediate CT images at the completion of surgery [5]. This would allow for immediate intervention if necessary before closure. Others have highlighted the O-arm's capability to obtain CT images with multicut reconstructions along with navigation to make it ideally suitable for MISS [21, 23].

In a recent international, multicenter, prospective study over a 16-month period, 353 patients underwent 1922 pedicle screw placements using the O-arm [5]. It was determined that 2.5% of the screws were misplaced and mean patient radiation dose was equivalent to half the dose of a 64-multislice CT scan [5]. Though the study contained a small number of



(a) (b)

Figure 1: Intraoperative images of the percutaneously placed reference pin and attached navigation frame in the left ilium inferior to the level of the posterior superior iliac spine (PSIS).

MIS cases, the authors suggested that future studies should evaluate the O-arm in a large series of MIS procedures.

In this paper, we describe our perioperative MIS technique for placing percutaneous spinal instrumentation utilizing the O-arm with navigation.

2. Surgical Technique and Pearls

2.1. Patient Positioning. All O-arm MISS patients were placed prone on a Jackson radiolucent spinal operating table, and all pressure points were padded appropriately. The dorsal lumbar spine was sterilely prepped and care was taken to drape the entire lumbar spine as wide as possible. The authors recommend having a wide draping area as it allows for skin surface anatomy identification (posterior superior iliac spine, iliac crest, and midline spinous processes) and gives orientation during the entire procedure.

2.2. Navigated Reference Frame. Selection of ideal reference frame and placement are dependent on the goals of the surgeon and anatomy of the patient. A percutaneous reference pin was routinely placed in the left ilium inferior to the level of the posterior superior iliac spine for short-segment percutaneous pedicle screw instrumentation (Figures 1(a) and 1(b)). For MISS in the lower lumbar spine (L3-S1), we found that the posterior superior iliac spine (PSIS) reference frame oftentimes interfered with the trajectory and instruments for insertion of the ipsilateral pedicle screws. As a result, in these instances, we would select a midline percutaneous incision directly over a proximal spinous process and use the navigated spinous process clamp reference frame directed away from the surgical area. Placement of the StealthStation workstation (Medtronic, Inc.) and StealthStation (LED detector camera) was placed at the foot of the bed for PSIS frames and head of the bed for the midline spinous process reference frame. Careful attention to "line-of-sight" issues for the navigated reference frame and StealthStation placement in the room are two examples of instrument issues that a surgeon must consider in order to maximize the workflow for a navigated MISS.

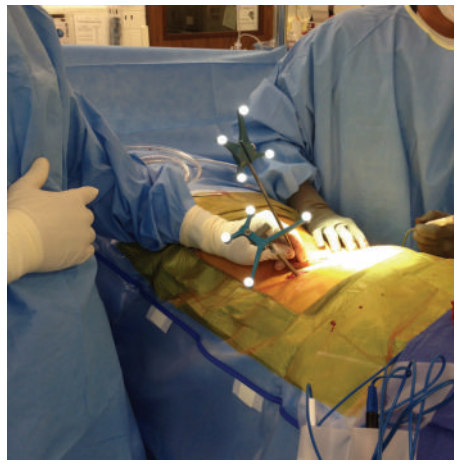


Figure 2: Intraoperative images demonstrating the use of the navigated probe to plan out the paramedian laterally based skin incisions.

2.3. CT Image Acquisition. Three-dimensional CT images were obtained using a cone beam mobile CT scanner (O-arm, Medtronic, Inc.) and were transferred to the computer-assisted StealthStation surgical navigation workstation. All navigated probes and instrumentation were calibrated. Although it is possible to keep the O-arm in the sterile surgical field during the entire procedure, it was our preference to remove the O-arm and station it in the operating room.

2.4. Incision. Paramedian laterally based skin incisions were planned out using a navigated probe (Figure 2). Planning pedicle screw trajectories using the navigated probe with "forward-projection" on the StealthStation allowed for accurate placement and incisional length. For patients where a midline incision was necessary (in the case of decompression), subfascial exposure or separate percutaneous paramedian skin incisions were selected for pedicle screw insertion.

2.5. Placement of Spinous Process Pin (Optional). In our earlier experience with PSIS percutaneous reference frames,

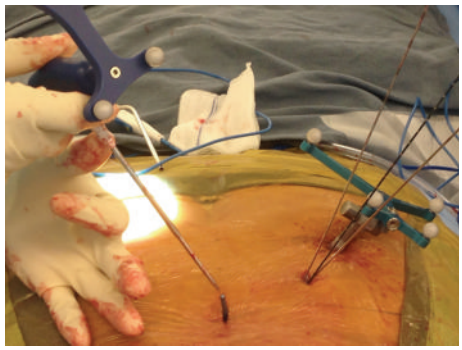


Figure 3: Intraoperative image demonstrating the Caspar pin that was inserted, prior to image acquisition, into the bony spinous process to enable the surgeon to use this pin as a reliable checkpoint for accuracy for all navigated instruments.

a Caspar pin was directly inserted through a percutaneous midline incision into one of the spinous processes within the acquired CT image. In MISS navigation surgery, there is oftentimes no clear anatomic point that can be referenced to determine navigation accuracy. Especially in morbidly obese patients, bony surface anatomy can be hard to palpate and assess. By obtaining a CT image with the Caspar pin inserted into the bony spinous process, the surgeon can reliably use this point as a check for accuracy for all navigated instruments (Figure 3).

2.6. Navigated Insertion of Instrumentation. A navigated dilator was inserted through the Wiltse paraspinal muscle interval and docked onto the ideal pedicle screw starting point—lateral to the facet joint (Figures 4(a) and 4(b)). Serial dilators were inserted and a navigated cannulated awl (Jamshidi) was used to enter the center of the bony pedicle canal as determined by the navigated axial, coronal, and sagittal planes (Figure 5). Precise placement of the initial Jamshidi is critical to achieving high accuracy with navigated MISS pedicle screws. Anatomic variances of dorsal vertebral bone surfaces and pedicle starting points can be irregular and difficult to dock. We found that it was critical to insert the navigated Jamshidi awl in a very lateral-to-medial starting trajectory in order to minimize "slipping" off the starting point. In addition, we emphasize inserting the Jamshidi with minimal pulling/pushing of surrounding soft tissue. Our technique emphasizes the concept of inserting the Jamshidi through the paraspinal muscles like "throwing a dart." Minimizing soft tissue retraction and manipulation minimizes variance in navigation trajectory and ultimately translates into more accurate pedicle screws. Guide wires were inserted through the cannulated Jamshidi to maintain pedicle trajectory and position. Once the pedicle was cannulated, a navigated tap was used to tap the bony pedicle tract and the desired size and length screw was determined via the StealthStation measurements. The largest sized pedicle screw with 1-2 mm of circumferential bony containment was finally inserted into the pedicle with a navigated screwdriver and confirmed on the StealthStation computer screw projection (Figure 6). It is noted that significant downward forces during tap cannulation and screw insertion can be applied to the vertebral body, thereby moving the vertebral body from its original imaged position. This can lead to significant inaccuracy and misplaced instrumentation. Current navigation technology is unable to account for shifts in vertebral body position and dynamic change in the spinal bony anatomy. As a result, we recommend extreme care in minimizing extreme forces that would displace or alter the alignment of the operated spine.

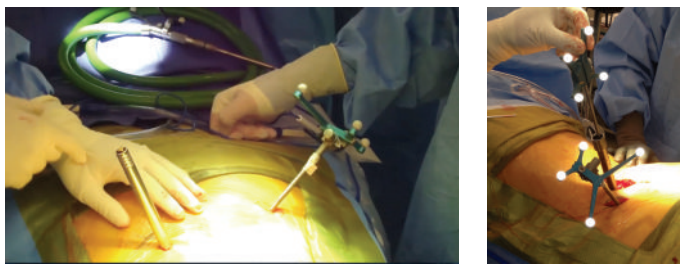
In short-segment lumbar fixation, we inserted the rod under direct visualization using a rod holder (Figures 7(a) and 7(b)). For longer segments and degenerative scoliosis cases, we utilized instrumentation that had low profile reduction MIS towers for ease of rod delivery (Figure 8). All patients underwent decortication and dorsal onlay of bone on the lateral lamina, facet, and transverse processes. Final MISS paramedian incisions are demonstrated next to a previous midline 2-level laminectomy incision (Figure 9).

2.7. Guide Wires. Management of guide wires during navigated MISS is extremely critical. As there is no ability to navigate the tip of the guide wire in real time, there is a theoretical risk of inadvertently pushing the guide wire through the vertebral body and into the abdominal cavity. In our technique, during navigated MISS, we pay special attention to guide wire location. After a cannulated instrument or screw is started in the proximal pedicle, we recommend pulling the guide wire back several inches. This essentially eliminates the possibility of inadvertent guide wire advancement. "Guide wireless" navigated MISS techniques have also been previously described [24]. The reverse-projection option on the StealthStation computer screen allows for saving of pedicle trajectory without guide wires. However, we found that using guide wires was much more reproducible and reliable and led to faster delivery of pedicle taps, screws, and overall surgery [7–9].

2.8. Postoperative Course. Intraoperative confirmatory O-arm images and postoperative CT scans were analyzed for evidence of bony pedicle wall breach. The majority of postoperative CT scans were obtained in the outpatient setting for diagnosis purposes or to confirm evidence of bony fusion. Whenever possible, immediate postoperative CT scans were generally not obtained on asymptomatic patients secondary to concern for undue radiation exposure.

3. Discussion

The newest generation of navigation technology—intraoperative computed tomography image-guided navigation (CT-IGN) with the mobile O-arm scanner—has made a tremendous impact on spinal surgery and there is a wealth of literature on the topic [10, 11, 25]. Increasing imaging resolution has led to improved accuracy of instrumentation placement in the thoracic and lumbar spine, primary versus revision cases, which has in turn led to overall superior clinical outcomes [6–9, 12]. Baaj et al. recently published an



(a) (b)

Figure 4: Intraoperative images demonstrating navigated dilators inserted through the paraspinal muscle and docked onto the ideal pedicle screw starting point as determined by navigation.

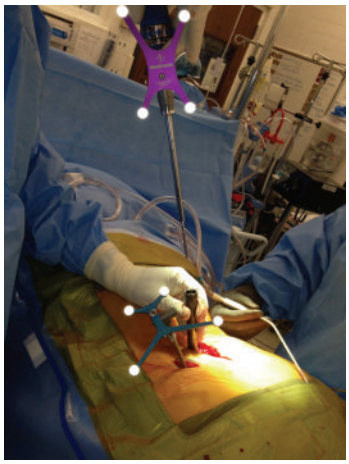


Figure 5: A navigated cannulated awl is passed through the soft tissue dilator and enters the center of the pedicle as determined by navigation.

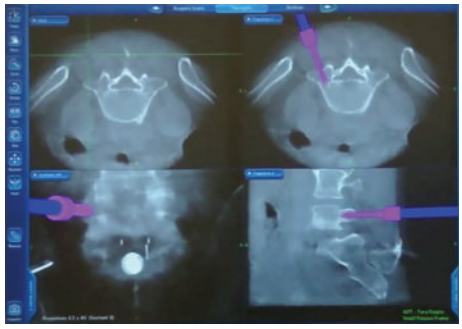
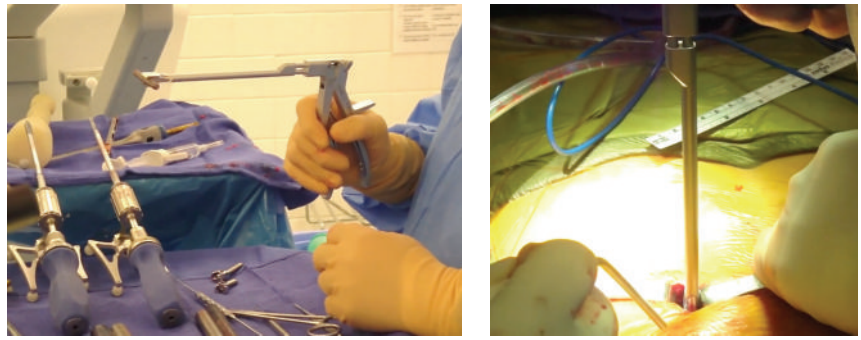


Figure 6: StealthStation computer screen projection of a pedicle screw being inserted into the pedicle with a navigated driver.

exclusive study on O-arm technology and its use in MIS spine surgery [25]. They presented 14 cases of complex, multilevel segmental fusions in which a total of 110 screws were placed percutaneously or transfascially. Their mean estimated blood loss (EBL) was minimal at 156 cc and mean operative time was 296 min, which included repositioning time. There were a total of 6 screw breaches (4 lateral and 2 medial) without neurological deficits. They concluded that their technique is practical and consistently reliable at providing insertion accuracy and corresponding improved outcomes, though long-term follow-up is required for confirmation. Cho et al. also studied the O-arm with mini-open TLIF and found 4 pedicle perforations >2 mm in 82 screw insertions in 20 patients without neurological injury [26]. Of special significance, they emphasized the importance of a cutaneous mounted dynamic reference frame in providing accuracy in 3D image-guided navigation, which in their study was over the sacral hiatus.

In a more recent study, Lau et al. investigated computer-guided intraoperative O-arm fluoroscopy in aiding the visualization of pedicle screw placement via minimally invasive transforaminal interbody fusion (MITLIF) [27]. While previous studies reported on the increased accuracy of percutaneous pedicle screw placement in MIS, Lau et al. reported the O-arm's effect on decreasing the incidence of facet violations [27]. Because in minimally invasive techniques screws are inserted percutaneously, there is decreased visualization of the facet joints and thus a risk of facet violation and future adjacent segment disease. While the authors expected lower rates of facet fusion, this was not the case. In fact, although not statistically significant and potentially confounded by higher body mass index (BMI) patients, the O-arm group had greatest facet violations. Adjusting for BMI, the O-arm group was not associated with higher or lower risk of facet violations, although BMI did remain as an independent risk factor [27].

Park et al. were the first to publish a study to evaluate the O-arm alongside minimally invasive pedicle screw placement [3]. In 11 patients with 52 screws, they found a misplacement rate of 7.5% and no breach was greater than 2 mm, numbers that were very similar to previous studies utilizing similar computer-guidance in open spinal procedures. Although a preliminary study in a small number of patients, their technique was found to be comparatively accurate and safe. A year later, Garrido and Wood reported their experience with the O-arm alongside MIS procedures in another region, the lumbopelvic junction [28]. Their goal was a technique for lumbopelvic fixation that would minimize extensive dissection and its associated sequelae, decrease radiation exposure, provide better picture quality, and facilitate the complexity of hardware placement. In the study, 5 patients underwent 10 O-arm guided iliac bolts with neither violations of the sciatic notch nor misplacement of bolts. At the same



(a) (b)

Figure 7: Intraoperative images of a short-segment lumbar fixation case demonstrating insertion of the rod under direct visualization using a rod holder.

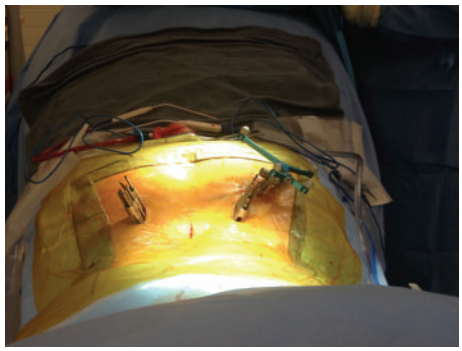


Figure 8: Intraoperative image of a longer segment lumbar fixation case utilizing instrumentation that had low profile reduction MIS towers for ease of rod delivery.

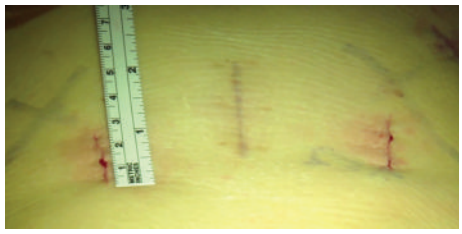


Figure 9: Intraoperative image of the MISS paramedian incision adjacent to a previous midline 2-level laminectomy incision.

time, their technique together with the O-arm helped them achieve the goals they set out to accomplish.

Three-dimensional image guidance has also been applied to the cervical spine. Because it offers a vast amount of anatomic information and allows safer approaches around complex anatomy, such technology can be quite helpful for navigating the cervical spine [23]. Though it was not a minimally invasive techniques-based study, Nottmeier and Young published on 3D image guidance for screw placement in the occipitocervical region [29]. Eighty-two screws in 18 patients were placed at C1, C2, or occipital levels without any complications and only a single screw had minimal breach postoperatively. Kim et al. published a series on modified transcorporeal anterior cervical microforaminotomy (MTACM) assisted by O-arm navigation [23]. They presented 8 patients with radicular upper extremity symptoms who underwent this procedure without complications and with postoperative improved symptoms. The combination of a minimally invasive technique and O-arm guidance enabled improving both the accuracy and the outcomes of the procedure. More recently, Del Curto et al. reported on a similar technique of minimally invasive posterior cervical microforaminotomy assisted by O-arm navigation with also similar effective and safe results [30].

Oertel et al. presented 50 patients that underwent spinal stabilization surgeries, 10 of which were through percutaneous pedicle screws [21]. Of the 278 total pedicle screws inserted, only 9 screws breached (all medially, <2 mm) without nerve root injury. They reported that, compared to standard CT-based navigation and Fluoromerge, O-arm-based navigation is the most precise and accurate method. Additionally, their experience indicated that the image quality of the O-arm is almost identical to a CT scan and only in patients with a weight of >250 lbs does the image quality begin to degrade. In terms of ergonomics and workflow, the authors stated that the apparatus is designed to best support a quick setup for easy acquirement of images with minimal technical hurdles and memory robotic movement to quickly relocate to the ideal position [21].

The O-arm's application to MISS procedure was recently described in a major study by Houten et al. [4]. They presented a large clinical series of MIS percutaneous screw placement using O-arm imaging and compared the results with fluoroscopy-guided surgery. All patients in the study underwent minimally invasive lumbar interbody fusion (MIS-TLIF, DLIF, and XLIF) mostly for the treatment of spondylolisthesis. The O-arm group had 52 patients with 205 screws and the fluoroscopy-based group had 42 patients with 141 screws. The perforation rate was 3% versus 12.8% ($P < 0.001$) and the mean operative time was 200 versus 221 minutes ($P < 0.03$), respectively. The study builds upon the results of Oertel et al., reporting similar excellent outcomes with O-arm in MISS cases [21]. Additionally, they found that image quality was maintained even with patients over

>300 lbs (maximum 339 lbs). Lastly, they noted that the O-arm allowed the surgeon to place screws without having to wear heavy lead which is required with fluoroscopy.

4. Advantages and Disadvantages of the O-Arm System

The cone beam O-arm system offers several advantages over prevailing imaging methods, especially for MISS which heavily benefits from use of navigation. There is the capacity for reduction in radiation exposure to the operating room staff that has been cited extensively in the literature [4, 5, 31, 32]. It was reported that, through an assessment of its dosimetric features, an O-arm scan sends about 50% of the radiation dose of 64-cut CT scan [33]. A second advantage of the cone beam O-arm is its ability to provide a more detailed view of the pedicles that allows for more accurate screw placement. This has been shown in studies to decrease the likelihood of neural injury and negative clinical sequelae [4]. Silbermann et al. also reported that navigation guidance with cone beam CT imaging was significantly more accurate in screw placement when compared with freehand technique, reaching almost 100% [34]. Accuracy of cone beam CT navigation has been packaged with automatic registration and versatility in software to minimize human error and reduce overall operative time. With the final ability to promptly acquire postoperative scans to avoid revision surgery, current technology cone beam CT navigation has evolved to provide the surgeon with numerous invaluable advantages. Disadvantages of current CT image navigation have also been reported. Current capital expenditure costs for the O-arm mobile CT scanner are estimated to be approximately $700,000 and the StealthStation guidance system approximately $250,000. Although costs of new technology are steadily decreasing over time, it is imperative that more research on cost-effectiveness be undertaken in order to financially justify navigation technology [10].

Competing Interests

The authors declare that they have no competing interests.

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Clinical Study

Technical Aspects on the Use of Ultrasonic Bone Shaver in Spine Surgery: Experience in 307 Patients

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Aim. We discuss technical points, the safety, and efficacy of ultrasonic bone shaver in various spinal surgeries within our own series. *Methods*. Between June 2010 and January 2014, 307 patients with various spinal diseases were operated on with the use of an ultrasonic bone curette with microhook shaver (UBShaver). Patients' data were recorded and analyzed retrospectively. The technique for the use of the device is described for each spine surgery procedure. *Results*. Among the 307 patients, 33 (10.7%) cases had cervical disorder, 17 (5.5%) thoracic disorder, 3 (0.9%) foramen magnum disorder, and 254 (82.7%) lumbar disorders. Various surgical techniques were performed either assisted or alone by UBShaver. The duration of the operations and the need for blood replacement were relatively low. The one-year follow-up with Neck Disability Index (NDI) and Oswestry Disability Index (ODI) scores were improved. We had 5 cases of dural tears (1.6%) in patients with lumbar spinal disease. No neurological deficit was found in any patients. *Conclusion*. We recommend this device as an assistant tool in various spine surgeries and as a primary tool in foraminotomies. It is a safe device in spine surgery with very low complication rate.

1. Introduction

Spinal surgery has improved with the introduction of operating microscopes and high-speed drills. Occasionally, a surgical approach requires microscopic bone dissection. However, the spinning and increased heat production when drilling with diamond burrs under the microscope may cause damage to the soft tissues such as the dura, nerve roots, the cord, and vessels.

Ultrasonic bone removers have been used for skull base surgery for several years [1] and they have been introduced to spinal surgery recently [2–6]. The most frequently used bone remover is "scalpel-type" ultrasonic bone curette. It has a thin (0.7 mm) and somehow wider tip, resembling a tip of a knife, which is available only for cutting bone. It creates a narrow incision in the vertebral arch for laminectomy and splitting laminoplasty [7–10]. However, due to its tip the "scalpel-type" ultrasound device is not used to remove osseous spurs or ossified lesions when decompressing the nerve roots. We report our experience and discuss the technique with the ultrasonic bone remover used with a microhook tip in cervical, thoracic, and lumbar spine surgeries.

2. Materials and Method

2.1. Subjects. From June 2010 to January 2014, 307 subjects with various spinal disorders were operated on using the ultrasonic bone shaver (UBShaver). Data from each subject were collected retrospectively from the hospital files. The patient's demographics, disease type, type of surgery, complications, preoperative Oswestry Disability Index (ODI) and Neck Disability Index (NDI), and one-year follow-up ODI and NDI scores were recorded.

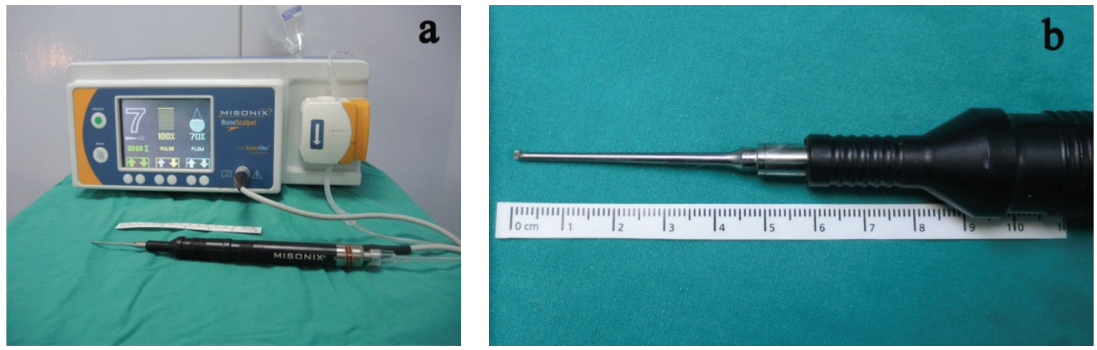
The number of patients, level of disorder, type of pathology, and surgical technique are presented in Table 1.

All patients have given their informed consent for participation in this study. This study has been approved by the local

Table 1: The number of patients, gender, age, surgical data, and follow-up data are given for each pathology type operated with the aid of Misonix ultrasonic bone shaver. Values are given as mean (range) when applicable.

Pathology level	Type of pathology	Number of cases (*n*)	Gender M/F (*n*)	Age at surgery (years)	Surgical technique	Operation duration (min)	Blood transfusion (mL)	Dural tear (*n*)	Preop ODI (%)	Postop ODI (%)	Preop NDI (%)	Postop NDI (%)
Lumbar	Unstable lumbar central and/or lateral stenosis (>1 level)	136	54/82	68 (45–71)	Laminectomy + extended foraminotomy + posterior stabilization + fusion	196 (90–257)	500 (250–750)	4	42 (32–56)	18% (6–28)	IA	IA
	Lateral recess syndrome	70	23/47	52 (31–68)	Hemilaminectomy + limited foraminotomy	75 (55–120)	0	1	38 (24–45)	16% (6–24)	IA	IA
	Far lateral disc	16	7/9	63 (43–72)	Lateral foraminotomy	73 (42–135)	0	0	25 (12–45)	8 (4–12)	IA	IA
	Recurrent disc herniation	32	14/18	58 (30–69)	Revision hemilaminectomy + limited foraminotomy	75 (64–134)	0	0	28 (14–35)	8 (2–12)	IA	IA
Thoracic	Spinal intramedullary tumors	5	1/4	46 (25–65)	Laminectomy	213 (75–278)	0 (0–250)	0	46 (32–56)	25 (8–36)	IA	IA
	Traumatic vertebral body fractures	12	8/4	57 (28–76)	Laminectomy and exposing pedicle anatomy	214 (97–256)	500 (0–750)	0	49 (42–56)	38 (12–48)	IA	IA
Cervical	Cervical stenosis	22	12/10	71 (65–78)	Posterior laminoplasty	154 (100–195)	500 (0–750)	0	IA	IA	58 (25–75)	16 (8–26)
	Chiari malformation	3	1/2	38 (29–45)	C1 laminectomy + foramen magnum decompression	143 (98–184)	250 (0–500)	0	IA	IA	12 (4–25)	8 (4–24)
	Cervical vertebral body fracture	3	2/1	47 (43–68)	Corpectomy + anterior fusion	137 (116–174)	500 (250–750)	0	IA	IA	68 (23–80)	34 (8–45)
	Cervical disc, calcified, and osteophytes	8	3/5	65 (47–73)	Resection of calcified disc and end plates	107 (65–146)	0	0	IA	IA	15 (2–18)	9 (3–19)

*Preop ODI: preoperative Oswestry Disability Index; postop ODI: postoperative Oswestry Disability Index; preop NDI: preoperative Neck Disability Index; postop NDI: postoperative Neck Disability Index; hr: hour; min: minutes; IA: inapplicable.



(a) (b)

Figure 1: (a) Misonix device with irrigation equipment and a straight hand piece and (b) tip of the Misonix ultrasonic bone shaver are illustrated.

ethical committee of Muğla Sıtkı Koçman University Ethical Committee-Clinical Research Section (BAP-02342014).

2.2. Instrument. We have used Misonix (MXB-S1, Farmingdale, New York, USA) as an ultrasonic bone curette which is designed for precise removal of rigid bone while remaining atraumatic to soft tissues underneath. The hand piece has an interchangeable tip with an irrigation jet nozzle. The tip of the instrument oscillates in linear fashion back to front at the frequency of ultrasound. It uses a piezoelectric transducer to convert electrical signal into a mechanical vibration. Micromovements are produced at the frequency of 22.5 kHz which only cuts mineralized tissue. We have used the microhook shaver tip (MXB-S1) which is 1.8 mm in width, with a short extension and a silicon cover (Figures 1(a) and 1(b)). The surgical device used at our unit comprised a power supply with a footplate and a straight hand piece.

2.3. Surgical Techniques

2.3.1. Lumbar Posterior Applications. The most frequent application of the UBShaver is for posterior lumbar surgery. It is practical and safe to use around the lateral recess and the foramen. The use of the thin ultrasonic bone shaver tip (1.8 mm) makes it safe to insert it into very narrow epidural space. In severe lumbar stenosis cases, we performed a total laminectomy with extended foraminotomy. The first step in laminectomy is to create a safe epidural space. It is an advantage to use UBShaver in very narrow epidural spaces where the Kerrison rongeur is not applicable. Once a window is opened, laminectomy is carried out with the Kerrison rongeurs or high-speed drills. After performing the laminectomy, the ligamentum flavum is exposed and the foraminotomy is started with removing the medial surface of the inferior articular process with the UBShaver. At this point it is crucial not to excise the ligamentum flavum too early, since it protects the dura underneath. Cotton patties are not needed as long as the ligamentum flavum is intact. Then the medial aspect of the superior articular process is exposed and removed with the UBShaver. The decompression of the neural foramen is continued by removing the lateral aspect of the superior articular process. If necessary, the inferolateral wall of the pedicle can also be thinned. The last step to decompress the foraminal exit zone is when the pars interarticularis is removed with the UBShaver.

In lateral lumbar stenosis surgery, we performed a hemilaminectomy with limited foraminotomy (Figure 2). Hemilaminectomy is performed in a similar fashion as described above. In limited foraminotomy, the medial surface of the inferior articular process and the superior articular process is removed, and the ligamentum flavum is excised. To be able to widen the lumbar foramen the decompression is continued with the medial part of the pars interarticularis. The anterior cortex of the pars interarticularis is removed along the nerve root, decompressing the foraminal exit zone, in cases with very lateral stenosis. In limited foraminotomy, the posterior surface of the pars interarticularis is kept intact with at least a five-millimeter thickness for stability reasons.

In far lateral disc herniation, the lateral foraminotomy was performed with a posterolateral muscle splitting approach [11]. The pedicle-transverse process junction and the intertransverse ligament are exposed. The lateral border of pars interarticularis together with the superolateral aspect of the superior facet of the caudal vertebra is excised by using the UBShaver to decompress the foramen laterally.

In recurrent disc herniation cases, the key step is to find the bony edge of the previous hemilaminectomy or foraminotomy site. The UBShaver is introduced to widen the foramen and to find the "untouched" dura through the fibrotic tissue.

2.3.2. Thoracic Posterior Applications. In cases of intradural or intramedullary spinal tumors the UBShaver can be used safely for the laminectomy at the thoracic level without putting any download pressure to the spinal cord. In vertebral body fractures at this level, in order to expose the pedicle, the UBShaver can also be used efficiently in similar fashion that is previously described in the lumbar section.

2.3.3. Cervical Posterior Applications. In the posterior cervical approach for an extensive ossified posterior longitudinal ligament and/or a severe canal stenosis, we have performed

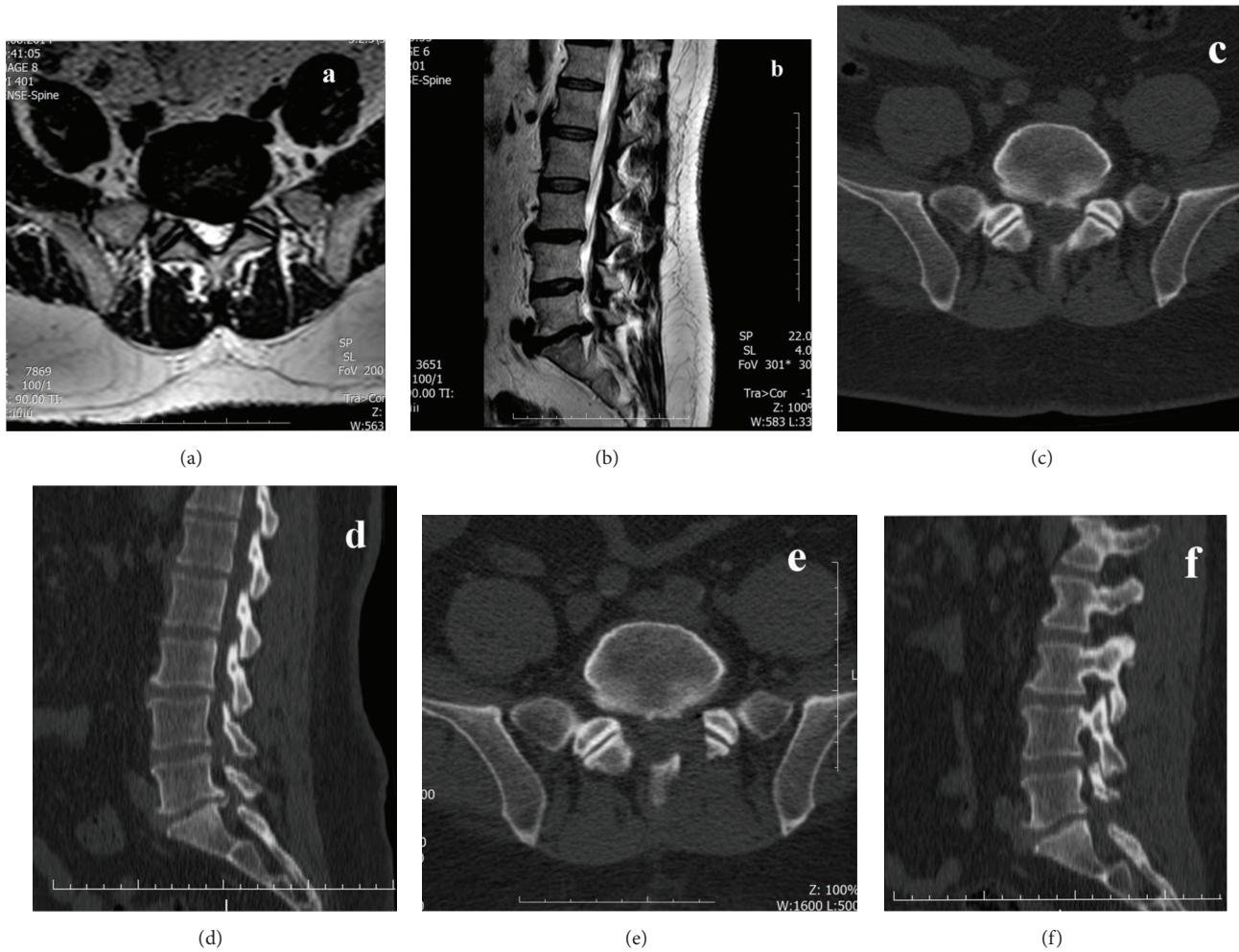


Figure 2: Preoperative (a) axial and (b) sagittal MRI with T2 weighted image and (c) axial and (d) sagittal CT images of a calcified left L5-S1 level disc herniation causing lateral recess syndrome and postoperative (e) axial and (f) sagittal CT images demonstrating decompressed foramen with limited foraminotomy.

an open door laminoplasty. The UBShaver is useful when removing the inner cortex of the lamina without damaging the epidural venous plexus and the nerve roots.

In foramen magnum decompression for a Chiari I malformation the decompression of the lateral edge of the foramen magnum is often not easy to perform, when using rongeurs and drills, due to the dull angle of the edge and fear of injuring the vertebral artery. With the UBShaver, the lateral edge of the foramen can easily be removed for foramen magnum decompression without any risk of damaging the vertebral arteries or the epidural venous plexus.

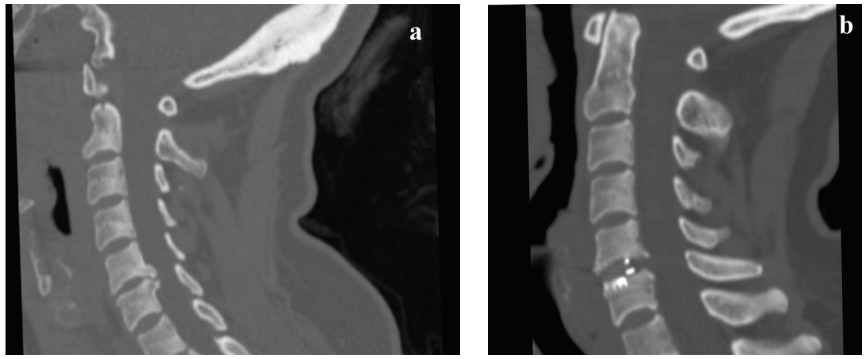
2.3.4. Cervical Anterior Applications. In an anterior approach for cervical disc herniation, osteophytes in the posterior surface of the end plates make the operation technically demanding. Removal of the osteophytes on both sides, close to the foramen, was done successfully with the UBShaver (Figure 3). However, it was challenging to remove the midline osteophytes because the hand piece has a short extension (57 cm) and blocks the microscopic vision. This problem was overcome by expanding the disc level with a Caspar distractor. However, we recommend the use of a longer tip or a tailor tip shaver for osteophytectomies in the anterior cervical approach.

In cases of cervical tumors or fractures, in which the corpectomy is needed, the UBShaver is the main tool to complete the vertebral body bone removal adjacent to the posterior longitudinal ligament.

3. Results

In the 307 cases we found a predominance of women (182 (59%)). The mean values of the operation time differ from 73 minutes to 196 minutes for different lumbar pathologies, 169 minutes to 213 minutes for thoracic pathologies, and 107 minutes to 154 minutes for cervical pathologies.

The need for blood transfusion was low. Most blood transfusions (500 mL) were needed for lumbar stenosis cases (136/307, 44%). For thoracic (12/307, 3%) and for cervical



(a) (b)

Figure 3: (a) Preoperative and (b) postoperative sagittal CT images of a C5-6 disc herniation with osteophytes.

(3/307, 1%) vertebral fractures the need for blood transfusion was low.

The mean preoperative ODI scores in lumbar and thoracal cases were highest in thoracal vertebrae fracture cases (48%). At the follow-up, one year after surgery, ODI score dropped to 18% in lumbar stenosis cases and to 8% in lumbar disc herniation cases. The preoperative NDI score in cervical cases was the highest at 68% in cervical vertebrae trauma cases and it dropped to 34% at follow-up (Table 1).

There were five cases of dural tear among the lumbar cases. Four of the patients with dural tear were severe stenotic cases. They had calcified dura mater at the midline laminectomy stage and no cerebrospinal fluid support to emulsify the oscillation power from the ultrasound device. The remaining one patient with a dural tear had a lateral recess syndrome. It occurred at the foraminotomy stage in which the ligamentum flavum was excised before the bony removal was done. All cases occurred in the first 50 cases when we started to use this instrument as an assisting tool.

There was no postoperative infection or wound healing problems, and we had no reoperations related to these morbidities. There were also no neurological deficits related to the application of this tool.

4. Discussion

We have experienced that the ultrasonic bone curette is a useful instrument in very narrow epidural spaces, while avoiding excessive heat production, minimizing blood loss and operating time, and therefore limiting the risk of mechanical injury. We can recommend the device for various spinal surgery fields and especially as the only tool in limited foraminotomies.

We have used the microhook shaver tip (1.8 mm) which can be easily introduced to very narrow epidural spaces. The shaver tip osteotome causes fragmentation and cavitation in the bone [17]. The hand piece is light weighted, can be readily manipulated with one hand, and is cooled by automatic irrigation of physiologic saline when applied [13].

There are several publications presenting successful applications of ultrasonic bone curette with various hand pieces (Table 2). It has been used for several indications from tumors to vascular malformations and for several levels from foramen magnum to sacral level [12, 14–19]. It is presented as either a primary tool for minimally invasive surgery or an assisting tool for decompression and stabilization. However, there are some concerns related to its application regarding heat generation and prolonged operating time. The heat generated by an ultrasonic device on bone has been reported to be no more than that generated by high-speed drills [19]. It has also been shown that there is no danger of causing thermal injury to the surrounding important neural and vascular structures [12]. However, one study reported a spinal cord injury caused by prolonged application of the instrument at one location [5]. Some authors have claimed that somewhat longer operation time was needed during application of the ultrasonic bone curettes when high amount of bone bulk was to be removed [8, 9]. They presented a mean operation time of 243 minutes for hemilaminectomy in mostly spinal tumor cases [8]. In our series, 118 (38%) patients with lumbar disc pathologies had a mean operating time of 75 minutes with the device as the primary tool. In 158 (51%) cases with cervical and lumbar stenosis the UBShaver was used as an assisting tool and the surgery was completed in approximately 180 minutes. Our figures were lower compared to data presented in literature and the surgeons felt that it reduced the time spent in the operating theater.

The incidence of injury to the dura mater has been reported to be similar or even lower by the use of the ultrasonic bone curette when compared with air drill systems [3, 4, 18]. Many have reported no complications with dural tear when using ultrasonic bone curettes [5, 6, 8, 9], and others have reported an incidence of dural tears between 1.6% and 9.8% [16, 19, 20]. In our series, with high number of cases, we had only five cases with dural tears (1.6%). Four of our patients with dural tear were severe stenotic cases with calcified dura mater which had no cerebrospinal fluid support to emulsify the oscillation power from the ultrasound device. The remaining one patient had a lateral recess syndrome. However, all these five patients were among the first 50 cases in our series and each surgeon (authors: Derya Burcu Hazer, Barış Yaşar, and Aytaç Akbaş) has experienced at least one dural tear within their first 15–20 cases. In these cases

Table 2: The literature review of the application of the ultrasonic bone remover.

	Instrument	Number of cases	Level of the pathology	Technique	Complication
Nakagawa et al., 2005 [4]	UBShaver	76	Chiari malformation, cervical, thoracic, lumbar	Microsurgical decompression	None
Schaller et al., 2005 [12]	UBC-scalpel	2	Tethered cord, lumbar	Laminectomy	None
Kim et al., 2006 [5]	UBShaver	546	Chiari malformation, cervical, thoracic, lumbar	Foraminotomy, lateral recess exposure	5 dural tears, 1 transient spinal cord injury
Nakase et al., 2006 [7]	UBShaver	98	Chiari malformation, cervical, thoracic, lumbar	Microsurgical decompression	None
Ito et al., 2009 [13]	UBC-scalpel	12	Lumbar	Laminoplastic laminotomy and hemilaminotomy	1 dural tear
Landi et al., 2011 [14]	UBC-not specified	1	Thoracal, calcified disc	Transversoarthropediculectomy	None
Matsuoka et al., 2012 [8]	UBC-scalpel	33	Chiari malformation, cervical, thoracic, lumbar	Recapping hemilaminoplasty	None
Morimoto et al., 2012 [10]	UBC-scalpel	26	Lumbar	Medial fenestration	None
Kim et al., 2012 [15]	UBC-unknown	Not detailed	Cervical	Foraminal decompression in cervical anterior fusion	Not detailed
Bydon et al., 2013 [3]	UBC-scalpel	88	Thoracolumbar	Microsurgical decompression	5 dural tears
Hu et al., 2013 [16]	UBC-scalpel	128	Chiari malformation, cervical, thoracic, lumbar	Facetectomy, laminotomy, laminectomy, en bloc resection, the Smith-Petersen osteotomy, pedicle subtraction osteotomy	2 dural tears
Al-Mahfoudh et al., 2014 [17]	UBC-scalpel	62	Chiari malformation, cervical, thoracic, lumbar	Laminotomy, corpectomies	1 dural tear
Bydon et al., 2014 [2]	UBC-scalpel	10	Thoracolumbar	Microsurgical decompression	3 dural tears
Onen et al., 2015 [18]	UBC-scalpel	23	Cervical myelopathy	Cervical laminectomy	1 C5 radiculopathy
Hazer et al., 2016 (this study)	UBShaver	307	Chiari malformation, cervical, thoracic, lumbar	Facetectomy, laminotomy, laminectomy, en bloc resection, pedicle subtraction osteotomy	5 dural tears

UBC: ultrasonic bone curette.

of lumbar stenosis the instrument was used as an assisting tool. Ligamentum flavum was removed in the beginning of the surgery and the dura was left bare. Additionally, in these first cases we have applied the instrument in a more "vertical plane." After these 50 cases, we have spared the ligamentum flavum to limit the risk of dural tear. We have also applied the instrument in a more horizontal plane to decrease the thickness of the bone rather than cutting it (Supplementary Video, in Supplementary Material available online at http://dx.doi.org/10.1155/2016/8428530). We can claim that surgeons who want to start using the instrument would need about 15–20 cases to reach their own learning curve and feel comfortable with the device as an assisting tool. We recommend that due to the depth of the surgical field and a more narrow working space the application of the instrument in anterior cervical cases should be performed after achieving the learning curve.

Some safety aspects have been pointed out by others. The energy of the instrument should be decreased to 60% and the instrument should not stay on one point more than 10 seconds [6, 21]. In laminectomy cases, the lamina can be thinned until a thin bone lamella is remaining and then cut with the bone curette [6].

To our knowledge the main reason for an iatrogenic dural tear when using the UBShaver is the application of the tip directly to one point for a long time. Additionally, with our described limited foraminotomy technique the posterior supporting elements, such as the supraspinous and

the interspinous ligaments and the spinous process, can be preserved [11]. We recommend intermittent usage of the device, cotton protection with constant irrigation, and use of an operating microscope when necessary.

In studies comparing the application of ultrasonic bone remover and high-speed drill in spinal cases, the hospital stay, the duration of the surgery, and the blood loss were found to be significantly lower with the ultrasonic bone remover [3, 18]. In our series we have also detected low blood loss and most of our cases were completed in 90 minutes. We have also found that the UBShaver has a local haemostatic effect and reduces the bone bleeding, which presented as no blood transfusion used in one-level lumbar surgery.

The clinical follow-up with the ODI and the NDI scores showed a decrease in the ODI score one year after surgery in lumbar stenosis cases (42% to 18%), and a similar major decrease was detected in the NDI score in cervical stenosis cases (58% to 16%). Our scores are similar to those found recently in the literature when using the conventional surgical method [20, 22]. No others, using the technique with ultrasonic bone removers, have been presenting data with a clinical improvement. A limitation of this study is the lack of a comparison group operated on with conventional techniques. However, we still believe that the equipment can improve spine surgery by decreasing the operating time and lowering the complication rates.

All new surgical devices have a learning curve. We would like to highlight some technical key points when using the UBShaver in spine surgery that might help surgeons who wish to use the equipment:

(1) Intermittent usage and cotton protection with constant irrigation are mandatory.

(2) In lumbar surgery the ligamentum flavum can be left until the end of the bone removal process, since it acts as a natural barrier.

(3) The ultrasonic bone remover with a shaver tip is very effective in foraminotomy when a lateral recess syndrome or far lateral stenosis is present. It can be used as the only instrument when performing a limited foraminotomy, without causing any instability.

(4) In anterior approaches to the cervical spine, especially when removing midline posterior osteophytes, a longer attachment and a tailor shaver tip should be used.

(5) In thoracic vertebral fractures the device can be used to expose the pedicle in dislocated vertebral fractures and performing laminectomies without applying any download pressure on the spinal cord.

5. Conclusion

The ultrasonic bone curette is a useful instrument, limiting heat production and decreasing the risk of mechanical injury, when applied close to dura mater or other neural tissues. We recommend the device for application alone in limited foraminotomy and in various other spinal surgery fields as a complement to high-speed drills and other instruments. However, further refinement of this tool is necessary before it can be used in anterior osteophytectomy in the cervical spine surgery. We suggest that the tips should be longer and have an ability to work at wider angles. The hand pieces should be made slender for easier maneuverability.

Competing Interests

The authors declare no competing interests. The paper submitted does not contain information about drugs.

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Research Article

Navigated Transtubular Extraforaminal Decompression of the L5 Nerve Root at the Lumbosacral Junction: Clinical Data, Radiographic Features, and Outcome Analysis

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Purpose. Extraforaminal decompression of the L5 nerve root remains a challenge due to anatomic constraints, severe level-degeneration, and variable anatomy. The purpose of this study is to introduce the use of navigation for transmuscular transtubular decompression at the L5/S1 level and report on radiological features and clinical outcome. *Methods*. Ten patients who underwent a navigation-assisted extraforaminal decompression of the L5 nerve root were retrospectively analyzed. *Results*. Six patients had an extraforaminal herniated disc and four had a foraminal stenosis. The distance between the L5 transverse process and the para-articular notch of the sacrum was 12.1 mm in patients with a herniated disc and 8.1 mm in those with a foraminal stenosis. One patient had an early recurrence and another developed dysesthesia that resolved after 3 months. There was a significant improvement from preoperative to postoperative NRS with the results being sustainable at follow-up. ODI was also significantly improved after surgery. According to the Macnab grading scale, excellent or good outcomes were obtained in 8 patients and fair ones in 2. *Conclusions*. The navigated transmuscular transtubular approach to the lumbosacral junction allows for optimal placement of the retractor and excellent orientation particularly for foraminal stenosis or in cases of complex anatomy.

1. Introduction

Compression of the L5 nerve root at the lumbosacral junction is a rare occurrence and is usually due to extraforaminal lumbar disc herniation (ELDH) or (extra)foraminal stenosis (EFS). ELDH or far-lateral disc herniations are relatively rare, accounting only for 1–12% of all lumbar disc herniations [1]. Extraforaminal disc herniations at the L5/S1 level are the most uncommon type, with reported rates from the magnetic resonance imaging era varying between 6.5 and 25% of all ELDH, while the (extra)foraminal stenosis is an underreported pathology and it is only recently that it has been studied as a distinct causative factor [2]. Although many surgical techniques have been described for the treatment of ELDH and EFS, there is rather a consensus that the extraforaminal, muscle-splitting, minimally invasive techniques come with many advantages for the stability of the lumbar spine and the postoperative course.

The short distance between the broad L5 transverse process and the sacral ala, the broader pars interarticularis of the L5 lamina, the coronally oriented facet joints, and the iliac crest laterally make the operative corridor very narrow, particularly in older patients with collapsing of the L5/S1 disc and facet hypertrophy. Adding to the anatomic constrains, the fact that the ELDH and EFS at the lumbosacral level are rare occurrences limits the surgeons' exposure and the possibility to become familiar with the extraforaminal decompression of the L5 spinal nerve. In this report, we introduce and discuss the combination of the neuronavigation with a minimally

invasive intermuscular approach utilizing a tubular retractor and the operating microscope.

2. Materials and Methods

Ten consecutive patients who underwent a navigation-assisted transmuscular transtubular approach for extraforaminal compression of the L5 nerve root were retrospectively analyzed. The records were reviewed for demographic data; type of L5 compression (herniated disc or extraforaminal stenosis); pre- and postoperative clinical symptoms, as well as duration of symptoms and type of conservative treatment used; intraoperative data; length of stay; and duration of follow-up. Pain evaluation and neurological assessment were conducted preoperatively as well as immediately postoperatively and at the time of the last follow-up examination, using the numeric rating scale (NRS), the validated German version of the Oswestry Disability Index (ODI-D), and the Macnab scale [3, 4]. All patients underwent a preoperative spiral CT and MRI imaging of the lumbar spine. The type of L5 root compression was classified as either "disc herniation"—when there was an extraforaminal rupture or a contained disc herniation—or as "(extra)foraminal stenosis" for the cases where there was a diffuse disc bulging with variable grade of segmental degeneration, causing intra- and/or extraforaminal compression of the nerve. Using reconstructed images on axial, sagittal, and coronal levels, two independent raters (P. Stavrinou and C. Kabbasch) measured the optimal angle of approach at an axial level; this was defined as the angle through which Kambin's triangle (i.e., the triangular space over the dorsolateral disc, the exiting nerve root, and the dura) could be approached with minimum interference from the iliac crest and the lateral facet. The distance between the L5 transverse process and the para-articular notch of the sacrum was also measured.

After induction of general anesthesia, patients were positioned prone on the carbon operating table with chest and pelvic bolsters. In lateral view, a 3 mm spinal process screw (25 mm length) was inserted in percutaneous fashion in the spinal process of L4 for fixation of the reference array. Using a Ziehm Vario 3D C-Arm (Ziehm Imaging GmbH, Germany), a 3D scan of the patient was acquired and the data set was transferred automatically to the navigation system. Using the Brainlab pointer and a virtual tip offset of variable length, the entry point and surgical trajectory were identified. A paramedian incision was made through the skin and fascia and, with the pointer as a guide, the initial dilator was passed through the paraspinal muscles until bone contact was made. After sequential dilation and insertion of the 19 mm dilator, the DePuy Insight Retractor was inserted and connected to the flex arm. At this point the position of the retractor was controlled with the navigation pointer and, if necessary, adjustments were made (Figure 1). Even before dissection of the soft tissue, the anatomic landmarks were identified with the pointer. The remnant soft tissue was removed under microscope until visualization of the lateral superior articular process of S1. Depending on the anatomical constrains in the individual patient, a drill was used to shave down the lateral facet and, if needed, the inferior margin of the L5

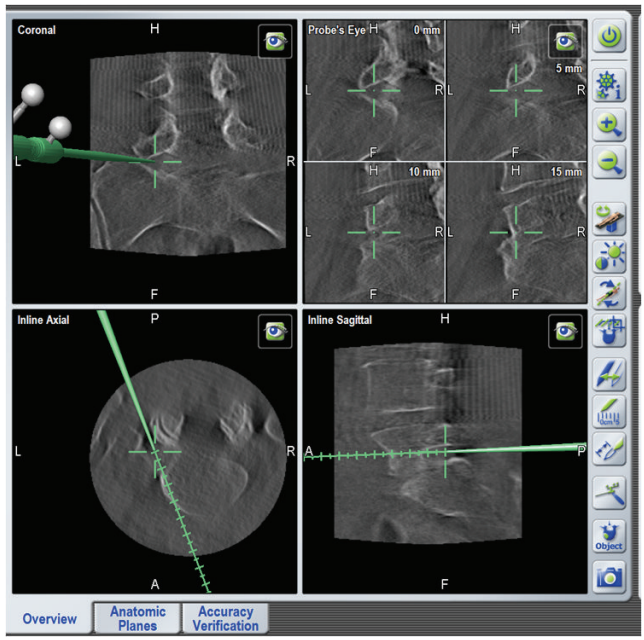

Figure 1: Screenshot from the Brainlab neuronavigation system. Orientation and identification of the anatomic landmarks with the use of pointer through the tubular retractor.

transverse process. Cranial angulation of the retractor as planned preoperatively helped to avoid the sacral ala in all cases. Further surgical strategy was adapted to the underlying pathology; in cases of a ruptured disc the nerve root was identified and retracted using a dissector, taking care not to injure the radicular vessels (Figure 2). The disc fragment was mobilized and removed with a hook followed by a conservative discectomy, meaning removal of disc material that may not be herniated yet but is in continuity with the herniated fragment or hanging loose in the intervertebral space. Removal of the whole disc material was not attempted. In cases of foraminal stenosis, the bony decompression is more important, and the drilling of the bony confines was more generous. After identification of the exiting nerve root, the osteophytes were also removed. Due to annular bulging, a discectomy was performed along the intra- and extraforaminal portion of the disc. At the end, the exploration along the nerve route up to the lumbosacral tunnel showed no signs of nerve impingement. Hemostasis was performed mainly with copious irrigation and bipolar cauterization as the retractor is slowly removed. No drainage was used and the wound was closed in standard fashion. Patients were mobilized on the first postoperative day.

3. Results

Of the ten patients treated, there were seven men and three women. The mean age was 50.2 (±12.1) years (range 35–75 years). All patients complained about unilateral radicular pain in the distribution of the fifth lumbar nerve root. The right side was affected in three (27.3%) and the left side in seven (63.6%) cases. All patients were initially treated

Table 1: Case summaries. LDH indicates lumbar disc herniation; RP: radicular pain; FF: foot flexion paresis; BTF: big-toe flexion paresis; SD: sensory deficit; PA: per os analgetics; IV: intravenous analgetics; Ph: physiotherapy; PRI: periradicular infiltration.

Case number	Age (yrs), sex	Pathology	Preoperative symptoms	Duration of symptoms (weeks)	VAS (preop)	Conservative treatment	VAS (postop-follow-up)	ODI	Macnab	Complications
1	42, F	LDH	RP	5	7	PA, IV	3-2	6	2	None
2	58, M	LDH	RP, FF(4), SD	48	10	PA, IV, PRI	2-5	32	3	Dysesthesia (3 months)
3	62, F	Stenosis	RP, FF(3), BTF(4)	4	8	PA, Ph	1-0	2	2	None
4	35, F	LDH	RP	2	9	PA, IV	2-2	12	2	Recurrence
5	37, F	LDH	RP, SD	2	9	PA, IV, PRI	5-2	22	2	None
6	48, F	Stenosis	RP	32	8	PA, PRI	2-0	2	1	None
7	44, F	Stenosis	RP	48	10	PA, IV, PRI	1-4	24	3	None
8	51, F	Stenosis	RP, SD	4	8	PA, IV	1-1	4	2	None
9	75, F	LDH	RP, FF(3), BTF(4)	5	9	PA, IV	2-1	4	1	None
10	51, M	LDH	RP	6	8	PA, IV	2-2	4	1	None

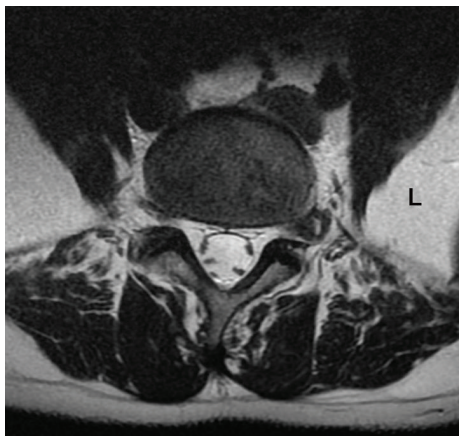

Figure 2: Axial T2-weighted MRI reveals extraforaminal ruptured disc on the left side (patient number 5). Therapy consists of removal of the fragmented disc segment without bone removal or discectomy. Navigation allows for a safe transmuscular approach.

Table 2: Summary of the radiographic measurements of the intertransversal space at the L4/5 and L5/S1 level as well as of the optimal angle of approach at the axial level.

	Mean	Min	Max	SD
Intertransversal space L4/5[†]	21.6	16.2	25.4	2.8
Intertransversal space L5/S1[†]	10.5	3	15.4	3.9
Angle of approach[*]	21°	14°	26°	21

[*]Interrater reliability $r = 0{,}71$ indicating substantial agreement between the two raters (P. Stavrinou and C. Kabbasch).
[†]Measurements in millimeter (mm).

conservatively with various methods, usually prescribed by the family physician. The duration of symptoms was highly variable, with seven patients complaining of acute onset and duration of pain of about four weeks and three patients reporting an aggravation of a familiar chronic radicular pain (Table 1). The pain was reported as being severe in all cases (mean NRS 8.6). Five of the patients complained about hypoesthesia or paresthesia along the L5 dermatome, while three of them also experienced a foot or toe flexion paresis. The mean preoperative ODI score was 64 (±19.4, range 30–94). Seven out of ten patients were overweight and the mean body mass index (BMI) was 27.7 (range 23.4–38).

Based on preoperative imaging as well as intraoperative findings, six patients had a disc herniation and four had a foraminal stenosis. On CT, the mean distance between the two adjacent transverse processes at the L4/5 level was twice the one measured between the L5 transverse process and the para-articular notch of the sacrum at the L5/S1 level, indicating a twice as narrow "working canal" through which the L5 nerve root must be decompressed. ($M_{\mathrm{L4/5}} = 21.6$ versus $M_{\mathrm{L5/S1}} = 10.5$ mm). Table 2 summarizes relevant measurement regarding the working canal and the optimal angle of approach.

Mean operation time was 130.5 minutes (range 98–217 minutes) with no significant difference between herniated disc and foraminal stenosis cases ($M_{\mathrm{dh}} = 137.8$ versus $M_{\mathrm{fs}} = 119.5$ min), and mean blood loss was 77 mL (range 50–150 mL). In only one patient with a disc protrusion was drilling of the lateral facet necessary; however, all foraminal stenosis cases required drilling of the facet joint and the caudal surface of the L5 transverse process. Conservative discectomy was performed in all cases. There were no intraoperative complications. One patient (patient number 4, Table 1) developed an early disc herniation recurrence which required a revision surgery, and another had dysesthesia along the L5 dermatome that resolved after three months. Mean hospital stay was five days. All patients reported significant relief of their preoperative pain. NRS at discharge averaged at 2.1. The patients were followed up for a mean of 22 (8–38) months.

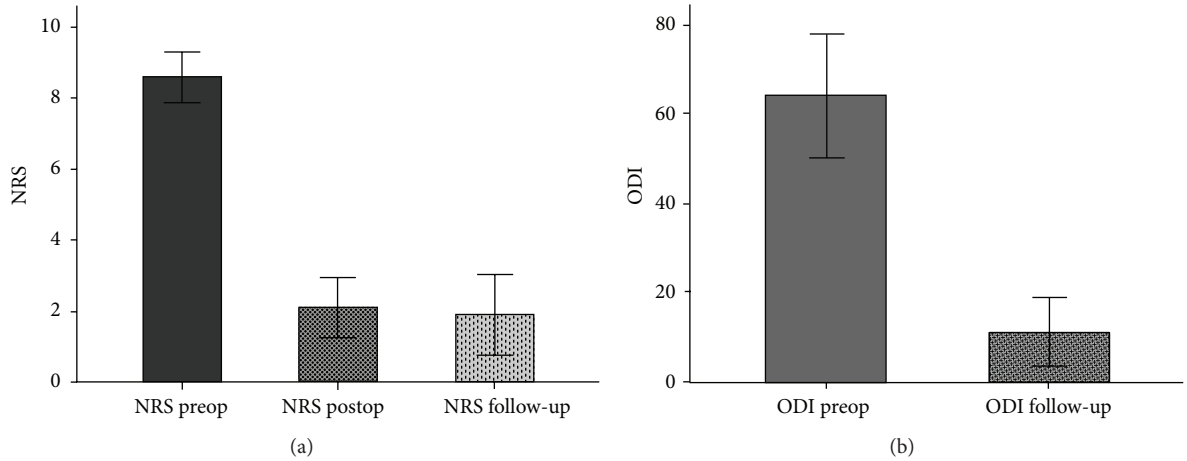

Figure 3: (a) Mean NRS preoperatively, postoperatively, and on follow-up. (b) Mean ODI-D preoperatively and on follow-up. Error bars show 95% CI.

All patients that had a preoperative motor deficit improved at least one grade on the muscle strength scale, while the sensory deficits resolved in all cases but one, in which a mild hypoesthesia persisted (Table 1). NRS on follow-up remained low ($M = 1.9$). Pain postoperatively, both directly after the operation and on follow-up, was significantly improved compared to preoperatively ($F_{(2,18)} = 115$, $p < 0.001$) (Figure 3(a)). There was also a significant improvement of the ODI score at the final follow-up compared to preoperative scoring ($M = 11$, $F_{(1.9)} = 142.4$, $p < 0.001$) (Figure 3(b)). General clinical outcome based on the Macnab scale was excellent in three (30%) patients, good in five (50%), and fair in two (20%). Nine out of ten patients returned to their jobs or resumed their preoperative activities.

4. Discussion

The extraforaminal disc herniation and (extra)foraminal stenosis at the lumbosacral junction are diagnostic and therapeutic challenges. The rarity of the ELDH and even more that of the EFS make these pathologies easy to overlook, often resulting in failed back syndrome [5]. Conservative treatment remains the first-line therapy, but it usually has limited effect on the marked pain due to the involvement of the dorsal root ganglion [6]. In our series, six out of ten patients had at least three CT-guided periradicular injections of the L5 root without relevant improvement (Table 1). For patients that fail conservative treatment, various surgical techniques have been discussed. Midline approaches with muscle retraction and partial facetectomy are widely employed, and the advantages and disadvantages have frequently been discussed [6–9]. In our opinion, the biggest advantage of the midline approach is familiarity with the procedure. The problem is that the anatomic features of the lumbosacral junction make this advantage less relevant. The coronally oriented facet joints; the wider pedicles; the shorter length from the caudal transverse process to the superior edge of the inferior articular process; and, more importantly, the prominent iliac crest make the necessary extended muscle mobilization and subperiosteal dissection extremely arduous. These difficulties become more evident in cases with foraminal stenosis. The foraminal stenosis in these patients is usually the combined result of the degenerative changes of the lumbosacral junction, that is, facet hypertrophy, disc collapse, osteophytes, and so forth. Decompression of the intra- and extraforaminal space in these cases is only possible with significant removal of the facet joint, which in turn can cause further accelerated degeneration with secondary instability and chronic lumbar pain [9]. On the other hand, since both the view and the approach are perpendicular, cautious reduction of the facet joint—in an attempt to prevent instability—can lead to remaining foraminal stenosis, particularly in cases with significant segmental degeneration or intraforaminal disc bulging.

The transmuscular paramedian approach to the extraforaminal space, first described by Wiltse and Spencer, requires no muscle detachment and less bone removal [10, 11]. With time, even more refined, minimally invasive techniques were developed, but, initially, the L5/S1 segment was still considered more or less *terra nullius*: Foley et al. described their experience with 11 patients with far-lateral disc herniations but did not operate at the lumbosacral junction [12]. Cervellini et al. presented their series of 17 patients but did not operate on the lumbosacral junction either, claiming that application of this technique is not possible at the L5-S1 level due to anatomical constrains [13]. Grainer-Perth et al. reported on 15 patients with ELDH that were treated with microendoscopic technique, but only one of them was operated on at the L5/S1 level with moderate results [14]. After 2007, several studies reported their results with minimally invasive extraforaminal decompression of the L5 nerve: Kotil et al. analyzed 14 patients and demonstrated effective decompression of the L5 root in 13 of them [15]. Pirris et al. presented their results on four patients using a muscle-splitting technique and a microscope, while Zhou et al. utilized a METRx intertransverse decompression on five patients with excellent outcomes in three and good outcomes in two [16, 17]. D. Y. Lee and S.-H. Lee

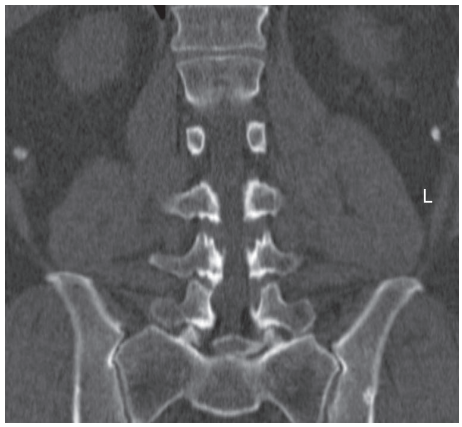

Figure 4: Extraforaminal stenosis at the lumbosacral junction. The degeneration of the lower lumbar spine leads to collapsing of the L5-S1 segment, contact between the sacrum and the L5-transverse process, and a very narrow operating window on the symptomatic side (left) that requires significant bone removal (patient number 3).

presented a large series with 65 patients who underwent microscopic decompression at the L5-S1 level [18]. They reported disappointing results—significantly worse than those presented in most studies—and attributed those to an incorrect understanding of the anatomy at the lumbosacral junction, especially in cases with foraminal compression of the L5 nerve.

The literature suggests very good clinical results with extraforaminal approaches—both microscopic and endoscopic—as long as there is adequate decompression of the affected nerve. The challenge is achieving an adequate decompression while at the same time avoiding unnecessary bone and soft tissue trauma all through a very narrow and deep corridor and a highly variable anatomy. The endoscope is certainly a valuable tool in experienced hands, but the learning curve is extensive. While most surgeons are familiar with the use of the microscope, operating through a tubular retractor limits the surgical exposure and deprives the surgeon of the familiar landmarks. Additionally, the rarity of the extraforaminal disc herniation and stenosis of the L5-S1 level makes it rather hard to accumulate experience, particularly in low-volume departments. The use of navigation helps circumvent that problem. It allows an optimal placement of the tubular retractor, even in the absence of any visual anatomical landmarks and an estimation of the distance to the structures of interest. Another significant advantage is the assessment of necessary bone removal in cases of foraminal stenosis or challenging anatomy: the inability to decompress the intraforaminal area has been considered one of the limitations of the approach (Figure 4). Navigation allows for a precise assessment of the necessary degree of facet resection, thus minimizing the risk for residual stenosis or instability.

Our results are comparable to those in the literature. It should be noted that most studies refer only to extraforaminal disc herniation. Very few previous studies have included patients with (extra)foraminal stenosis, sometimes with unfavorable results [18, 19]. In our small series, good results were achieved despite the fact that four out of ten patients had extra/foraminal stenosis. Moreover, none of the patients developed low back pain or did eventually require fusion. We believe this is also due to precise reduction of the surrounding bony structures, tailored to each patient's individual pathology and anatomy with the aid of the navigation. The mean blood loss of 77 mL is comparable with that described in the literature [16–18, 20], but our mean surgical time of 130.5 minutes is rather long. This could be attributed to three factors: first, the fact that four of our patients had an EFS which is more complex to treat than a disc herniation; second, most of our patients being overweight; and finally, the implementation of the navigation itself.

5. Conclusions

The transmuscular extraforaminal decompression of the L5 nerve root at the lumbosacral junction is an effective and minimally invasive technique. The aid of the navigation allows for a patient-tailored approach and adequate surgical exploration even in face of complex lesion anatomy.

Competing Interests

The authors declare that they have no competing interests.

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