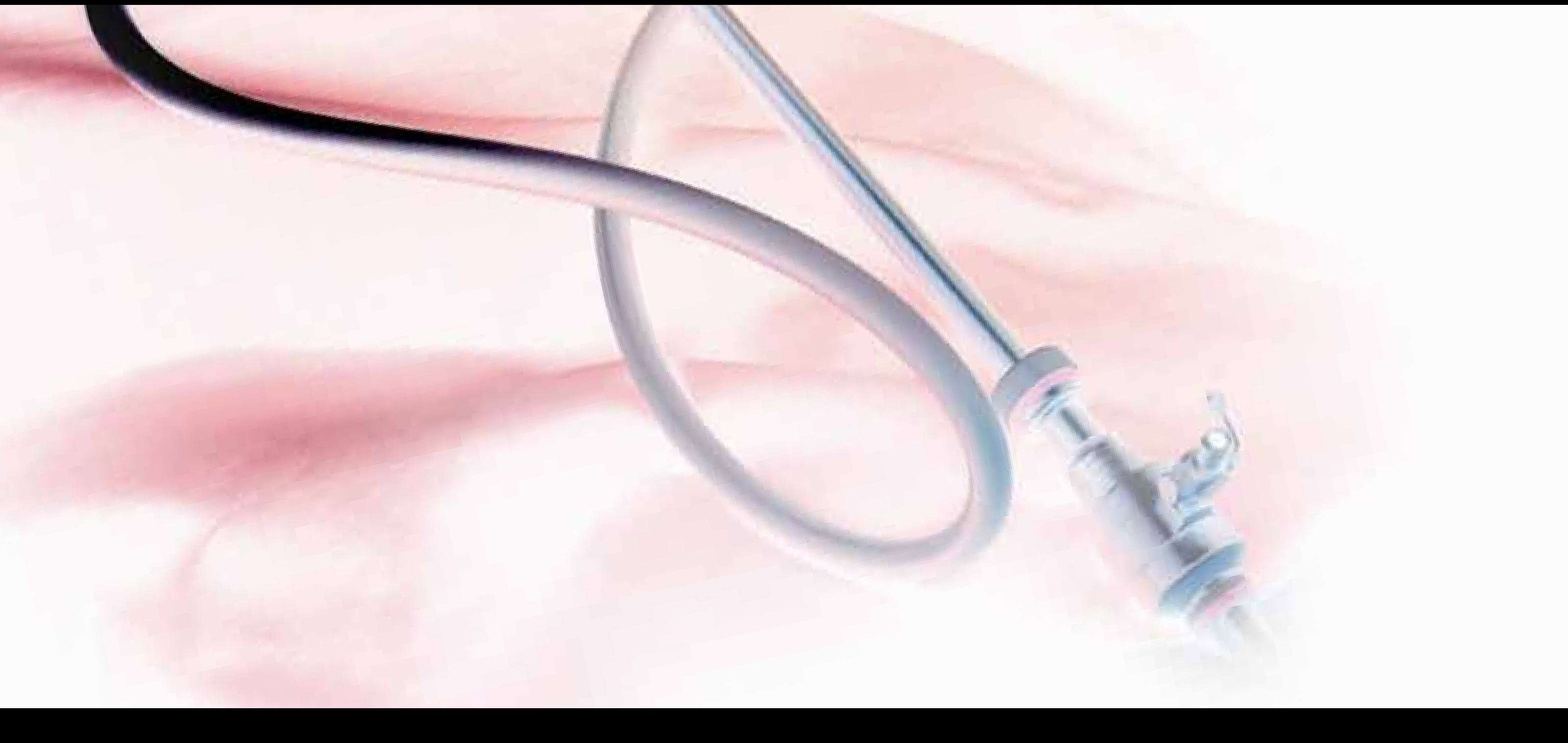
Minimally Invasive Surgery

Current Advances and Evidence in Minimally Invasive Spine Surgery

Guest Editors: Richard G. Fessler, Zachary A. Smith, Nicholas Slimack, Justin S. Smith, and Richard J. Parkinson



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Editorial Board

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Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 508415, 1 page
doi:10.1155/2012/508415

Editorial

Current Advances and Evidence in Minimally Invasive Spine Surgery

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Received 10 December 2012; Accepted 10 December 2012

It has been our privilege to serve as Guest Editors for this special focusing on the topic of current advances in *minimally invasive spine surgery*. Given the continuous and rapid advancement of spine technologies and techniques, an issue such as this can only begin by describing many of the advances in the field. However, with the critical help of our contributors, we hope this issue provides the readers with a better understanding of modern minimally invasive spine surgery.

The primary goal of minimally invasive surgery is to minimize procedure-related morbidity. Commonly, this is reflected in diminished tissue injury, less blood loss, shorter hospital stays, and decreased postoperative pain. To reflect this, two articles have discussed outcomes with two more established and commonly applied techniques. A. Wong and colleagues review the current literature reported on outcome data following the minimally invasive treatment of lumbar stenosis. Similarly, A. Habib and colleagues review outcomes following minimally invasive TLIF (transforaminal lumbar interbody fusion).

Minimally invasive techniques were first applied to a more focused scope of surgical indications. However, more recent advances have allowed surgeons to use these techniques for more challenging pathologies. Consistent with this, a number of articles in this issue address the technical nuances of these advanced techniques. For instance, F. De Iure and colleagues describe their experience in 122 patients treated with percutaneous fixation for thoracolumbar burst fractures. M. Wang describes and presents outcomes of a less invasive technique for the percutaneous placement of iliac screws. Additional articles address such topics as advances in interspinous fixation, the use of fenestrated screw technology, and operative corridors for minimally invasive corpectomy.

Acknowledgment

We would like to thank the participating authors for their time and contributions to this special issue. We have been fortunate to have the valued contributions of both orthopedic surgeons and neurosurgeons, each with a wealth of unique and rich experiences in the field. In addition, we would like to thank the editors and staff of the journal for their support, expertise, and patience during this undertaking. We hope this issue will act as a resource to stimulate further advances in the field and allow us to continuously improve the lives and health of our patients.

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Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 507826, 11 pages
doi:10.1155/2012/507826

Clinical Study

Minimally Invasive Spinal Arthrodesis in Osteoporotic Population Using a Cannulated and Fenestrated Augmented Screw: Technical Description and Clinical Experience

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Received 16 March 2012; Revised 30 June 2012; Accepted 5 July 2012

Academic Editor: Justin S. Smith

We describe a percutaneous or minimally invasive approach to apply an augmentation of pedicle fenestrated screws by injection of the PMMA bone cement through the implant and determine the safety and efficiency of this technique in a clinical series of 15 elderly osteoporotic patients. Clinical outcome and the function were assessed using respectively the Visual Analogue Scale (VAS) score and the Oswestry Disability Index (ODI). Peri- and post-operative complications were monitored during a minimum of 2 years of follow-up. Radiographic follow-up was based on plain fluoroscopic control at 3, 6 and 12 months and every year. In this approach, four steps were considered with care: optimal positioning of the screws, correct alignment of the screw heads, waiting time before the injection of cement, fluoroscopic control of the cement injection. Using these precautions, only 2 minor complications occurred. VAS scores and ODI questionnaires showed a statistically significant improvement up to 13.3 months postoperatively. No radiological complications were observed. Based on this experience, PMMA augmentation technique through the novel fenestrated screws provided an effective and long lasting fixation in osteoporotic patients. Applying this procedure through percutaneous or minimally invasive approach under fluoroscopic control seems to be safe.

1. Introduction

Due to the progressive increase of life span and the improvement of the quality of life (QoL) of the elderly, the surgical indications for degenerative and trauma lumbar spine in the aging population is increasing. The current elderly population desires to remain active and resists the acceptance of disability and low back pain. It becomes unavoidable for a spine surgeon to encounter patients with osteoporosis or other decreased bone quality who require spinal decompression and stabilization for degenerative spinal diseases, spinal trauma, infection, tumor, or inflammatory spinal diseases [1–3]. In the young population, the conventional posterior pedicle screw arthrodesis associated with lumbar interbody fusion (LIF) is widely used in spinal surgery to attain rigid stabilization after surgical intervention in situations leading to a progressive mechanical instability [4, 5]. Despite the demonstrated efficacy, some drawbacks are currently reported associated to the extensive soft-tissue dissection that is necessary to facilitate the insertion of the screws and prepare the fusion bed. The muscular incision increases perioperative blood loss, the postoperative pain, and the hospitalization time increases the risk of failed back surgery syndrome [6–9]. As a result, interest has increased for less traumatic surgical approaches that are associated with minimally invasive techniques for pedicle screw placement and LIF, with less postoperative pain and blood loss than conventional open procedures [10].

In the aging population, this interest for minimal invasive techniques is not as evident, probably because the conventional spinal arthrodesis is already considered as challenging [11, 12]. It has been well documented that bone mineral density (BMD) is one of the main factors related to spinal instrumentation failure. The ability of screws to

resist pullout from bone is directly related to the BMD [13]. Many potential complications, such as screw loosening, migration, or pullout, compromising the surgical outcome have been described. Several authors reported the efficiency of the augmentation techniques by injecting PMMA into the vertebral body through the pedicle before inserting the screw. However, most pedicle screws are not designed to be used with PMMA. Also, introduction of PMMA through a tapped hole can increase the risk of PMMA leakage through potential breaches that could occur in the pedicular wall during the tapping before screw insertion [14]. To avoid this, a novel-concept cannulated screw with fenestrations in the distal portion of the screw has been designed. After insertion of the screw into the pedicle, cement can be injected and will distribute evenly around the thread of the screw to improve fixation performance [15, 16]. The purpose of this paper is to describe a novel technique using cannulated and fenestrated PMMA augmentable screw in percutaneous and minimally invasive spinal posterior arthrodesis and to report the safety and efficiency of this technique in a prospective patient series.

2. Materials and Methods

2.1. Study Patients. A consecutive prospective series of 15 osteoporotic patients operated on between March 2010 and July 2011 (12 female, 3 male, mean age 71.2 years (60–88)) with osteoporotic compression/burst fracture (4 patients), degenerative spondylolisthesis (5 patients), and spinal and/or foraminal stenosis (6 patients) underwent MIS posterior pedicle arthrodesis with or without interbody fusion with PMMA cement augmentation of pedicle screws. All patients were included in this study based on the results of a DEXA bone mineral density examination showing osteopenia to severe osteoporosis according to the WHO criteria. The mean T score was −2.7 (−2.1 to −4.1). Figure 1 shows the new model of cannulated and fenestrated pedicle screw featuring fenestrations that allows cement injection through the implant. Expedium fenestrated screws (DePuy Spine, Johnson & Johnson) was used in all cases.

Inclusion criteria were as follows: (1) patient over 60 years of age; (2) demonstration by DEXA bone mineral density examination of osteopenia to severe osteoporosis according to the WHO criteria; (3) evidence of spinal trauma, degenerative or deformative spinal disorders with an indication of stabilization and realignment of the thoracolumbar or lumbar spine. Patients were excluded from the study in case of (1) previous history of spinal infection; (2) spondylolisthesis > grade III; (3) severely increased risk for surgery under general anaesthesia due to cardiovascular, pulmonary, or other concomitant diseases. The mean follow-up period was 13,3 months (6 to 24 months). Table 1 shows the demographic characteristics of the included patients and their clinical data. All patients were evaluated using CT scan or MRI to define the surgical indication and to measure the pedicle diameter and length prior to surgery.

In all cases, preoperative clinical data were collected: pain intensity was evaluated by the VAS and the function was assessed by the ODI [17].

Figure 1: The titanium Expedium fenestrated screw (VIPER MIS Spine System, DePuy Spine, Johnson & Johnson) is a polyaxial, fully cannulated with six fenestrations in the grooves of the distal portion of the thread and an opening at the distal tip.

2.2. Surgical Technique and Instrument. All the patients were operated under general anaesthesia. A “flash” dose of antibiotic (cephalosporin) was injected intravenously 1/2 hour before the incision and renewed once the surgery lasted longer than 3 hours.

Patients were placed in a prone position on a radiolucent standard operating table with chest and pelvis supported to gain correction of kyphotic deformity when needed. Conventional C-arm fluoroscopy was used for the entire procedure (Arcadis; Siemens; Munich, Germany).

The novel pedicle screw used in this series was the titanium Expedium fenestrated screw (VIPER MIS Spine System, DePuy Spine, Johnson & Johnson) which is a polyaxial and fully cannulated screw with six fenestrations in the grooves of the distal portion of the thread and an opening at the distal tip (Figure 1). A specific delivery system, including alignment guides, cement delivery cannula for use with the V-MAX Mixing, and delivery system, was used to inject the cement under controlled pressure through the cement cannula. PMMA bone cement (Vertebroplastic, DePuy Spine, Johnson & Johnson) (Figure 2) was extruded through the fenestrations to fill the spaces inside the osteoporotic cancellous bone.

2.3. Operative Steps. Under exact fluoroscopic anteroposterior view of the vertebral body, the projections of the target pedicles are identified and drawn on the skin. Depending on the surgical plan, a pure bilateral percutaneous pedicle screw arthrodesis or a combination of unilateral percutaneous associated with a contralateral mini-open (modified Wiltse [5]) can be realised.

For the pure percutaneous fenestrated screw placement, a skin incision is made 10 to 20 mm lateral to the pedicle's upper quadrant projection. The thoracolumbar fascia is split and a targeting needle is used to introduce a K-wire guide inside the pedicle. Successive AP and lateral fluoroscopic images are taken to accurately identify the pedicle entry point, the optimal position of the needle at the posterior wall of the vertebral body, and the good alignment of the needle with the desired screw trajectory. A K-wire guide is then placed in the needle and advanced in the two-thirds of the vertebral body. We placed pedicle K-wire guides in all target pedicles as during the first step of the procedure.

Dilators of progressively larger sizes are used to create the working channel by dilating the muscle tissue. A tap (undersized to the screw) is advanced over the K-wire to prepare the screw placement. The fenestrated screw is inserted into the pedicle guide over the K-wire with a selected

Table 1: Clinical data of patients undergoing fenestrated pedicle screw augmentation[a] through minimally invasive approach.

Patient number	Sex/Age (yrs)	Preoperative diagnosis	Comorbidity factors	Surgical history	T/	Fixation levels	Surgical procedure	Bone graft	Complication	PMMA extravasation (number of screw related)	FU (mo)
(1)	F/60	Degenerative discopathy, stenosis	None	Disc herniation	N	L3-S1	Percutaneous augmented FS + miniaccess TLIF	Autologous + allograft (Ant.)	Transient Radiculitis, Screw misplacement	None	24
(2)	F/61	L4 Burst fracture	BMI > 30, AVC, viral hepatitis, depression	N	Y	L3-S1	Percutaneous augmented FS	None	None	None	18
(3)	F/74	L1 Burst fracture	NH Lymphoma, cerebral hematoma, dementia, ethylism	N	N	D12-L2	Percutaneous augmented FS	None	None	None	12
(4)	F/73	L1 Burst fracture	Angor, ethylism, depression, arteritis MI	Disc herniation	Y	D12-L3	Percutaneous augmented FS	None	None	None	12
(5)	F/66	Degenerative spondylolisthesis, disc herniation	Nephrectomy, hypertension, pace maker, epidural fibrosis	Arthrodesis	N	L4-L5	Percutaneous augmented FS + miniaccess TLIF	Autologous + allograft (Ant.)	None	None	21
(6)	F/71	Degenerative discopathy, stenosis	None	N	Y	L3-S1	Percutaneous augmented FS + miniaccess TLIF	Autologous + allograft (Ant.)	None	None	12
(7)	M/70	Degenerative discopathy, stenosis	Hypothyroidism	N	N	L2-L3	Percutaneous augmented FS	None	None	Lateral external venous plexus, asymptomatic (1)	12
(8)	F/75	Degenerative discopathy, stenosis	Rheumatoid arthritis	N	N	L4-L5	Percutaneous augmented FS + miniaccess TLIF	Autologous + allograft (Ant.)	None	Posterior leakage asymptomatic (none)	14
(9)	M/83	Degenerative discopathy, stenosis	HTA, ischemic cardiomyopathy, prostate adenoma, atrial fibrillation, renal insufficiency	N	N	L4-S1	Percutaneous augmented FS + miniaccess TLIF	Autologous + allograft (Ant.)	None	Lateral external venous plexus, asymptomatic (1)	16

Table 1: Continued.

Patient number	Sex/Age (yrs)	Preoperative diagnosis	Comorbidity factors	Surgical history	T/	Fixation levels	Surgical procedure	Bone graft	Complication	PMMA extravasation (number of screw related)	FU (mo)
(10)	F/71	Degenerative discopathy, stenosis	Depression, hypertension	Laminectomy	Y	L4-S1	Percutaneous augmented FS	None	None	None	17
(11)	F/75	Degenerative spondylolysthesis, stenosis	BMI > 25, type 2 diabetes, hypertension, parkinson	N	N	L3-L5	Percutaneous augmented FS + miniaccess TLIF	Autologous + allograft (Ant.)	None	None	13
(12)	F/58	L4 burst fracture	Hypertension, depression	N	Y	L3-S1	Percutaneous augmented FS	None	None	None	10
(13)	M/78	Degenerative discopathy, stenosis	Obesity, hypertension, type 2 diabetes	N	N	L3-S1	Percutaneous augmented FS + miniaccess for bone graft	Autologous + allograft (Post Lat.)	Subcutaneous infection	Posterior leakage asymptomatic (1)	8
(14)	F/72	Degenerative spondylolysthesis, stenosis	BMI > 30, cerebral aneurysm embolized	Laminectomy	N	L2-L4	Percutaneous augmented FS + miniaccess for bone graft	Autologous + allograft (Post Lat.)	None	None	12
(15)	F/68	Degenerative spondylolysthesis, stenosis	None	Arthrodesis	N	L2-S1	Percutaneous augmented FS + miniaccess for bone graft	Autologous + allograft (Post Lat.)	None	Intradiscal extravasation, asymptomatic (1)	6
Total	12F/3M, 71.2 yrs[b]					78 augmented screws			2 out of 15, 13,3%	5 out of 15, 30% (no symptomatic)	13,3 mo mean FU

[a]PMMA: polymethylmethacrylate; [b]mean age (yrs); T/: tobacco; CA: carcinoma; BMI: body mass index; FS: fenestrated screws; TLIF: transforaminal lumbar interbody fusion; FU: followup; ant.: Interbody anterior bone graft; Post Lat.: posterolateral bone graft.

Figure 2: The cement is extruded through the fenestrations to fill the spaces inside the osteoporotic cancellous bone. The cement used is PMMA bone cement (Vertebroplastic, DePuy Spine, Johnson & Johnson).

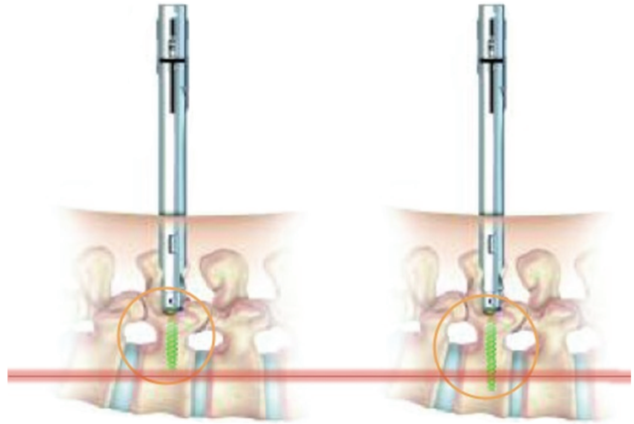


Figure 3: When fenestrated screw is placed through the percutaneous or miniopen approach, the length of screw is important because of the risk of extravasation of PMMA bone cement. An optimal alignment with the pedicle is recommended. Position of the holes must be located as far as possible from the posterior wall.

length of screw and the position of the holes, located as far as possible from the posterior wall to prevent possible PMMA leakage into the spinal canal (Figure 3). Each fenestrated screw is attached to an extender sleeve. When all the fenestrated screws are optimally placed, we suggest to make a trial of the unconstraint placement of the rod to avoid positioning issues during the definitive rod placement after cement injection. After PMMA augmentation, alteration of the screw position is no longer possible (Figures 4(a) and 4(b)).

The rod insertion is done through one of the percutaneous skin incisions under the muscular fascia. After correct rod placement, the closure tops are tested.

When a central canal decompression or a transforaminal interbody fusion (TLIF) is planned, the described percutaneous procedure is done unilaterally along with a miniopen approach as illustrated by Holly et al. [18] using a multiple blade retractor before the placement of the pedicle screws. The bone graft used for the TLIF or for the posterolateral fusion is a mixture of (1) autologous local bone shavings, (2) allograft from cadaver bone bank, and (3) bone marrow aspirated from the posterior iliac crest. When the canal recalibration or the placement of interbody cage filled with bone graft is done, the fenestrated screws are placed over the K-wire using the same steps as described before.

The screw and the cement delivery system are connected using a specifically designed connector. The PMMA bone cement is delivered through the cement cannula placed within the cannulation of the fenestrated screws under continuous image intensifier visualization (Figure 5). The amount of cement injected into each screw varies from 1.5 to 3 mL. We experienced that the ideal amount of cement to inject was 2 mL. To prevent cement leakage, the injection was done in a higher viscosity state (started 5 minutes after mixing). The cement injection was stopped in case of any leakage of cement (anterior, posterior, or into an adjacent disc) (Figure 6).

2.4. Perioperative Data. A total of 78 fenestrated screws were implanted (min 4; max 10 per patient), in combination with standard cannulated Viper screws (when sacral screws were placed bicortically). The operative blood loss, duration, and complications were monitored. PMMA extravasations were documented if occurred during the injection procedure.

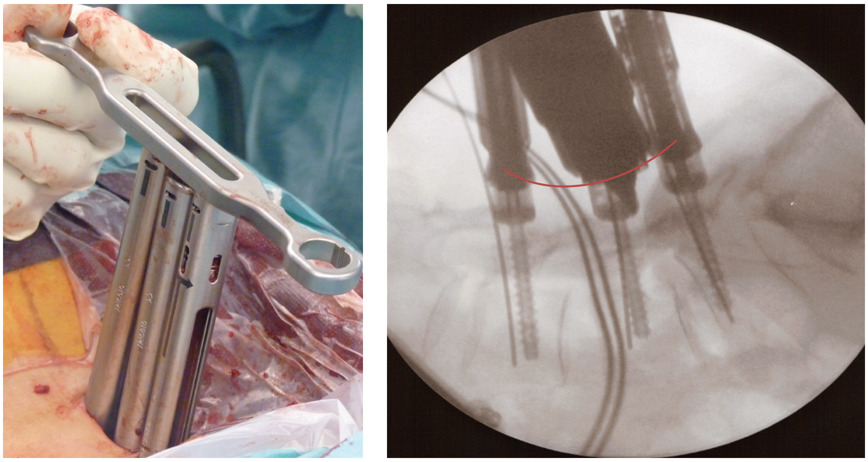
2.5. Postoperative Care. Depending on patient's clinical situation, patients were allowed to ambulate with protected thoracolumbar-sacral orthosis or lumbar-sacral orthosis 48 hours after surgery. The orthosis was maintained until the confirmation of the optimal screw placement and the absence of radiological complications on a postoperative thoracolumbar CT scan. All patients were followed up at the outpatient department at 3, 6, and 12 months, and then regularly every year.

The followup was clinically documented using the ODI [17]. In addition, the patients had to assess their radicular and low back pain on a 10 cm VAS between 0 (no pain) and 10 (maximal pain). The preoperative and postoperative VAS and ODI were compared with a paired t test. Statistical significance level was defined as $P < 0.05$.

2.6. Radiological Outcome Assessments. A radiographic evaluation was also performed at each followup based on standard radiographs for signs of screw loosening, loss of sagittal alignment (kyphosis), and screw migration. Optimal intervertebral or posterolateral fusion was considered on radiographs if (1) presence of bone bringing inside and/or around the cage and (2) absence of radiolucency lines around screws or cages were noted at 12-month follow-up radiographic control.

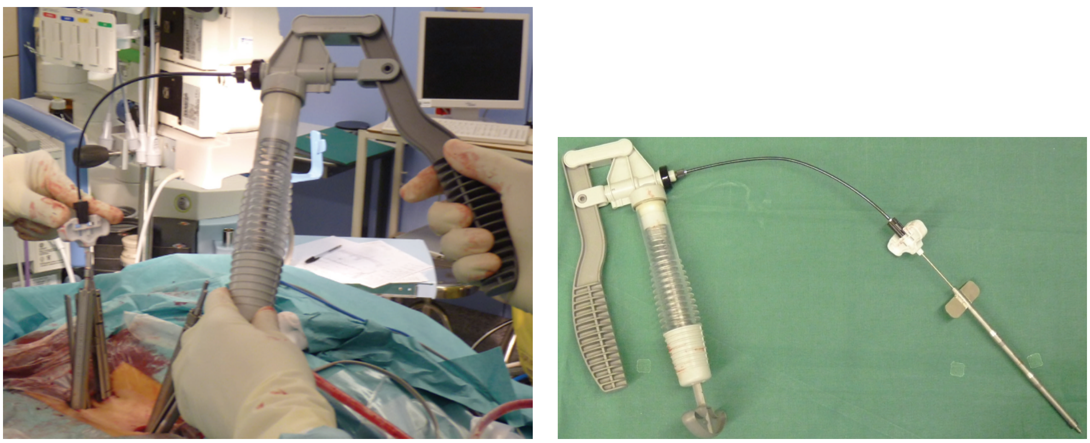
3. Results

The clinical results are summarized in Table 1. All 15 patients had osteoporosis with a DEXA bone mineral density examination showing moderate to severe osteoporosis.



(a) (b)

Figure 4: The optimal alignment of the heads of the screws is important. He can be controlled at the top of the screw extenders (a) or on a lateral fluoroscopic view (b). When all the fenestrated screws are optimally placed, we suggest testing the unconstraint placement of the rod to avoid positioning issues during the definitive rod placement after cement injection.



(a) (b)

Figure 5: The screw and the cement delivery system are connected using a specifically designed connector. The PMMA bone cement is delivered through the cement cannula placed within the cannulation of the fenestrated screws under continuous image intensifier visualisation.

Seventy-eight cement-augmented fenestrated screws were placed on a total of 82 screws (4 bicortical standard screws were placed in S1 without injection of PMMA). The surgical indication was degenerative in 73.3% (11/15 patients) and osteoporotic burst fracture in 26.6% (4/15 patients). Short segment fusions were performed in 3 patients to reduce operative times and minimize potential morbidity. Comorbidity factors were found in 12/15 of the patients. Medical history of previous spinal surgery was noted in 6/15 patients (2 disc herniation surgeries, 2 decompression laminectomies, 2 arthrodesis). 5/15 of the patients were smokers. The surgical procedure consisted of percutaneous stabilisation using the augmented fenestrated screws in 6 cases and an unilateral percutaneous stabilisation associated with a contralateral TLIF or bone graft placement through a miniaccess approach in 9 patients. The mean operative time was 165 min ± 54.4 (range, 80–275 min), and the mean perioperative blood loss was 261.4 mL ± 195 (range, 30–600 mL). The mean cement injection per pedicle was 2.02 mL ± 0.56 (range, 1.5–3.0 mL). The injection of PMMA was done in a minimum of 5 minutes after mixing to obtain a high viscosity consistency of the cement. Despite this waiting time, PMMA asymptomatic extravasations were observed in 5/15 patients. PMMA extravasations were posterior towards the spinal canal ($n = 2$), in the intervertebral disc ($n = 1$), and into the external venous plexus ($n = 2$). PMMA extravasations were noted in 4 of the 78 fenestrated screws placed (5% of screws). There were no cases of severe morbidity post-operatively (no death, no myocardial infarction, no pulmonary emboli, or intraoperative hypotension). Two postoperative complications related to the procedure were noted: and one S1 screw misplacement associated with a nerve radiculitis (no cement

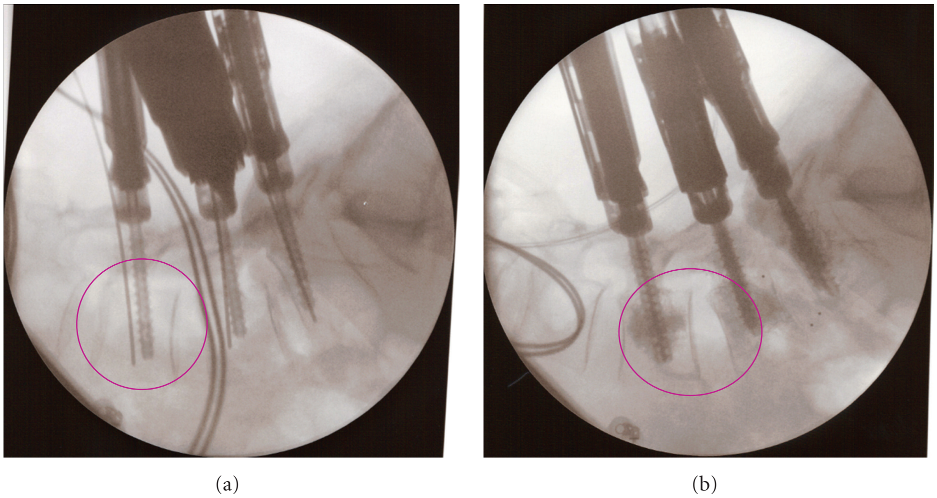


Figure 6: Injection must be done under fluoroscopic control to immediately stop the injection in case of cement extravasation.

Table 2: Means LVAS, RVAS, and ODI scores at preoperative, discharge, 6 months and 1-year postoperative.

	Lumbar VAS (LVAS)	Radicular (VAS)	ODI
Preoperative	7.6 ± 1.8	6.4 ± 1.7	34.1 ± 11.6
Discharge	4.4 ± 1.9*	1.6 ± 1.4*	
6 months postop.	3.0 ± 2.6*	1.5 ± 1.8*	16.2 ± 8.8*
1-year postop.	1.7 ± 2.9*	1.1 ± 1.5*	14.9 ± 9.7*

* $P < 0.01$ when compared to same score at preoperative.

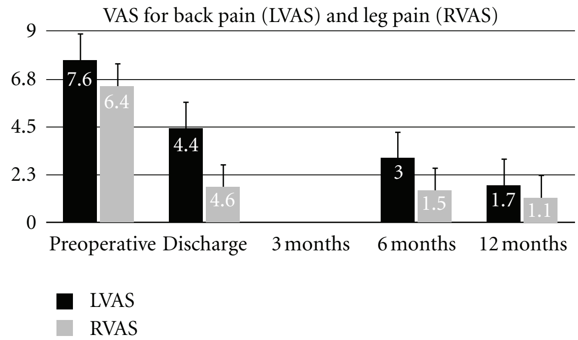


Figure 7: Clinical outcomes preoperatively and over 1 year postoperative followup. Results are expressed as mean scores ± Standard deviation at each time point. LVAS: Low back visual analogue score (1–10) of pain, RVAS: radicular VAS.

injected through this screw), one subcutaneous infection with multisensible *staphylococcus epidermidis* treated with 2 weeks of antibiotherapy. Patients were observed at regular intervals for a maximum of 2 years. The mean follow-up period in this study was 13.3 months (range, 6–24 months). At the end of follow-up period we noted no construct failure, no screw fractures, no loss of correction, or screw pullout.

Based on the VAS for back pain and leg pain, pain intensity was significantly improved at discharge, 6 months and 1-year followup (Table 2), The back function evaluated by ODI score showed significantly improvement when compared between preoperative and discharge period including 6-month and 1-year followup (Figure 7). Based on the 1-year follow-up Rx control, the fusion was considered as completed in all cases where TLIF or posterolateral bone graft were placed (7 patients). In fracture cases, no bone graft was placed. Nevertheless, the burst fracture was consolidated in all patients. In patients 7 and 10, despite the absence of interbody bone grafting, a spontaneous progressive interbody fusion was noted.

3.1. Illustrative Case

3.1.1. Presentation and Examination. This 83-year-old woman presented with more than 5-year history of low back pain, more significant left buttock, lateral calf, and foot pain, as well as intermittent claudication. The pain increased while walking, but the pain was reduced when sitting or bending forward. On physical examination, hypoesthesia was noted in the L5 dermatome bilaterally. The pinprick sensation was decreased in the L-5 dermatome and no motor weakness was detected. The deep tendon reflexes were reduced in the left leg and the straight leg-raising sign was negative. Electromyography examination suggested left L-4 and L-5 radiculopathy. Sagittal MR imaging revealed L4-L5 and L5-S1 discopathy and disc herniation, spinal stenosis, and bilateral foraminal stenosis more marked at the level (Figures 8(a) and 8(b)).

3.1.2. Surgical Procedure. A right percutaneous arthrodesis with augmented fenestrated pedicle screws in L4-L5 and S1 combined with a contralateral minimal access total L4-5 and L5-S1 facetectomy and TLIF (with interbody cages filled with a mixed allograft and autologous bone marrow) was performed. A recalibration of the canal was performed through the unilateral miniaccess. A minimal asymptomatic paravertebral lateral extravasation of PMMA was noted.

3.1.3. Postoperative Course. The patient's case was reviewed at 12 months postoperatively. Control lumbar spine radiography confirmed the stability of the fusion, as well as the absence of hardware failure (Figures 8(c) and 8(d)). Clinically, the patient noted a significant reduction of the preoperative pain and a walking perimeter objectively increased.

4. Discussion

In recent years, minimally invasive surgical techniques to perform spinal stabilization have gained in popularity due to the demonstration of reduced perioperative muscular damage, blood loss, postoperative pain, and rehabilitation time [19–24]. Reported as safe and effective in the normal population, those techniques have been referred to the aging population with poor bone quality as a contraindication. Indeed, in elderly patients, the conventional open procedure of arthrodesis using posterior pedicle screws are considered as a challenge. Many complications have been reported and correlated with decreasing bone mineral density [11–13].

Carreon et al. [25] reported after lumbar arthrodesis that at least 1 major complication occurred in 21% and at least 1 minor complication in 70% of elderly patients. Okuda et al. [26] reported 16% of postoperative complications in elderly patients after PLIF with pedicle screw placement. Dong et al. [27] was the first to analyse the potential interest of a mini-open TLIF approach for single-level instrumentation degenerative spondylolisthesis and stenosis with instability in elderly adults and reported a good clinical and radiological outcome associated with a low rate (7.4%) of minor complications. Nevertheless, more recently, in a larger retrospective series, Lee and Fessler [28] reported an overall rate of perioperative and postoperative complications of 20% without significant difference comparing with a young population. Karikari et al. [29] retrospectively reviewed their series of elderly patients who underwent minimally invasive lumbar interbody fusion and found an overall rate of major complications of 7.4% and a total complication rate of 32.4%. Unfortunately, they failed to distinguish posterior and lateral based approaches in their analysis of minimally invasive lumbar interbody fusion, limiting the applicability of their results. The mean followup in this study was 14.7 months. None of the above-mentioned studies reported their fusion rate at the end of followup.

In our study, we firstly describe the different surgical steps of the percutaneous (or through an miniopen access) placement of a novel cannulated and fenestrated screw designed to allow the injection of a PMMA bone cement through the implant following the optimal positioning of the screw inside the pedicle and the vertebral body. This augmentation technique was already reported in conventional open approach to reduce the complications related to the bone-implant interface (pullout of screw, implant fracture) [15, 30, 31] but never through a percutaneous or minimally invasive approach.

Various studies demonstrate that PMMA bone cement used to augment screws in osteoporotic bone enhance the screw-bone fixation by 49 to 162% [32, 33].

Fransen [15] suggests that the direct injection of cement through the screw can provide to the implant an immediate improved anchoring and that the filling of the vertebral body (VB) can decrease the risk of compression fractures at the treated levels. This technique can also be used in association with kyphoplasty of the fractured VB, allowing correction of the kyphosis with short-length constructs [15]. This augmentation technique also reduces the risk of extravasation of injected cement. Cement extravasation was observed when a screw was inserted inside a screw hole prefilled with cement [34]. In 2005, Yazu et al. published an experimental study conducted on osteoporotic cadaveric vertebrae and compared the performance of fenestrated screws with traditional screws without cement augmentation. Yazu et al. concluded that cement injection could be controlled more accurately using fenestrated screws, reducing the risk of leakage into the canal and/or foramina [35]. Recently, Amendola et al. [36] confirmed in a prospective cohort series of 21 patients that fenestrated screws for cement augmentation provided effective and long lasting fixation in patients with poor bone quality due to osteoporosis or tumors. No cases of loosening were recorded after a mean followup of 36 months. In our series, no major complication was reported. Two patients developed minor complications (1 transient radiculitis and 1 subcutaneous infection). There were no late complications after 1 year of follow-up. To the best of our knowledge, this paper is the first report of a cement augmentation technique of pedicle screws through a percutaneous or minimally invasive approach. In this technique, three steps must be considered as critical. First, the positioning of the screw must be perfectly aligned with the pedicle with a good convergent trajectory. No fractures of the anterior and lateral cortex of vertebral body can be tolerated to avoid cement extrusion in the retroperitoneal space. Secondly, to avoid breakage of the cement bridges between the screw and the bone, a definitive positioning of the screw must be controlled and the fixation system should be locked and the rods tested in position before injecting. No torsion movement should be applied to the screw after injecting the cement. Thirdly, the cement injection started only when the cement reached a high viscosity state to avoid extravasation. Finally, cement injection must be performed under continuous fluoroscopic imaging to provide immediate visual feedback and control to stop the injection in case of any sign of extravasation. Despite this caution technique, we report 33% of radiological PMMA cement extravasation; however, none were symptomatic. As it has been demonstrated that the pullout strength did not significantly increase with the volume of cement injected over a range of 1.5 mL [37, 38], we suggest to inject maximum 1.5 to 3.0 mL of cement per screw. In this serie, the mean volume of injection was 2.02 mL $\pm$ 0.56 per screw. In Table 3, we summarized the suggested tips to prevent PMMA cement extravasations.

Similarly, as described for the young population, in our elderly population the MIS procedures were associated with a low rate of peri- and postoperative blood loss, postoperative pain, hospital stay, and recovery time. The clinical state of the patients was significantly improved and this improvement was maintained during the short followup of this clinical

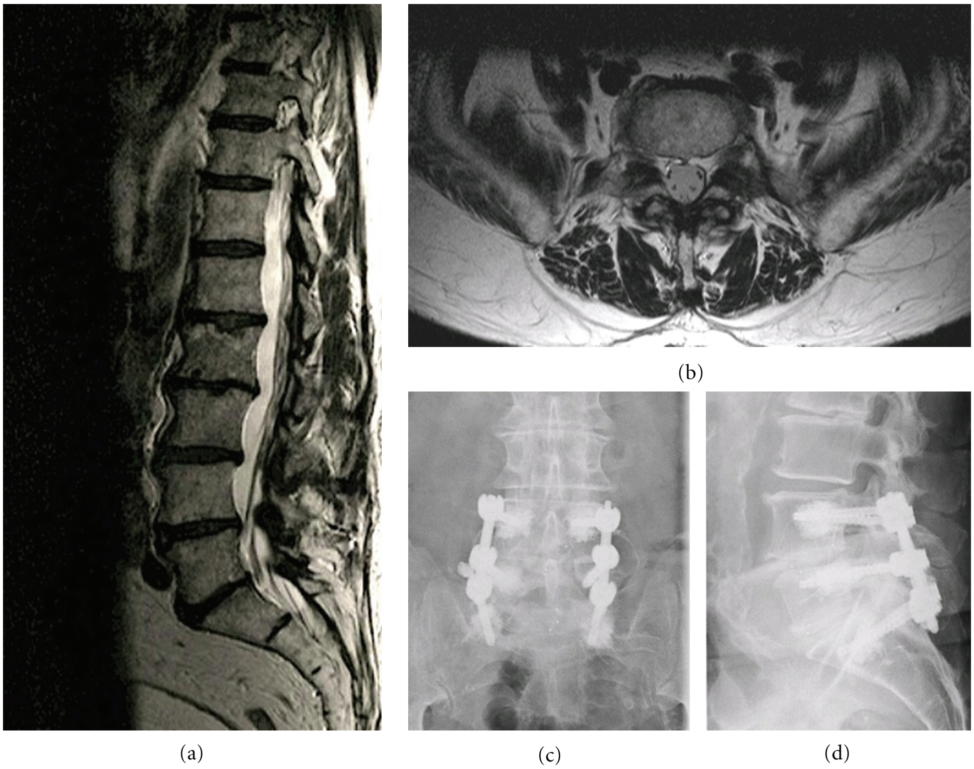


Figure 8: Illustrative Case number 9. Radiological studies obtained in a 83-year-old man. Sagittal (a) and axial (b) T2-weighted magnetic resonance images of the lumbar spine, showing narrowing of the spinal canal at L4–5 and L5-S1 and bilateral foraminal stenosis. (c and d): AP and lateral radiograph at 12 months postoperative demonstrating the proper position of the screws and cages, and the absence of implant-related complication.

Table 3: Tips suggested to prevent PMMA cement extravasations.

(1) An optimal positioning of the fenestrated pedicle screws is crucial
(2) Screws must be placed in the middle of the pedicle to avoid cortical breaches
(3) A good preoperative CT planning is recommended to select the correct diameter of screws
(4) No injection if breaches suspected or if bicortical screw fixation
(5) Start injection of cement when the high viscosity is obtained
(6) Make injection under fluoroscopic control
(7) Prefer the used of a controlled delivery system so as the V-MAX to be able to stop immediately the injection
(8) Avoid to inject high volume of cement (we suggest 1.5 to 3 mL/screw)

series. The radiological outcome was also excellent in all cases. Paré et al. [38] tested the biomechanical removal of cement augmented pedicle screws in cadaver spines. In the majority of screws, the removal was easy; in two removals, some bone cement remained attached to the screws and created secondary fractures to the pedicle. They suggested to control this potential removal in a real clinical situation under fluoroscopic control to prevent inadvertent damage on pedicle.

In this primary experience, a systematic amount of radiation exposure was not available. Nevertheless, we highly suggest to monitor the annual radiation exposure of surgeons and to apply all recommendations to reduce this exposure. The need for lead shielding cannot be overstated. The use of thyroid shielding, leaded glasses, and radiation attenuation gloves is absolute. Despite the interest of this study, a longer followup would be important in order to consider this novel technique as an effective one. A controlled randomized study could be suggested.

5. Conclusions

The PMMA augmentation technique of fenestrated pedicle screws is a safe technique to increase the pullout strength of screws placed in osteoporotic spines. This is the first clinical report of this augmentation technique through a percutaneous and/or a minimally invasive approach. We can confirm the safety and efficacy of this technique to prevent the short-time complications as described in performing arthrodesis in aging populations. The ultimate safety of using this technique in this vulnerable population needs of course to be confirmed in a larger series with a longer followup. The risk associated to PMMA extravasation remains the critical part of this technique. At the start of injecting the high viscosity consistency of the cement, the strict usage of fluoroscopic control should be used to immediately detect

any radiological sign of extravasation to prevent severe complications.

References

[1] R. T. Greenfield III, D. A. Capen, J. C. Thomas Jr. et al., "Pedicle screw fixation for arthrodesis of the lumbosacral spine in the elderly. An outcome study," *Spine*, vol. 23, no. 13, pp. 1470–1475, 1998.

[2] S. S. Hu, "Internal fixation in the osteoporotic spine," *Spine*, vol. 22, no. 24, pp. 43S–48S, 1997.

[3] K. Yone, T. Sakou, Y. Kawauchi, M. Yamaguchi, and M. Yanase, "Indication of fusion for lumbar spinal stenosis in elderly patients and its significance," *Spine*, vol. 21, no. 2, pp. 242–248, 1996.

[4] A. D. Steffee and D. J. Sitkowski, "Posterior lumbar interbody fusion and plates," *Clinical Orthopaedics and Related Research*, no. 227, pp. 99–102, 1988.

[5] L. L. Wiltse and C. W. Spencer, "New uses and refinements of the paraspinal approach to the lumbar spine," *Spine*, vol. 13, no. 6, pp. 696–706, 1988.

[6] B. R. Weber, D. Grob, J. Dvorák, and M. Müntener, "Posterior surgical approach to the lumbar spine and its effect on the multifidus muscle," *Spine*, vol. 22, no. 15, pp. 1765–1772, 1997.

[7] J. Rantanen, M. Hurme, B. Falck et al., "The lumbar multifidus muscle five years after surgery for a lumbar intervertebral disc herniation," *Spine*, vol. 18, no. 5, pp. 568–574, 1993.

[8] D. H. See and G. H. Kraft, "Electromyography in paraspinal muscles following surgery for root compression," *Archives of Physical Medicine and Rehabilitation*, vol. 56, no. 2, pp. 80–83, 1975.

[9] T. Sihvonen, A. Herno, L. Paljarvi, O. Airaksinen, J. Partanen, and A. Tapaninaho, "Local denervation atrophy of paraspinal muscles in postoperative failed back syndrome," *Spine*, vol. 18, no. 5, pp. 575–581, 1993.

[10] L. T. Khoo, S. Palmer, D. T. Laich, and R. G. Fessler, "Minimally invasive percutaneous posterior lumbar interbody fusion," *Neurosurgery*, vol. 51, supplement 5, pp. S166–S181, 2002.

[11] L. Y. Carreon, R. M. Puno, J. R. Dimar, S. D. Glassman, and J. R. Johnson, "Perioperative complications of posterior lumbar decompression and arthrodesis in older adults," *Journal of Bone and Joint Surgery A*, vol. 85, no. 11, pp. 2089–2092, 2003.

[12] C. S. Raffo and W. C. Lauerman, "Predicting morbidity and mortality of lumbar spine arthrodesis in patients in their ninth decade," *Spine*, vol. 31, no. 1, pp. 99–103, 2006.

[13] J. D. Coe, K. E. Warden, M. A. Herzig, and P. C. McAfee, "Influence of bone mineral density on the fixation of thoracolumbar implants: a comparative study of transpedicular screws, laminar hooks, and spinous process wires," *Spine*, vol. 15, no. 9, pp. 902–907, 1990.

[14] T. Takigawa, M. Tanaka, H. Konishi et al., "Comparative biomechanical analysis of an improved novel pedicle screw with sheath and bone cement," *Journal of Spinal Disorders and Techniques*, vol. 20, no. 6, pp. 462–467, 2007.

[15] P. Fransen, "Increasing pedicle screw anchoring in the osteoporotic spine by cement injection through the implant: technical note and report of three cases," *Journal of Neurosurgery*, vol. 7, no. 3, pp. 366–369, 2007.

[16] Y. Masaya, K. Akihiro, K. Riya, M. Kinoshita, and M. Abe, "Efficacy of novel-concept pedicle screw fixation augmented with calcium phosphate cement in the osteoporotic spine," *Journal of Orthopaedic Science*, vol. 10, no. 1, pp. 56–61, 2005.

[17] R. O. Niskanen, "The Oswestry low back pain disability questionnaire. A two-year follow-up of spine surgery patients," *Scandinavian Journal of Surgery*, vol. 91, no. 2, pp. 208–211, 2002.

[18] L. T. Holly, J. D. Schwender, D. P. Rouben, and K. T. Foley, "Minimally invasive transforaminal lumbar interbody fusion: indications, technique, and complications," *Neurosurgical Focus*, vol. 20, no. 3, article E6, 2006.

[19] R. E. Isaacs, V. K. Podichetty, P. Santiago et al., "Minimally invasive microendoscopy-assisted transforaminal lumbar interbody fusion with instrumentation," *Journal of Neurosurgery*, vol. 3, no. 2, pp. 98–105, 2005.

[20] J. D. Schwender, L. T. Holly, D. P. Rouben, and K. T. Foley, "Minimally invasive transforaminal lumbar interbody fusion (TLIF): technical feasibility and initial results," *Journal of Spinal Disorders and Techniques*, vol. 18, no. 1, pp. S1–S6, 2005.

[21] K. T. Kim, S. H. Lee, K. S. Suk, and S. C. Bae, "The quantitative analysis of tissue injury markers after mini-open lumbar fusion," *Spine*, vol. 31, no. 6, pp. 712–716, 2006.

[22] J. Wang, Y. Zhou, Z. F. Zhang, C. Q. Li, W. J. Zheng, and J. Liu, "Comparison of one-level minimally invasive and open transforaminal lumbar interbody fusion in degenerative and isthmic spondylolisthesis grades 1 and 2," *European Spine Journal*, vol. 19, no. 10, pp. 1780–1784, 2010.

[23] K. M. Scheufler, H. Dohmen, and V. I. Vougioukas, "Percutaneous transforaminal lumbar interbody fusion for the treatment of degenerative lumbar instability," *Neurosurgery*, vol. 60, no. 4, supplement 2, pp. S203–S212, 2007.

[24] F. Shunwu, Z. Xing, Z. Fengdong, and X. Fang, "Minimally invasive transforaminal lumbar interbody fusion for the treatment of degenerative lumbar diseases," *Spine*, vol. 35, no. 17, pp. 1615–1620, 2010.

[25] L. Y. Carreon, R. M. Puno, J. R. Dimar, S. D. Glassman, and J. R. Johnson, "Perioperative complications of posterior lumbar decompression and arthrodesis in older adults," *Journal of Bone and Joint Surgery A*, vol. 85, no. 11, pp. 2089–2092, 2003.

[26] S. Okuda, O. Takenori, A. Miyauchi, T. Haku, T. Yamamoto, and M. Iwasaki, "Surgical outcomes of posterior lumbar interbody fusion in elderly patients," *Journal of Bone and Joint Surgery A*, vol. 88, no. 12, pp. 2714–2720, 2006.

[27] Y. L. Dong, T. G. Jung, and S. H. Lee, "Single-level instrumented mini-open transforaminal lumbar interbody fusion in elderly patients," *Journal of Neurosurgery*, vol. 9, no. 2, pp. 137–144, 2008.

[28] P. Lee and R. G. Fessler, "Perioperative and postoperative complications of single-level minimally invasive transforaminal lumbar interbody fusion in elderly adults," *Journal of Clinical Neuroscience*, vol. 19, no. 1, pp. 111–114, 2012.

[29] I. O. Karikari, P. M. Grossi, S. M. Nimjee et al., "Minimally invasive lumbar interbody fusion in patients older than 70 years of age: analysis of peri-and postoperative complications," *Neurosurgery*, vol. 68, no. 4, pp. 897–902, 2011.

[30] M. C. Chang, C. L. Liu, and T. H. Chen, "Polymethylmethacrylate augmentation of pedicle screw for osteoporotic spinal surgery: a novel technique," *Spine*, vol. 33, no. 10, pp. E317–E324, 2008.

[31] M. H. Hu, H. T. H. Wu, M. C. Chang, W. K. Yu, S. T. Wang, and C. L. Liu, "Polymethylmethacrylate augmentation of the pedicle screw: the cement distribution in the vertebral body," *European Spine Journal*, vol. 20, no. 8, pp. 1281–1288, 2011.

[32] J. S. Tan, C. S. Bailey, M. F. Dvorak, C. G. Fisher, P. A. Cripton, and T. R. Oxland, "Cement augmentation of vertebral screws enhances the interface strength between interbody device and vertebral body," *Spine*, vol. 32, no. 3, pp. 334–341, 2007.

[33] D. J. Burval, R. F. McLain, R. Milks, and S. Inceoglu, "Primary pedicle screw augmentation in osteoporotic lumbar vertebrae: biomechanical analysis of pedicle fixation strength," *Spine*, vol. 32, no. 10, pp. 1077–1083, 2007.

[34] P. I. J. M. Wuisman, M. Van Dijk, H. Staal, and B. J. Van Royen, "Augmentation of (pedicle) screws with calcium apatite cement in patients with severe progressive osteoporotic spinal deformities: an innovative technique," *European Spine Journal*, vol. 9, no. 6, pp. 528–533, 2000.

[35] M. Yazu, A. Kin, R. Kosaka, M. Kinoshita, and M. Abe, "Efficacy of novel-concept pedicle screw fixation augmented with calcium phosphate cement in the osteoporotic spine," *Journal of Orthopaedic Science*, vol. 10, no. 1, pp. 56–61, 2005.

[36] L. Amendola, A. Gasbarrini, M. Fosco et al., "Fenestrated pedicle screws for cement-augmented purchase in patients with bone softening: a review of 21 cases," *Journal of Orthopaedics and Traumatology*, vol. 12, no. 4, pp. 193–199, 2011.

[37] B. M. Frankel, T. Jones, and C. Wang, "Segmental polymethylmethacrylate-augmented pedicle screw fixation in patients with bone softening caused by osteoporosis and metastatic tumor involvement: a clinical evaluation," *Neurosurgery*, vol. 61, no. 3, pp. 531–537, 2007.

[38] P. E. Paré, J. L. Chappuis, R. Rampersaud et al., "Biomechanical evaluation of a novel fenestrated pedicle screw augmented with bone cement in osteoporotic spines," *Spine*, vol. 36, no. 18, pp. E1210–E1214, 2011.

Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 657342, 9 pages
doi:10.1155/2012/657342

Review Article

Minimally Invasive Transforaminal Lumbar Interbody Fusion: A Perspective on Current Evidence and Clinical Knowledge

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Received 17 March 2012; Accepted 17 June 2012

Academic Editor: Nicholas Slimack

This paper reviews the current published data regarding open transforaminal lumbar interbody fusion (TLIF) in relation to minimally invasive transforaminal lumbar interbody fusion (MI-TLIF). *Introduction*. MI-TLIF, a modern method for lumbar interbody arthrodesis, has allowed for a minimally invasive method to treat degenerative spinal pathologies. Currently, there is limited literature that compares TLIF directly to MI-TLIF. Thus, we seek to discuss the current literature on these techniques. *Methods*. Using a PubMed search, we reviewed recent publications of open and MI-TLIF, dating from 2002 to 2012. We discussed these studies and their findings in this paper, focusing on patient-reported outcomes as well as complications. *Results*. Data found in 14 articles of the literature was analyzed. Using these reports, we found mean follow-up was 20 months. The mean patient study size was 52. Seven of the articles directly compared outcomes of open TLIF with MI-TLIF, such as mean duration of surgery, length of post-operative stay, blood loss, and complications. *Conclusion*. Although high-class data comparing these two techniques is lacking, the current evidence supports MI-TLIF with outcomes comparable to that of the traditional, open technique. Further prospective, randomized studies will help to further our understanding of this minimally invasive technique.

1. Introduction

The advent of minimally invasive surgery has provided surgeons new techniques for treating clinical disease. Within the field of spinal surgery, techniques in lumbar interbody arthrodesis have shown a continued evolution of procedural approach and instrumentation. Minimally invasive spine surgery aims to reduce approach related morbidity, while producing clinical outcomes comparable to its open predecessors. One important example of this is the development of minimally invasive techniques for lumbar interbody fusion, including transforaminal lumbar interbody fusion (TLIF) [1].

The MI-TLIF technique, has displayed comparable outcomes to open TLIF, while adding the benefits of less approach-related morbidity, decreased intraoperative blood loss, and shorter hospital stays [2]. However, critics of the technique have noted that the MI-TLIF has longer operative times and exposes patients to increased fluoroscopic radiation. Over the past decade MI-TLIF has been shown to have a number of benefits, especially with regard to perioperative outcomes. However, it may have its own unique challenges and potential morbidity. Ultimately, comparing the known literature of a traditional, open TLIF approach to published reports on MI-TLIF will identify the unique risks and benefits associated with each. This understanding may help guide improved clinical decision making for patients presenting with lumbar degenerative disk disease.

In this paper, we evaluate the literature to examine the efficacy of MI-TLIF compared to its open counterpart. In addition, key studies discussing the risks and benefits of MI-TLIF were included to more thoroughly explore the nature of the technique and its application.

2. Materials and Methods

In this paper, the authors have used the PubMED/MEDLINE search engines to search for relevant reports addressing the topic of transforaminal lumbar interbody fusion. This was primarily done from Janurary 2000 to Janurary 2012. However, a few historical reports have been added for completeness. Included in this search was the following key phrases: "Minimally invasive," "transforaminal," "interbody fusion,"

and “lumbar.” We included only English language reports. Further, although articles were first identified by abstract, only full text manuscripts were used to compile this review of the topic. We did not include individual case reports unless associated case series data was included. Further, inclusion criteria were based on the study’s contribution in terms of original data, technical variations, and contrasts between open and minimally invasive versions of the procedure ideally completed at the same institution.

In total, 14 articles were selected on the aforementioned basis. All contributed to the established body of the literature pertaining to lumbar arthrodesis techniques, particularly different variants of TLIF. Six of the 14 articles were prospective studies, while the remaining 8 were retrospective (Table 1).

3. MI-TLIF Technique

After failed conservative management for a minimum of 6 months, surgery becomes the next therapeutic option for patients presenting with degenerative disc disease (DDD), radiculopathy with spinal instability, and/or grade 1 spondylolisthesis. Initially patients are assessed through radiological investigations including X-ray (AP, lateral, flexion, and extention), and noncontrast lumbosacral MRI. Length of hospitalization is determined by postoperative pain control and functional dependence, with patients of advanced age or medical comorbidities often requiring longer postoperative recovery. However, a majority of patients are admitted the day of surgery and discharged within 24–72 hours after operation.

Under general anesthesia, patients are fixed in a Wilson frame in a prone position. The patient is prepped and draped in standard fashion, and a fluoroscopic C-arm is positioned in the sterile field. Under fluoroscopic guidance the appropriate level is marked and a 3 cm incision is made 4.5 cm of off midline. A k-wire is targeted to the bony complex at the surgical level and serial dilators are consecutively passed to split the muscle fibers. Proper orientation is confirmed by fluoroscopic imaging. A working channel is placed, the dilators are removed, and the channel is secured appropriately for adequate visualization of the medial portion of the facet and inferior lamina. A curette is used to detach the ligamentum flavum from the inferior edge of the lamina, and a kerrison is used to perform the hemilaminectomy. The unilateral facet can be removed using an osteotome or high-speed drill. Following adequate exposure of the disc space, a discectomy is performed using a pituitary rongeur and curette.

Curved and angled curettes and a disc scraper are then used to prepare the end plate. An appropriately sized interbody spacer is inserted into the disc space, and a half sponge of BMP is packed into the disc space. Fluoroscopy is used to confirm proper positioning of the interbody cage. After removal of the working channel, a jamshidi needle is localized to the unilateral pedicle either above or below the discectomy level, and positioning is checked using fluoroscopic imaging. A K-wire driver is used to insert a guide wire into the superficial portion of the pedicle. A SEXTANT percutaneous screw system (Medtronic Inc; Memphis, TN) is used to pass a cannulated pedicle screw over the K-wire and into the pedicle under fluoroscopic guidance. This is repeated at all desired pedicles on either side. The SEXTANT holding sleeves are mated, the percutaneous rod holder and guide are attached, and a small skin incision is made to pass the rod percutaneously through the screw head. After correct positioning of the rod is confirmed with fluoroscopy, the screw head is tightened, the rod holder is released, and the holding sleeve is removed. Skin closure is accomplished in the standard fashion. For a full detailed description see Lawton et al. [18], see Figures 1 and 2 for illustrative cases from patients treated with the MI-TLIF procedure.

4. Review of the Literature

As noted, our review included 14 articles. Follow-up times ranged across all articles from 6 months to 42 months. The mean follow-up was 20 months, with a mean patient cohort of 52 patients. Within seven of the articles that directly compared outcomes of open TLIF with MI-TLIF, mean duration of MI-TLIF surgery was 220 minutes, compared to 218 minutes for its open counterpart. Furthermore, blood loss was found to be on average 282 mL in MI-TLIF cases, while open TLIF resulted in 693 mL of blood loss. The length of stay for MI-TLIF was found to be 5.6 days, while open TLIF had patients in the hospital for an average of 8.1 days (see Table 2).

4.1. Complications. Though the literature displayed possible benefit of MI-TLIF relative to its open counterpart, both procedures are associated with possible complications. Major sources of complications shared by MI-TLIF and Open TLIF are allograft malposition, pedicle screw malposition, and infection [8]. Some minor complications found in both open and MI studies were hematoma, anemia, and cerebrospinal fluid leakage [8]. In both lumbar arthrodesis techniques, placement of a k-wire is necessary, and this k-wire is held in place to formally place the expandable retractor moving the k-wire could result in entrance to the vertebral canal and possible damage to the nerve roots or cauda equina, which had the potential to occur in either TLIF technique [9].

Each approach was also associated with its own unique complications. Complications more likely to be found in the open TLIF approach include infections and muscular trauma as a result of the increased exposure and soft tissue dissection [9]. In addition, increased exposure has been shown to be potentially associated with 23.5% of reported complications being infectious in nature, within the open TLIF studies. Open TLIF may have a slightly lower rate of neurological complications, for neurological deficits were a considerably lower proportion of total complications, 11.8%, when compared to MI-TLIF’s 20.7%. However, there were a greater variety of unique complications to open TLIF, as shown by 23.4% of complications coming in the form of dural tears, ileus, and atelectasis among others. Please refer to Table 3 for further analysis.

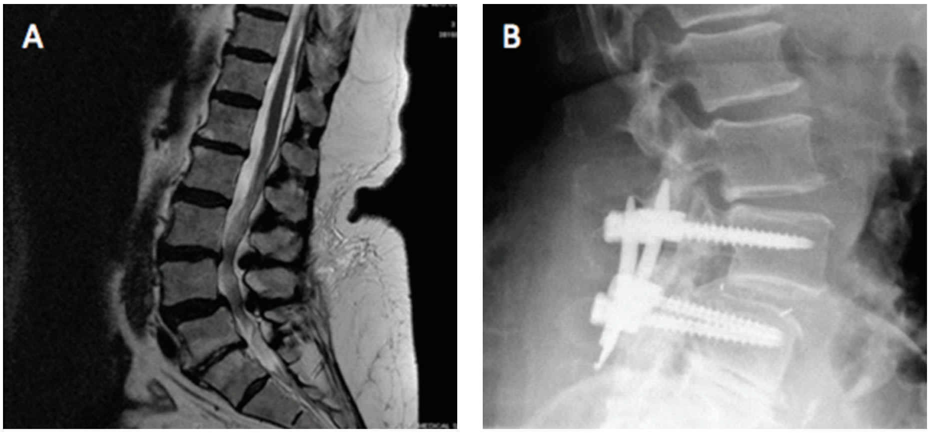
In the MI-TLIF literature reviewed, many authors discussed the challenging learning curve associated with MI-TLIF, which makes certain complications, particularly those related to instrumentation more likely [5]. Endoscopic

Table 1: Summary of research studies reporting data on MI-TLIF.

Author (year)	Study design	Follow-up	Number of patients	Significant results
Scheufler et al. (2007) [10]	Retrospective	8 months, 16 months	53	OR time equivalent between pTLIF and mini-open TLIF Blood loss and postoperative pain reduced reduced in pTLIF
Villavicencio et al. (2010) [8]	Retrospective	37.5 months	63 and 76 patients	Mean blood loss lower in MI-TLIF Mean duration of hospital stay shorter in MI-TLIF Rate of neurological deficit was greater in the MI-TLIF group
Schizas et al. (2009) [5]	Prospective	22 months (MI) 24 months (O)	36 patients (O = 18, MI = 18)	MI-TLIF: decreased blood loss, shorter hospital stay, and decreased pain Steeper learning curve in MI-TLIF
Dhall et al. (2008) [4]	Retrospective	24 months (MI) 34 months (O)	21 (MI) 21 (O)	MI-TLIF: less blood loss, shorter LOS
Jang and Lee (2005) [13]	Pilot	30 months	100 consecutive patients	Significant reduction in pain, ODI, and TIS Improvement in lordosis from 2° to 9°, anterior disc height 6 to 14 mm, and posterior disc height from 4 to 8 mm
Peng et al. (2009) [3]	Prospective	6 months, 2 years	29 (MI), 29 (O)	MI-TLIF: fluoroscopic time increased, longer operative times, less blood loss, decreased morphine use, and decreased LOS
Beringer and Mobasser (2006) [15]	Prospective	6 months	8	All had solid bone fusions
Park and Foley (2008) [16]	Retrospective	Minimum 24 months, Mean 35 months	40	Mean ODI 55 → 16 post-op Mean leg and back pain VAS 65 and 52, improving to 8 and 15 Reduction of spondylolisthesis was achieved in all cases, with a mean decrease in forward translation of 76%
Deutsch and Musacchio (2006) [11]	Prospective	6–12 months	20	85% had >20 point reduction in ODI ODI 57 → 25 VAS 8.3 → 1.4
Jang and Lee (2005) [13]	Prospective	19 months	23	NRS back pain 7.5 → 2.3 NRS leg pain 7.4 → 0.7 Mean ODI 33.1 → 7.6

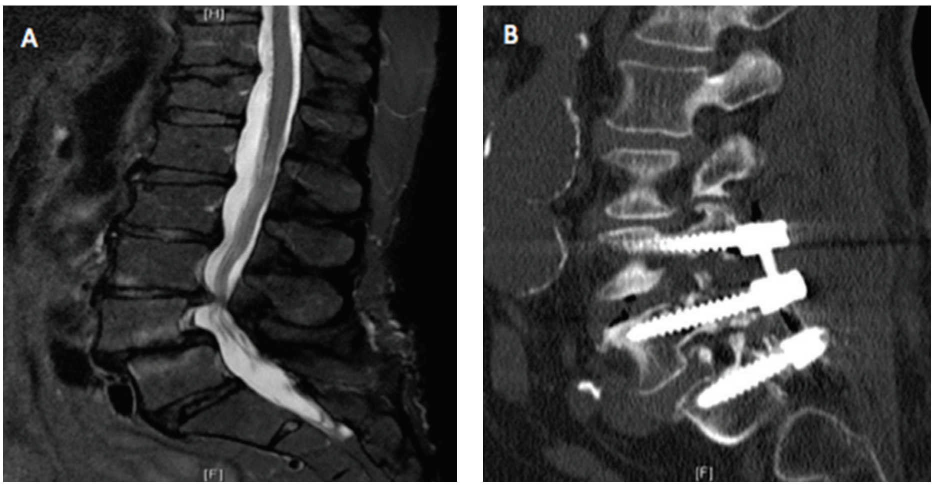
Table 1: Continued.

Author (year)	Study design	Follow-up	Number of patients	Significant results
Isaacs et al. (2005) [6]	Retrospective	n/a	20	METLIF: less blood loss, less postoperative wound drainage, no dural violation, less pain medication, and shorter LOS
Shunwu et al. (2010) [9]	Prospective cohort study	24–42 months	32 (MI), 30 (O)	MI: reduced blood loss, les postoperative back pain, lower serum creatine kinase, shorter time to ambulation, and shorter LOS
Wang et al. (2010) [7]	Prospective	Minimum 13-month follow-up	MI = 42, O = 43	MI: reduced blood bloss, less postoperative back pain, shorter LOS, greater radiation time
Foley et al. (2003) [2]	Retrospective	12–20 months, mean 22 months	39 patients	Twenty-six had excellent outcomes and 12 had good ones, as determined by the modified MacNab criteria
Schwender et al. (2005) [14]	Retrospective	22.6 mean follow-up	49 patients	Estimated blood loss of 140 mL, mean length of hospital stay 1.9 days, and all 45 patients presenting with preoperative radiculopathy had resolution of symptoms
Dong et al. (2008) [12]	Retrospective	38.6 mean follow-up	27 patients	Solid fusion in 77.8% of patients, clinical success achieved in 88.9% of cases
Anand et al. (2006) [17]	Prospective	30	100	Improvement in VAS, ODI, TIS, and NRS for back, 99% fusion



(a) (b)

Figure 1: (a) Preoperative lateral MR image of a 72 y/o female patient with back and left leg pain and L4/L5 spondylolisthesis; (b) post-operative lateral MR image from a patient who underwent an MI-TLIF for spondylolisthesis at L4/L5.



(a) (b)

Figure 2: (a) Preoperative lateral MR image of a 66 y/o female with L4/L5 and L5/S1 spondylolisthesis and neuroforaminal stenosis; (b) Post-operative lateral MR image from a patient who underwent an MI-TLIF for spondylolisthesis at L4/L5, L5/S1.

visualization of the spinal structure limits the field of view for the surgeon, making identification of already unfamiliar landmarks even more difficult. Though visualization techniques have improved over time, percutaneous fixation systems do not have the ability to reposition three dimensionally [10]. Tubular dilator retractors can result in poor decompression while resulting in higher rates of neurological injuries [4]. Of all complications presented in the MI-TLIF comparative literature, approximately 1 in 5 were related to neurological complications (Table 4). Schizas et al. wrote of possible inexperience leading to inappropriate placement of transpedicular screws, and inadequate preparation of intervertebral cage and fusion site which can lead to further instrumentation related complications.

The operative surgeon additionally must be familiar with 3D lumbar anatomy and be able to carefully interpret 2D radiographic images to make a mental reconstruction. This is a unique skill and one that is not as critical with a traditional, open approach. The surgeon must be able to read anterior-posterior and lateral imaging in order to accurately insert percutaneous pedicle screws, thereby allowing for possible misinterpretation leading to complications [14]. Screw misplacement and cage migration or subsidence accounted for 44.8% of complications reported in MI-TLIF comparative studies.

Radiation exposure is another area of interest. MI-TLIF itself presents with increased risk to the surgeon related to increased radiation exposure due to lengthened intraoperative fluoroscopy times. Though many may claim that a surgeon's experience level with minimally invasive procedures will dictate their fluoroscopy times, some studies found no significant difference as experience increased [7]. Very few studies reported the duration and radiation exposure resulting from X-ray and fluoroscopy. Authors who did

Table 2: Comparative studies basic data.

Author	Mean duration of surgery MIS	Mean duration of surgery open	MIS blood loss	Open blood loss	Length of stay MIS	Length of stay open
Villavicencio et al.	222.5	214.9	163 mL	366.8	3	4.2
Shunwu et al.	159.2	142.8	399.8	517	9.3	12.5
Wang et al.	156 (X-ray 84)	145 (37)	264	673	10.6	14.6
Peng et al.	216.4 (fluoro 105.5 s)	170 (35.2)	150	681	4	6.7
Schizas et al.	348 (X-ray 2.7 cGy/cm^2)	312 (1.8)	456	961	6.1	8.2
Dhall et al.	199	237	194	505	3	5.5
Isaacs et al.	300	276	226	1147	3.4	5.1

Table 3: Complications found in studies comparing open TLIF to MI-TLIF.

		Complication type		Complication rate	
Author	Year	Open	MI	Open	MI
Peng et al. [3]	2009	Atelectasis-(1) UTI-(2) Infection-(1)	Infection-(1)	13.5%	6.9%
Dhall et al. [4]	2008	Radiculitis (1) Misplaced screw-(1)	Transient L-5 sensory loss (2) Misplaced screw (1) Cage migration (1)	2%	5%
Schizas et al. [5]	2009	NR	Increased pseudarthrosis	2%	6%
Isaacs et al. [6]	2005	Infection Fluid shift/blood transfusion complications Positioning-related neuropraxia of the upper extremity	Transient leukopenia (1)	6%	0%
Wang et al. [7]	2010	Pedicle screw malposition (1) Dural tears (2)	Radiculopathy (2) Small dural tear (1)	4%	5%
Villavicencio et al. [8]	2010	CSF leak	Neurological deficit > 3 mos Pedicle screw malposition with reoperation	31.7%	31.6%
Shunwu et al. [9]	2010	Superficial wound infection (1) Deep wound infection (1) Deep venous thrombosis (1) Ileus (1)	Screw malposition (2) Superficial wound infection (1) Ileus (1)	5%	6%

Table 4: Complication rate by TLIF approach.

Complications	MI	Open
Infection	6.9%	23.5%
UTI	3.4%	11.8%
Neurologic deficits	20.7%	11.8%
Screw/Cage complications	44.8%	11.8%
CSF leak	10.3%	5.9%
Blood transfusion/coagulation	3.4%	11.8%
Other	10.5%	23.4%

report this data found that MI-TLIF had greater duration of radiation exposure for patients undergoing the procedure [3, 5, 7]. Due to the relative recent adoption of MI-TLIF use, the long-term effects of increased radiation exposure have not been evaluated. The development of 2D computer assisted fluoroscopy systems as well as the O-arm is a modern means to decrease this exposure risk. Further, careful attention to radiation safety in the operating room is critical.

4.2. Studies of Note. Following data collection and the literature review, it is clear that there is a paucity of data comparing MI-TLIF and open TLIF. To our knowledge, there remains no high-class studies that directly compare these two techniques. However, smaller studies, both prospective and retrospective in nature, have shown promise in regards to novel MI techniques for TLIF.

Scheufler et al. compared percutaneous transforaminal lumbar interbody fixation (pTLIF) with mini-open transforaminal lumbar interbody fixation (oTLIF) while utilizing the Wiltse method [10]. They found at 8 month and 16 month follow-up, overall clinical outcome did not differ between the two techniques. However, in terms of pain following the operation, pTLIF resulted in significantly lower

Table 5: MI-TLIF complication types and complication rates.

Author	Year	MI-TLIF complication type	MI-TLIF complication rates
Scheuffler et al. [10]	2007	CSF leak (1)	1.9%
Deutsch and Musacchio [11]	2006	Misplaced screw (1) CSF leak (2)	4
Dong et al. [12]	2008	UTI (1) Drug reaction (1) Subsidence	7.4%
Jang and Lee [13]	2005	Subsidence (3) Screw failure (1)	17.4%
Scwender et al. [14]	2005	Misplaced screws (2) Radiculopathy (2)	8.2%
Beringer and Mobasser [15]	2006	NR	NR
Park and Foley [16]	2008	NR	NR
Anand et al. [17]	2006	NR	NR

levels of pain ($P < 0.01$). Though the study showed no decreased advantages due to the percutaneous approach, a longer prospective study would be needed to further discern the success and functionality of each multilevel fusion.

In a study examining 42 patients with mean follow-up time of 29 months, Dhall et al. compared mini-open and open TLIF [4]. The authors found that mean estimated blood loss for mini-open (194 mL) was significantly lower ($P < 0.01$) than the open-group (505 mL). The length of stay was decreased for mini-open patients by on average, 2.5 days ($P < 0.01$). However, there were complications of neurologic nature in 2 patients, while 2 other patients required further revision. All 42 patients displayed fusion, and the authors felt that the mini-open technique was a possible substitute to open TLIF.

Schwender et al. performed one of the earlier studies (2001-2002) on 49 patients who had MI-TLIF. Majority of patients in the study either had degenerative disc disease with herniated nucleus pulposus (HNP) or spondylolisthesis [14]. 45 of 49 cases were completed at the L4-L5 or L5-S1 levels. Mean operative times were approximately 240 minutes, approximate blood loss was 140 mL, and hospital stays averaged 1.9 days. Complications were limited to four patients, two of which required screw repositioning while two others developed radiculopathy following the procedure. VAPS changed on average from 7.2 to 2.1 while ODI changed from 46 to 14 from preoperative assessment to final follow-up. Ultimately, all patients in the study had fusion on follow-up imaging. The author believed that MI-TLIF is at least equivalent if not a marked improvement over its open counterpart.

A variation of the accepted microendoscopic discectomy was completed by Isaacs and colleagues, which was termed METLIF [6]. METLIF was completed on 20 patients who had lumbar spondylolisthesis or mechanical back pain. This unique procedure compared favorably to patients who underwent PLIF at the same institutions. METLIF resulted in less blood loss, shorter hospital stays, and decreased postoperative narcotic administration. There were no associated procedural complications associated with the multicenter study. Ultimately, this new variation showed promise.

Schizas et al. examined their institutional experience executing both MITLIF and open midline transforaminal lumbar interbody fusion [5]. Their 36 patient cohort had isthmic spondylolisthesis or DDD which indicated for TLIF. The study found that length of surgery, postoperative pain, analgesia requirements, and VAS/ODI scores were not significantly different between the MI and open procedures. However, they did find that the MI-TLIF did result in significantly less blood loss and a shorter hospital stay. Complications found in the MI-TLIF group, three pseudorthrosis, may have likely been due to the surgeon's gradual adjustment to the novel instrumentation and visualization techniques associated (Table 5).

5. Discussion

Lumbar arthrodesis is an effective method for treating spinal pathology such as spondylolisthesis, DDD, and spinal instability. As minimally invasive spine procedures have emerged, variants such as minimally invasive discectomy and minimally invasive cervical foraminotomies have allowed for reduced complications related to tissue trauma, while reducing blood loss and shortening recovery time [4, 8, 19, 20]. However, no procedure comes without inherent risks. Due to MI-TLIF being a novel procedure for some surgeons, it takes increasingly longer for them to become effective in carrying it out. Villavicencio et al. compared safety and effectiveness of MI-TLIF and open TLIF, showing similar long-term outcomes over the course of the 37.5-month follow-up period [8]. Assigning 63 patients to the open arm and 76 patients to the minimally invasive arm of the study, the authors matched by prior lumbar surgery, diagnosis, and levels at which fusion was performed. They found significant improvement in mean estimated blood loss ($P < .0001$) for MI (163.0 mL) versus the open TLIF (366.8 mL). The study found improvements ($P = 0.02$) in mean duration of

hospitalization in MI-TLIF (3 days) relative to their open counterparts (4.2 days). In addition, rates of neurological deficit were significantly higher ($P = 0.02$) in the minimally invasive arm of the study (10.2%) compared to the open cohort (1.6%). Operative times, mean change in VAS scores, patient satisfaction, all significantly favored the open TLIF procedure. The authors hypothesized that the neurological deficits and other factors in favor of open TLIF could have occurred as a result of the surgical learning curve.

Once the procedure is mastered, its application can positively impact patient care in numerous ways. But, the fundamental advantage of MI-TLIF comes from its decrease in tissue trauma and overall exposure of the patient. This can reduce infection, blood loss, and time to recovery. A prospective cohort study was carried out by Shunwu et al. with 62 patients that had undergone single level TLIF by a single surgeon in a single hospital [9]. One cohort of 32 patients underwent MI-TLIF with the tubular retractor system, while the remaining patients underwent open TLIF. Serum creatine kinase levels, a measure of soft-tissue trauma, was measured on the third postoperative day. Also, time to ambulation and number of transfusions were also measured in the study. Shunwu and colleagues found that MI-TLIF resulted in significantly lower serum creatine kinase levels were found, while patients needed less transfusions and were able to walk earlier than their open counterparts. When comparing the two approaches, this study displayed that MI-TLIF still proposes significant quantifiable benefit in terms of decreased soft tissue trauma.

As a minimally invasive procedure, MI-TLIF can be utilized to treat particular pathologies, while maintaining the same high levels of clinical success as the open TLIF, even with over two years of follow-up. Thus, the long-term results are comparable to that of open TLIF. Park and Foley contributed an article to the literature that described MI-TLIF in 40 consecutive patients who were diagnosed with spondylolisthesis [16]. Their percutaneous approach resulted in reduction of spondylolisthesis in all cases, with an average follow-up time of 35 months. The average ODI decreased from 55 to 16, while the VAS scores decreased from 65 to 8 in leg and 52 to 15 in back. The average reduction in forward translation was 76%. This was yet another proof of MI-TLIF being a possible replacement to open TLIF in patients with degenerative or isthmic spondylolisthesis. In a prospective study that contrasted clinical and imaging outcomes for MI-TLIF and open TLIF procedures, Peng et al. found that MI-TLIF had equivalent long-term outcomes with open TLIF [3]. The patient cohort had 29 patients in each arm of the study, and 48 of 58 patients were women. The study examined, fluoroscopic times and found that MI-TLIF had significantly ($P < 0.05$) longer (105.5 seconds) compared to open (35.2 seconds). Thus, it is clear that the MI-TLIF cases ran significantly longer overall. Then, the authors discussed the significantly less blood loss, less morphine, and short hospitalization utilized for patients in the MI-TLIF cohort. Yet, open TLIF and MI-TLIF both were very similar in providing significant benefit to patients when rated by ODI, NASS, and VAS, all at follow-ups of six months and two years. In addition, there was no significant difference between open and MI-TLIF in terms of fusion rates, both which were approximately 80%. Peng and colleagues presented data that was supportive of MI-TLIF in terms of pain, hospitalization, and recovery, while at the same time retaining the high-fusion rate associated with open TLIF at two year follow-up.

Aside from particular pathologies that would benefit from MI-TLIF, there are certain populations that could benefit from the decreased tissue disruption and decreased blood loss. In elderly patients, Lee et al. completed a retrospective review of 27 consecutive cases and found a low complication rate and beneficial outcomes for patients over the age of 65 [12]. The average age of patients in the study was approximately 70 years, and each underwent a mini-open TLIF. They were then followed up for three years, displaying fusion rates of nearly 80%, similar to that seen in other studies. However, 44% of patients displayed adjacent segment degeneration, which was statistically significant in terms of its relation to sacral tilt following the procedure ($P = 0.006$). Two patients experienced minor complications in the perioperative period, one being a drug eruption and the other a urinary tract infection. Overall, the authors strongly felt that mini-open TLIF is a low-risk, beneficial option for the elderly.

6. Conclusion

Though the studies presented displayed heterogeneous patient populations with different indications for lumbar arthrodesis, there were many patterns seen across studies. Aside from possible complications such as screw displacement and neurological deficit, which were often related to a steep learning curve, MI-TLIF displayed no significant disadvantages when compared to open TLIF or other standard lumbar fusion techniques. The risks of blood loss, narcotic administration, pseudorthrosis, and infection all are equivalent if not decreased when utilizing MI-TLIF as a possible technique. Various postoperative recovery and pain rating scales often showed consistent improvement across many of the studies presented herein. MI-TLIF and open TLIF are quite similar in absolute indications and often present with similar complications, thus a randomized clinical trial would be beneficial in further elucidating the risks and benefits associated with each. As other variations emerge for MI-TLIF, such as METLIF, there is still need for an overall meta-analysis of all available data, comparing minimally invasive technique to traditional, open procedures.

Abbreviations

PLIF: Posterior lumbar interbody fusion
ALIF: Anterior lumbar interbody fusion
TLIF: Transforaminal lumbar interbody fusion
MI-TLIF: Minimally invasive transforaminal lumbar interbody fusion
DDD: Degenerative disc disease
LOS: Length of stay
VAS: Visual analog scale
ODI: Oswestry Disability Index.

Conflict of Interests

There is no conflict of interests or funding source for this paper or the data contained within it.

References

[1] C. D. Ray, "Threaded titanium cages for lumbar interbody fusions," *Spine*, vol. 22, no. 6, pp. 667–680, 1997.

[2] K. T. Foley, L. T. Holly, and J. D. Schwender, "Minimally invasive lumbar fusion," *Spine*, vol. 28, no. 15, supplement, pp. S26–S35, 2003.

[3] C. W. B. Peng, W. M. Yue, S. Y. Poh, W. Yeo, and S. B. Tan, "Clinical and radiological outcomes of minimally invasive versus open transforaminal lumbar interbody fusion," *Spine*, vol. 34, no. 13, pp. 1385–1389, 2009.

[4] S. S. Dhall, M. Y. Wang, and P. V. Mummaneni, "Clinical and radiographic comparison of mini-open transforaminal lumbar interbody fusion with open transforaminal lumbar interbody fusion in 42 patients with long-term follow-up: clinical article," *Journal of Neurosurgery: Spine*, vol. 9, no. 6, pp. 560–565, 2008.

[5] C. Schizas, N. Tzinieris, E. Tsiridis, and V. Kosmopoulos, "Minimally invasive versus open transforaminal lumbar interbody fusion: evaluating initial experience," *International Orthopaedics*, vol. 33, no. 6, pp. 1683–1688, 2009.

[6] R. E. Isaacs, V. K. Podichetty, P. Santiago et al., "Minimally invasive microendoscopy-assisted transforaminal lumbar interbody fusion with instrumentation," *Journal of Neurosurgery: Spine*, vol. 3, no. 2, pp. 98–105, 2005.

[7] J. Wang, Y. Zhou, Z. F. Zhang, C. Q. Li, W. J. Zheng, and J. Liu, "Comparison of one-level minimally invasive and open transforaminal lumbar interbody fusion in degenerative and isthmic spondylolisthesis grades 1 and 2," *European Spine Journal*, vol. 19, no. 10, pp. 1780–1784, 2010.

[8] A. T. Villavicencio et al., "Minimally invasive versus open transforaminal lumbar interbody fusion," *Surgical Neurology International*, vol. 1, article 12, 2010.

[9] F. Shunwu, Z. Xing, Z. Fengdong, and F. Xiangqian, "Minimally invasive transforaminal lumbar interbody fusion for the treatment of degenerative lumbar diseases," *Spine*, vol. 35, no. 17, pp. 1615–1620, 2010.

[10] K. M. Scheufler, H. Dohmen, and V. I. Vougioukas, "Percutaneous transforaminal lumbar interbody fusion for the treatment of degenerative lumbar instability," *Neurosurgery*, vol. 60, no. 4, supplement 2, pp. S-203–S-212, 2007.

[11] H. Deutsch and M. J. Musacchio Jr., "Minimally invasive transforaminal lumbar interbody fusion with unilateral pedicle screw fixation," *Neurosurgical Focus*, vol. 20, no. 3, article E10, 2006.

[12] Y. L. Dong, T. G. Jung, and S. H. Lee, "Single-level instrumented mini-open transforaminal lumbar interbody fusion in elderly patients," *Journal of Neurosurgery: Spine*, vol. 9, no. 2, pp. 137–144, 2008.

[13] J. S. Jang and S. H. Lee, "Minimally invasive transforaminal lumbar interbody fusion with ipsilateral pedicle screw and contralateral facet screw fixation," *Journal of Neurosurgery: Spine*, vol. 3, no. 3, pp. 218–223, 2005.

[14] J. D. Schwender, L. T. Holly, D. P. Rouben, and K. T. Foley, "Minimally invasive transforaminal lumbar interbody fusion (TLIF): technical feasibility and initial results," *Journal of Spinal Disorders and Techniques*, vol. 18, no. 1, supplement, pp. S1–S6, 2005.

[15] W. F. Beringer and J. P. Mobasser, "Unilateral pedicle screw instrumentation for minimally invasive transforaminal lumbar interbody fusion," *Neurosurgical Focus*, vol. 20, no. 3, article E4, 2006.

[16] P. Park and K. T. Foley, "Minimally invasive transforaminal lumbar interbody fusion with reduction of spondylolisthesis: technique and outcomes after a minimum of 2 years' follow-up," *Neurosurgical Focus*, vol. 25, no. 2, article E16, 2008.

[17] N. Anand, J. F. Hamilton, B. Perri, H. Miraliakbar, and T. Goldstein, "Cantilever TLIF with structural allograft and RhBMP2 for correction and maintenance of segmental sagittal lordosis: long-term clinical, radiographic, and functional outcome," *Spine*, vol. 31, no. 20, pp. E748–E753, 2006.

[18] C. D. Lawton, Z. A. Smith, A. Barnawi, and R. G. Fessler, "The surgical technique of minimally invasive transforaminal lumbar interbody fusion," *Journal of Neurosurgical Sciences*, vol. 55, no. 3, pp. 259–264, 2011.

[19] O. Adogwa, S. L. Parker, A. Bydon, J. Cheng, and M. J. McGirt, "Comparative effectiveness of minimally invasive versus open transforaminal lumbar interbody fusion: 2-year assessment of narcotic use, return to work, disability, and quality of life," *Journal of Spinal Disorders & Techniques*, vol. 24, no. 8, pp. 479–484, 2011.

[20] D. Lau, J. G. Lee, S. J. Han, D. C. Lu, and D. Chou, "Complications and perioperative factors associated with learning the technique of minimally invasive transforaminal lumbar interbody fusion (TLIF)," *Journal of Clinical Neuroscience*, vol. 18, no. 5, pp. 624–627, 2011.

Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 538697, 5 pages
doi:10.1155/2012/538697

Research Article

The Interspinous Spacer: A Clinicoanatomical Investigation Using Plastination

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Received 23 January 2012; Accepted 23 April 2012

Academic Editor: Justin S. Smith

Purpose. The relatively new and less-invasive therapeutic alternative "interspinous process decompression device (IPD)" is expected to result in improved symptoms of neurogenic intermittent claudication (NIC) caused by lumbar spinal stenosis. The aim of the study was to analyze IPD position particularly regarding damage originating from surgical implantation. *Methods*. Anatomic assessments were performed on a fresh human cadaver. For the anatomic examination, the lumbar spine was plastinated after implantation of the IPDs. After radiographic control, serial 4 mm thick sections of the block plastinate were cut in the sagittal (L1–L3) and horizontal (L3–L5) planes. The macroanatomical positioning of the implants was then analyzed. The insertion procedure caused only little injury to osteoligamentous or muscular structures. The supraspinous ligament was completely intact, and the interspinous ligaments were not torn as was initially presupposed. No osseous changes at the spinal processes were apparent. Contact of the IPD with the spinous processes was visible, so that sufficient biomechanical limitation of the spinal extension seems likely. *Conclusions*. Minimally invasive IPD implantation with accurate positioning in the anterior portion of the interspinous place is possible without severe surgical trauma.

1. Introduction

Lumbar spinal stenosis (LSS) with neurogenic intermittent claudication (NIC) is one of the most common degenerative spinal diseases in the elderly [1–3].NIC is a specific symptom complex occurring in patients with LSS.

NIC is characterized by increasing leg, buttock, and/or groin pain with or without lower back pain when walking a certain distance or reclining. Forward bending or sitting leads to rapid pain relief.

LSS is seen frequently in clinical practice. 3 to 4% of all patients consulting a general physician with pain in the lower back region have LSS. Nearly 15% of the patients who see a specialist for lower back pain have LSS [4]. Annual incidence rates of 5/100,000 have been reported [5]. In the United States, the cost of NIC to society from medical treatment and loss of productive work hours reaches tens of billions of dollars annually [6].

Nonoperative therapy is initially considered with oral nonsteroidal anti-inflammatory drugs (NSAIDs), other analgetics, and physical therapy. This regimen can be intensified by adding epidural pain treatment (steroids, opioids, and local anesthetics). In a third of all cases, this therapy decreases symptoms sufficiently that operative treatment can be avoided. In the remaining two-thirds, surgical intervention is necessary [7].

For LSS patients over 65 years undergoing surgery, open decompression is most frequently performed [1, 8, 9]. One problem associated with decompression procedures is trauma to the osteoligamentous structures, which vares in severity depending on the extent of surgery performed.

A relatively new and less invasive therapeutic alternative is insertion of an interspinous process decompression device (IPD). These implants are inserted between the spinal processes and are expected to result in improved symptoms.

The use of interspinous implants has grown markedly over the past few years.

Biomechanical studies have shown that IPDs significantly reduce intradiscal pressure as well as facet load, and they prevent narrowing of the spinal canal and neural foramina [10, 11]. Previous studies have shown benefits with the use of implanted devices (e.g., X-Stop) versus conservative therapy, especially with regards to the quality of life [6, 12].

For some patients with LSS, IPDs may be a viable alternative to open decompression [13]. IPDs may be used either as "stand alone" implants or to augment open decompression by preventing instability [14]. The main principle behind their design is the limitation of dynamic extension in the affected segment [13]. Radiologic studies have demonstrated that the use of interspinous devices affects spinal alignment as well as the dimensions of the spinal canal and neural foramina [15–17].

In addition, insertion of an IPD can be accomplished percutaneously through a 1.5 cm incision. This method is used for implantation of the Aperius PercLID device designed by Medtronic, Inc. This device has been on the market since 2006 and is CE certified. The inner core and outer shell of the implant are made of titanium (Ti-6Al-4V) with unfoldable fins. The Aperius PercLID is suitable for patients with degenerative lumbar spinal stenosis and can be implanted at the levels L1–L5. The typical candidate for this particular IPD is over 50 years of age with mild-to-moderate LSS symptoms (e.g., increasing leg, buttock, and/or groin pain with or without lower back pain when walking a certain distance or reclining), in whom conservative therapy has failed to bring sufficient relief. Most importantly, candidates for placement must report about an improvement of NIC by lumbar flexion and have undergone at least 6 months of failed nonsurgical treatment.

A number of studies published recently have shown significant clinical improvement after insertion of the Aperius PercLID implant [18–21].

One point of discussion is the relevance of damage to the posterior soft-tissue structures after implant insertion, although this depends highly on the choice of implant [22, 23].

To date, no clinicoanatomical investigations of interspinous spacers for the lumbar spine using sheet plastinates are available in the literature. The aim of the study is to evaluate macroscopic findings after IPD implantation by using the plastination techniques.

2. Materials and Methods

Four interspinous "stand alone" spacers (14 mm Aperius PercLID; Medtronic, Tolochenaz, Switzerland) were percutaneously implanted into the lumbar spine (L1–L5) of a fresh human cadaver, after which the segment specimens underwent plastination. The age of the female human cadaver was 83 years, and the lumbar spine had undergone no prior surgery.

For implantation, the body was placed in a prone position. After identification of the L4/5 segment by fluoroscopy, the skin incision (length 1.5 cm) was made 10 cm lateral to the midline. The 8 mm trocar was first introduced and placed in the anterior part of the interspinous space, guided by fluoroscopy. The 8 mm trocar was then removed and replaced by the 10 mm trocar. This procedure was repeated with the 12 mm and 14 mm trocars until sufficient distraction of the spinous processes was attained. The 14 mm IPD was then implanted. Device insertion to the interspinous space was guided by fluoroscopy. The fins of the implant were then unfolded and the insertion instrument disconnected. IPD implantation to the remaining lumbar segments proceeded in some fashion. The surgical procedure was the same which would be used in a patient.

After completion of the surgical procedures and isolation of the lumbar spine, fixation with 4% formaldehyde solution, careful dehydration and degreasing, and forced impregnation with epoxy resin (Biodur E12, Biodur E6, Biodur E600, BIODUR Products, Heidelberg, Germany) procedures were performed to attain block plastination [24].

Dehydration and degreasing with acetone were conducted until the water content was <0.5%. The solution was changed every four weeks. Due to the size of the sample, this process lasted 12 months. After radiographic control, serial 4 mm thick sections of the block plastinate were cut using a precision diamond-blade saw (Well Diamantdrahtsägen GmbH, Mannheim, Germany) in the sagittal (L1–L3) and horizontal (L3–L5) planes.

To increase transparency of the obtained cuts, secondary sheet plastination (Biodur E12, Biodur E1, Biodur AE 30, BIODUR Products, Heidelberg, Germany) was performed in a flat chamber.

After completion of plastination, the osteoligamentous structures and macroanatomical positioning of the implants were optically analyzed.

3. Results

25 sagittal cuts and 25 cross-sectional cuts were obtained. The inferior and superior spinous processes showed no fracture and remained completely identifiable in the sagittal plane. The implant was positioned within the anterior part of the interspinous space. The distance of the IPD to the inferior and superior layer of the spinous processes was minimal. Osseous contact with the processes appeared in all sheets (Figure 1).

In the sagittal plane both the superior and inferior spinous processes were mostly apparent, the anterior 2/3 of the interspinous ligament (ISL) was not discernible with the IPD in place. The visualized posterior 1/3 was undamaged. Complete integrity of the supraspinous ligament (SSL) was maintained (Figure 1). Furthermore, the thoracolumbar fascia and paraspinous musculature bordering the ISL/SSL, in particular the multifidus muscle, remained undamaged on sagittal and axial plane cuts (Figure 2).

The nerve roots were well delineated within the vertebral foramina. The spinal canal with the cauda equina and the filum were evident. Structures surrounding the spinal canal like the ligamentum flavum, the discal space, and

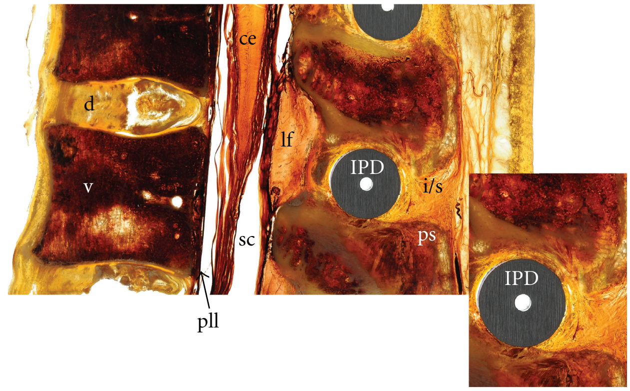

Figure 1: Sagittal cut with enlargement of the interspinous ligament. ce: conus medullaris; d: disc; f: intervertebral foramen; fj: facet joint; IPD: interspinous process device; i/s: inter/supraspinous ligament complex; lf: ligamentum flavum; mi: iliocostalis muscle; ml: longissimus thoracis muscle; mm: multifidus muscle; mp: psoas muscle; ms: spinalis muscle; nr: nerve root; pll: posterior longitudinal ligament; ps: spinous process; pt: transverse process; sc: spinal canal; tlf: thoracolumbar fascia; v: vertebra.

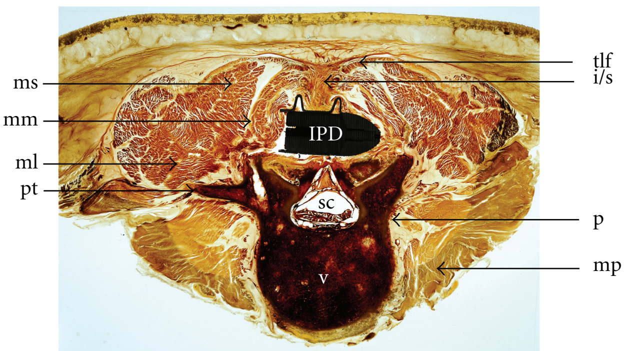

Figure 2: Horizontal cut segment L4/5.

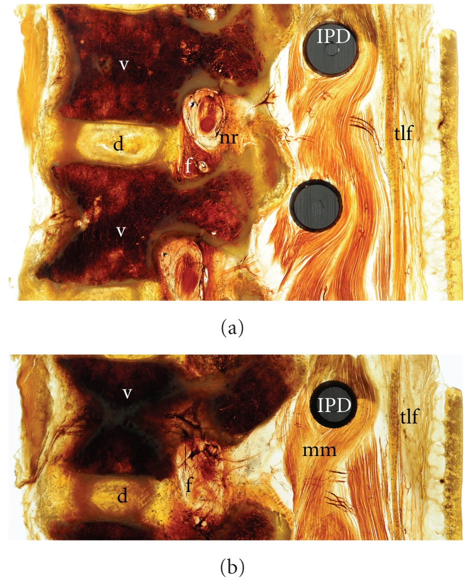

Figure 3: Paramedian sagittal cut with exposure of the intervertebral foramen and the normally placed nerve root.

the vertebral bodies were not distorted by the implant. The annulus fibrosus and the nucleus pulposus were clearly visible between the vertebral bodies of the segment (Figures 1, 3(a), and 3(b)). The psoas muscle formed the anterior border of the segment and was normal (Figure 2).

4. Discussion

LSS is caused by degenerative changes within the spinal canal, for example osseous or ligamentous hypertrophy, disc protrusion, and/or degeneration of the intervertebral disc with instability [25]. One minimally invasive treatment option that improves patient complaints is the implantation of an interspinous spacer.

Various studies have found that IPD placement in patients with degenerative LSS decreased symptoms [6, 12, 18–21, 26].

Previous studies have focused on the biomechanical effectiveness of the IPDs [10, 11].

The standard posterior midline approach to the spine has been associated with significant muscle morbidity, including muscle denervation, increased intramuscular pressure, ischemia, revascularization injury, and ligamentous damages [27–30]. In an effort to minimize this type of morbidity associated with open spine procedures, recent advances in minimal access technologies have led to implementation of minimally invasive approaches to all regions of the spine for decompression, arthrodesis, and instrumentation.

However, because IPDs are placed between the spinal processes, varying degrees of damage to the interspinous and supraspinous (ISL/SSL) ligaments are still possible.

The structures posterior to the lumbar spine are important for supporting the spine and preventing instability. For instance, the synergy of the ISL and SSL plays an important role in stability and limiting flexion [31, 32]. A biomechanical investigation concluded that the interconnections between the supraspinous and interspinous ligaments account for as much flexion stability as each of the supraspinous and interspinous ligaments [32]. The intricate collagen fiber cross-linking between the ISL, SSL, and thoracolumbar fascia, as well as the fixation to the spinous process, lend stability and extension to the lumbar spine during abdominal muscle contraction [33]. In any case, along with the paraspinous musculature, the ISL/SSL complex plays a significant role in the stabilization of the respective vertebral segments, and not only through limitation of flexion [9, 22, 32, 34].

Not only the direct injury of the posterior ligament structure but also the magnitude of approach-induced changes and degeneration of these structures particularly the ISL/SSL complex, are problematic. In an animal study, the Wiltse approach led to degeneration and therefore significant biomechanical weakening of the ISL/SSL without causing direct lesions, presumably from scar formation and

muscle spasms [35]. More marked degeneration, also of the neighboring vertebral segments, occurred after more invasive stabilizing and destabilizing (e.g., facetectomy) procedures [35].

Thus, to protect the integrity of the posterior structures and their functions as stabilizer and proprioceptive intermediaries, the most minimally invasive technique available should be selected.

To our knowledge, this study is the first to use plastination techniques to evaluate macroscopic findings after IPD implantation.

The aim of the study was to analyze IPD position particularly regarding damage originating from surgical implantation. The insertion procedure caused no injury to osteoligamentous or muscular structures. The supraspinous ligament was completely intact and the interspinous ligaments were not torn as was initially presupposed; they were merely displaced by the implant in the anterior 2/3.

No osseous changes at the spinal processes were apparent. Contact of the IPD with the spinous processes was adequate, so that sufficient biomechanical limitation of the spinal extension seems likely.

5. Conclusion

Minimally invasive IPD implantation with accurate positioning in the anterior portion of the interspinous place is possible without severe surgical trauma.

Forced impregnation with epoxy resin and subsequent secondary sheet plastination is an excellent technique for examining spine implants regarding anatomical relationships.

An analysis under dynamic loading, flexion, or extension of the vertebral column is not possible with this technique; however, any microradiographic investigations are conceivable.

Acknowledgment

T. Kaulhausen is supported by the German Federal Ministry of Research and Education (BMBF 01KN1106).

References

[1] M. A. Ciol, R. A. Deyo, E. Howell, and S. Kreif, "An assessment of surgery for spinal stenosis: time trends, geographic variations, complications, and reoperations," *Journal of the American Geriatrics Society*, vol. 44, no. 3, pp. 285–290, 1996.

[2] R. W. Porter, "Spinal stenosis and neurogenic claudication," *Spine*, vol. 21, no. 17, pp. 2046–2052, 1996.

[3] M. T. Vogt, P. M. Cawthon, J. D. Kang, W. F. Donaldson, J. A. Cauley, and M. C. Nevitt, "Prevalence of symptoms of cervical and lumbar stenosis among participants in the osteoporotic fractures in men study," *Spine*, vol. 31, no. 13, pp. 1445–1451, 2006.

[4] L. G. Hart, R. A. Deyo, and D. C. Cherkin, "Physician office visits for low back pain: frequency, clinical evaluation, and treatment patterns from a U.S. National survey," *Spine*, vol. 20, no. 1, pp. 11–19, 1995.

[5] T. L. Schulte, V. Bullmann, T. Lerner et al., "Lumbar spinal stenosis," *Orthopade*, vol. 35, no. 6, pp. 675–694, 2006.

[6] J. F. Zucherman, K. Y. Hsu, C. A. Hartjen et al., "A multicenter, prospective, randomized trial evaluating the X STOP interspinous process decompression system for the treatment of neurogenic intermittent claudication—two-year follow-up results," *Spine*, vol. 30, no. 12, pp. 1351–1358, 2005.

[7] T. Amundsen, H. Weber, H. J. Nordal, B. Magnaes, M. Abdelnoor, and F. Lilleås, "Lumbar spinal stenosis: conservative or surgical management? A prospective 10-year study," *Spine*, vol. 25, no. 11, pp. 1424–1436, 2000.

[8] J. N. Katz, "Lumbar spinal fusion: surgical rates, costs, and complications," *Spine*, vol. 20, no. 24, pp. S78–S83, 1995.

[9] J. N. Katz, S. J. Lipson, L. C. Chang, S. A. Levine, A. H. Fossel, and M. H. Liang, "Seven- to 10-year outcome of decompressive surgery for degenerative lumbar spinal stenosis," *Spine*, vol. 21, no. 1, pp. 92–98, 1996.

[10] K. E. Swanson, D. P. Lindsey, K. Y. Hsu, J. F. Zucherman, and S. A. Yerby, "The effects of an interspinous implant on intervertebral disc pressures," *Spine*, vol. 28, no. 1, pp. 26–32, 2003.

[11] C. M. Wiseman, D. P. Lindsey, A. D. Fredrick, and S. A. Yerby, "The effect of an interspinous process implant on facet loading during extension," *Spine*, vol. 30, no. 8, pp. 903–907, 2005.

[12] J. F. Zucherman, K. Y. Hsu, C. A. Hartjen et al., "A prospective randomized multi-center study for the treatment of lumbar spinal stenosis with the X STOP interspinous implant: 1-Year results," *European Spine Journal*, vol. 13, no. 1, pp. 22–31, 2004.

[13] R. Sobottke, K. Schlüter-Brust, T. Kaulhausen et al., "Interspinous implants (X Stop (R), Wallis (R), Diam (R)) for the treatment of LSS: is there a correlation between radiological parameters and clinical outcome?" *European Spine Journal*, vol. 18, no. 10, pp. 1494–1503, 2009.

[14] T. L. Schulte, C. Hurschler, M. Haversath et al., "The effect of dynamic, semi-rigid implants on the range of motion of lumbar motion segments after decompression," *European Spine Journal*, vol. 17, no. 8, pp. 1057–1065, 2008.

[15] M. Siddiqui, E. Karadimas, M. Nicol, F. W. Smith, and D. Wardlaw, "Influence of X stop on neural foramina and spinal canal area in spinal stenosis," *Spine*, vol. 31, no. 25, pp. 2958–2962, 2006.

[16] D. P. Lindsey, K. E. Swanson, P. Fuchs, K. Y. Hsu, J. F. Zucherman, and S. A. Yerby, "The effects of an interspinous implant on the kinematics of the instrumented and adjacent levels in the lumbar spine," *Spine*, vol. 28, no. 19, pp. 2192–2197, 2003.

[17] J. C. Richards, S. Majumdar, D. P. Lindsey, G. S. Beaupré, and S. A. Yerby, "The treatment mechanism of an interspinous process implant for lumbar neurogenic intermittent claudication," *Spine*, vol. 30, no. 7, pp. 744–749, 2005.

[18] R. Assietti and R. De Falco, "The first multicenter, prospective 6 month follow-up study of 21 patients treated with the Aperius (TM) PercLID (TM) system," in *Proceedings of the 13th European Congress of Neurosurgery*, pp. 607–613, 2007.

[19] P. Nardi, D. Cabezas, G. Rea, and B. L. Pettorini, "Aperius PercLID stand alone interspinous system for the treatment of degenerative lumbar stenosis: experience on 152 cases," *Journal of Spinal Disorders and Techniques*, vol. 23, no. 3, pp. 203–207, 2010.

[20] F. Collignon and P. Fransen, "Treatment of symptomatic degenerative lumbar spinal stenosis by a percutaneous standalone lumbar interspinous implant. Preliminary experience with the Aperius device," *Neurochirurgie*, vol. 56, no. 1, pp. 3–7, 2010.

[21] M. Galarza, A. P. Fabrizi, R. Maina, R. Gazzeri, and J. F. Martínez-Lage, "Degenerative lumbar spinal stenosis with neurogenic intermittent claudication and treatment with the Aperius PercLID System: a preliminary report," *Neurosurgical Focus*, vol. 28, no. 6, pp. 1–6, 2010.
[22] F. Heuer, H. Schmidt, L. Claes, and H. J. Wilke, "Stepwise reduction of functional spinal structures increase vertebral translation and intradiscal pressure," *Journal of Biomechanics*, vol. 40, no. 4, pp. 795–803, 2007.
[23] R. Scapinelli, C. Stecco, A. Pozzuoli, A. Porzionato, V. Macchi, and R. De Caro, "The lumbar interspinous ligaments in humans: anatomical study and review of the literature," *Cells Tissues Organs*, vol. 183, no. 1, pp. 1–11, 2006.
[24] G. Von Hagens, K. Tiedemann, and W. Kriz, "The current potential of plastination," *Anatomy and Embryology*, vol. 175, no. 4, pp. 411–421, 1987.
[25] H. Kosaka, K. Sairyo, A. Biyani et al., "Pathomechanism of loss of elasticity and hypertrophy of lumbar ligamentum flavum in elderly patients with lumbar spinal canal stenosis," *Spine*, vol. 32, no. 25, pp. 2805–2811, 2007.
[26] J. Kuchta, R. Sobottke, P. Eysel, and P. Simons, "Two-year results of interspinous spacer (X-Stop) implantation in 175 patients with neurologic intermittent claudication due to lumbar spinal stenosis," *European Spine Journal*, vol. 18, no. 6, pp. 823–829, 2009.
[27] Y. Kawaguchi, H. Matsui, and H. Tsuji, "Back muscle injury after posterior lumbar spine surgery: part 1: histologic and histochemical analyses in rats," *Spine*, vol. 19, no. 22, pp. 2590–2597, 1994.
[28] Y. Kawaguchi, H. Matsui, and H. Tsuji, "Back muscle injury after posterior lumbar spine surgery: part 2: histologic and histochemical analyses in humans," *Spine*, vol. 19, no. 22, pp. 2598–2602, 1994.
[29] Y. Kawaguchi, H. Matsui, and H. Tsuji, "Changes in serum creatine phosphokinase MM isoenzyme after lumbar spine surgery," *Spine*, vol. 22, no. 9, pp. 1018–1023, 1997.
[30] Y. Kawaguchi, S. Yabuki, J. Styf et al., "Back muscle injury after posterior lumbar spine surgery: topographic evaluation of intramuscular pressure and blood flow in the porcine back muscle during surgery," *Spine*, vol. 21, no. 22, pp. 2683–2688, 1996.
[31] G. A. Dumas, L. Beaudoin, and G. Drouin, "In situ mechanical behavior of posterior spinal ligaments in the lumbar region. An in vitro study," *Journal of Biomechanics*, vol. 20, no. 3, pp. 301–310, 1987.
[32] K. A. Gillespie and J. P. Dickey, "Biomechanical role of lumbar spine ligaments in flexion and extension: determination using a parallel linkage robot and a porcine model," *Spine*, vol. 29, no. 11, pp. 1208–1216, 2004.
[33] R. M. Aspden, N. H. Bornstein, and D. W. L. Hukins, "Collagen organisation in the interspinous ligament and its relationship to tissue function," *Journal of Anatomy*, vol. 155, pp. 141–151, 1987.
[34] G. M. Johnson and M. Zhang, "Regional differences within the human supraspinous and interspinous ligaments: a sheet plastination study," *European Spine Journal*, vol. 11, no. 4, pp. 382–388, 2002.
[35] Y. Kotani, B. W. Cunningham, A. Cappuccino, K. Kaneda, and P. C. McAfee, "The effects of spinal fixation and destabilization on the biomechanical and histologic properties of spinal ligaments: an in vivo study," *Spine*, vol. 23, no. 6, pp. 672–683, 1998.

Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 325095, 11 pages
doi:10.1155/2012/325095

Review Article

The Microendoscopic Decompression of Lumbar Stenosis: A Review of the Current Literature and Clinical Results

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Received 16 March 2012; Accepted 7 June 2012

Academic Editor: Nicholas Slimack

Lumbar stenosis is a well-defined pathologic condition with excellent surgical outcomes. Empiric evidence as well as randomized, prospective trials has demonstrated the superior efficacy of surgery compared to medical management for lumbar stenosis. Traditionally, lumbar stenosis is decompressed with open laminectomies. This involves removal of the spinous process, lamina, and the posterior musculoligamentous complex (posterior tension band). This approach provides excellent improvement in symptoms, but is also associated with potential postoperative spinal instability. This may result in subsequent need for spinal fusion. Advances in technology have enabled the application of minimally invasive spine surgery (MISS) as an acceptable alternative to open lumbar decompression. Recent studies have shown similar to improved perioperative outcomes when comparing MISS to open decompression for lumbar stenosis. A literature review of MISS for decompression of lumbar stenosis with tubular retractors was performed to evaluate the outcomes of this modern surgical technique. In addition, a discussion of the advantages and limitations of this technique is provided.

1. Introduction

Lumbar stenosis is a well-described pathologic condition typically resulting from spondylosis. This occurs throughout the spine but is more prevalent in the cervical and lumbar regions where relatively mobile segments combined with axial loading can lead to degenerative arthritic changes. A combination of hypertrophied facet joints and ligaments, disc herniation, spondylolisthesis, and osteophyte overgrowth can lead to lumbar stenosis and subsequent compressive neurologic symptoms [1].

This chronic and debilitating condition affects 5 out of 1000 Americans older than 50 years. Surgical decompression of lumbar stenosis is the most common surgery for patients older than 65 years of age [2]. Prospective randomized clinical trials have shown significantly greater improvements in patient functional outcome and quality of life with surgical intervention compared to medical management [2, 3]. The Maine Lumbar Stenosis Study and the Spine Patient Outcomes Research Trial (SPORT) have both shown statistically significant improvement in patient outcomes. Although some studies have reported that the beneficial effects downtrend over time, the SPORT trial suggested continued improvement of the beneficial effect [4–6].

Traditionally, lumbar stenosis is treated with an open, decompressive laminectomy with or without facetectomies. This has been very effective for improvement of clinical symptoms but may inadvertently lead to cases of iatrogenic spinal instability, requiring additional surgical intervention for stabilization [7–14]. Radiographic studies, cadaver models, and finite element analyses have shown that open decompressive laminectomies are effective for lumbar stenosis but may also disrupt the native anatomic support structures (supraspinous ligament, interspinous ligament, spinous process, lamina, facet joints, ligamentum flavum, and paraspinal musculature) leading to muscular atrophy [15–21] and potential long-term spinal instability [22, 23]. Subsequently, "minimally invasive spine surgery" (MISS)

was developed to focally address the diseased structures but minimize disruption of the surrounding normal anatomic structures (Figure 1). Muscle splitting serial tube dilators and retractors were designed to minimize disruption of the paraspinal musculature and provide direct and focal access to the diseased anatomy [24, 25].

Recent studies by multiple authors have shown similar patient outcomes with MISS approaches for lumbar decompression when these techniques are compared to the traditional open approach. Furthermore, these studies have also shown additional benefits of MISS approaches: decreased blood loss, shorter operative time, shorter hospital duration, decreased postoperative narcotic requirement, decreased rate of infection and CSF leak, and a decrease in time required for return to work [26–40] (Shih and Fessler, in submission). While the open laminectomy has been traditionally the treatment of choice for lumbar stenosis, the MISS approaches are rapidly evolving into the modern surgical solution. This paper will review and summarize the available literature on clinical outcomes and complications of minimally invasive surgical decompression of lumbar stenosis with the use of the tubular retractor systems.

2. Methods

We performed a literature search on MEDLINE/PUBMED to review current reports describing clinical outcomes or complications associated with the minimally invasive surgical decompression of lumbar stenosis. Keywords included microendoscopic decompression, minimally invasive, spine surgery, lumbar stenosis, and microsurgical decompression. The period included from 1991 to 2012 with restriction to articles in English. From the initial search, 157 articles were obtained and filtered. Only articles describing the MISS technique with tubular retractors in treating lumbar stenosis were reviewed in detail. Papers that were excluded include those that performed open laminectomies, unilateral hemilaminectomy for bilateral decompression without using tubular retractors, and bilateral approaches for decompression. All remaining articles were reviewed and listed in Table 1.

3. Results

A total of twelve articles were obtained that met our initial inclusion and exclusion criteria. For the purpose of this paper, the individual papers are identified by the first date of publication. The papers were a mixture of retrospective data and prospectively collected data. All of the patients in the papers had lumbar stenosis treated by microendoscopic decompression for stenosis (MEDS) through a tubular retractor system. The perioperative data included EBL, operative time, length of hospital stay, and mean follow-up time. The functional outcomes were self-reported by the patients via ODI, JOA, SF-36, VAS, or RMDQ questionnaires. The relevant outcomes data for each article is presented here in Section 3 but will be elaborated on in Section 4.

In 2002, Khoo and Fessler [29, 40] were the first authors to describe MEDS for lumbar stenosis. 25 consecutive patients were treated with MEDS and retrospectively compared to a historical control group of 25 consecutive patients treated with open laminectomies for lumbar decompression. For the MEDS group compared to the open laminectomy group, there was a statistical decrease in operative blood loss (68 cc versus 193 cc), postoperative narcotic requirement (31.8 eq versus 73.7 eq), and length of hospital stay (42 hr versus 94 hr) [29, 40]. After a one year follow-up, 90% of the patients in the MEDS group reported improved or complete resolution of their pain symptoms.

Castro-Menendez et al. prospectively treated 50 patients with a bilateral decompression via unilateral MEDS. The majority of the patients had low back pain (70%) with radicular symptoms (60%) for a duration of at least 30 months. Every patient received one level stenosis decompression. The mean operative time was 94.3 mins, hospital duration 3.16 days, and a follow-up time 48 months. Outcomes were measured by the modified MacNab scale (good, fair, poor), VAS, and ODI. At 6 months, the mean change from preop to postop back pain VAS score was 2.86 ($P < 0.01$). The mean change in leg pain VAS score was 6.8 ($P < 0.01$), and mean change in ODI was 36.82 ($P < 0.01$). 72% of patients reported increased tolerance in ambulation and 82% of patients reported positive satisfaction. According to the modified Macnab scale, good results were obtained in 72% of patients, fair results in 14% of patients, and poor results in 14% of patients. The authors had complications in 16% of patients, 5 patients with durotomies [41].

The steep learning curve of MISS approaches is reflected in the initial complication rate of many spine surgeons with minimal complications after increased operative experience. Ikuta et al. retrospectively evaluated 47 patients undergoing MEDS for lumbar stenosis without spondylolisthesis. From 2001 to 2003, 47 MEDS patients were compared to 29 patients from the open laminectomy group prior to the institution of MEDS. The MEDS group compared to the open laminectomy group had an average operative time of 124 mins versus 101 mins and EBL of 68 cc versus 110 cc. They had a total of 4 durotomies, 3 facet fractures, and 1 epidural hematoma during the initial series of patients reflecting the steep learning of curve of MEDS. However, they have not had any subsequent complications or any wound infections. Despite the relatively high rate of initial complications, the MEDS group compared to the open laminectomy group had a decrease in duration of fever (1.2 versus 3.5 days febrile) and decreased length of stay (18 versus 24 days) and use of narcotics (0.5 versus 3.4 days of narcotics). The postoperative improvement in JOA score was 72%, and the VAS score was 70.6% at the end of follow-up. After MEDS, the mean spinal canal diameter increased from 68 mm^2 to 145 mm^2. There was no evidence of postoperative spinal instability on dynamic X-rays despite performing MEDS on patients with preoperative spondylolisthesis [42].

Subsequently, Ikuta et al. retrospectively evaluated 37 patients undergoing MEDS for lumbar stenosis and spondylolisthesis with a mean follow-up of 38 months. Outcomes were measured by JOA and VAS questionnaires. Preoperative

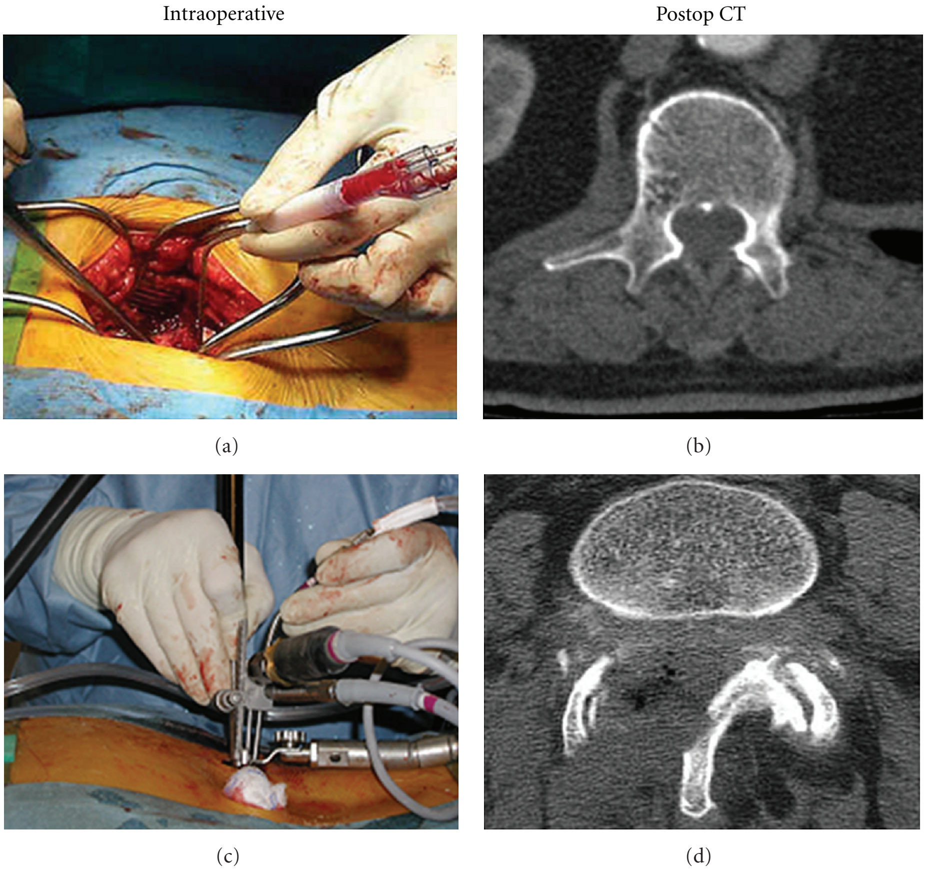


Figure 1: Illustrations of intraoperative surgical exposure and postoperative cross-sectional CT of lumbar spine with spinal canal decompression. Open laminectomy (a) and (b). Minimally invasive microendoscopic decompression (c) and (d).

JOA score was 14.1 and postoperative JOA was 23.5. Preoperative VAS score was 73 and postoperative VAS was 30. The mean preoperative cross-sectional diameter of the dural sac was 45 mm^2 and postoperative diameter was 142 mm^2. There was no statistical significance in postoperative dynamic X-rays (as measured by change in dynamic sagittal angle and % slip) to suggest instability with MEDS patients. 73% of patients reported excellent or good outcomes. 1 patient had a CSF leak without clinical symptoms [43].

Rahman et al. retrospectively compared MEDS to the open laminectomy technique in 126 patients. Similar to the aforementioned studies, the MEDS group on average had a lower EBL, shorter operative time, and decreased hospitalization when compared to the open laminectomy group. These trends were strikingly different when MEDS was performed for 3 levels or greater of stenosis or on a previously operated patient. The EBL for a 3-level open laminectomy case was 194 cc greater than a comparative MEDS and hospitalization was an additional 2.52 days (average MEDS hospitalization ~ 0.75 days). Overall complications of open laminectomy were 16.1% and MEDS was 7.9%. The open laminectomy group encountered 2 durotomies, 3 CSF leaks, 3 wound infections, and one death from postoperative sepsis. The MEDS group had 1 infection and 1 CSF leak [44].

Asgarzadie and Khoo compared 48 MEDS patients to 32 patients with open laminectomies with follow-up of four years. The average EBL for the MEDS group was 25 cc and 193 cc for the open laminectomy group. The preoperative ODI score in the MEDS group was 46 and 26 at 3 years. The average length of hospitalization for the MEDS group was 36 hours compared to 94 hours in the open laminectomy group. The rate of durotomies was 4% for the MEDS group [32].

Yagi et al. performed a prospective, randomized trial comparing the traditional open laminectomy approach to MEDS for bilateral decompression of lumbar stenosis in 41 patients. Single-level decompressions were performed, including patients with grade I spondylolisthesis without preoperative evidence of instability on dynamic X-rays. Outcomes were measured by pre- and postop imaging, VAS, JOA, cross-sectional areas of paraspinal muscles, and postoperative CPK-MM levels as a measurement of muscle destruction. Comparing the MEDS group to the open laminectomy group, the mean operative time was 71.1 mins versus 63.6 mins and EBL was 37 cc versus 71 cc, respectively. In addition, the MEDS group required decreased amounts of post-op analgesics, decreased levels of CPK-MM, decreased atrophy of paraspinal muscles, and improved functional outcome scores at the one-year follow-up. Postoperative

Table 1: Summary of current papers, outcomes, and complications of MEDS for lumbar stenosis.

Authors	Patients	Age	Functional outcome scores (VAS/ODI/SF-36)	Follow-up (months)	EBL (cc)	OR TIME (Mins)	Hospital (days)	Complications
Khoo, 2002	25	68	No functional outcomes	12	68	109	1.8	4 durotomies
Ikuta, 2003	47	66	JOA ^ 72%, VAS ^ 70.6%	22	68	124	18	4 durotomies, 3 facet fractures, and 1 EDH
Ikuta, 2004	30	69	No functional outcomes	16	44	98	18	10 spinal EDH
Rahman, 2005	126	68	No functional outcomes	NR	50	108	0.75	1 durotomy
Castro, 2005	50	56	VAS ^ 6.02, ODI ^ 30.23	48	NR	94.3	3.16	5 durotomies, 2 infections, and 2 instability
Ikuta, 2005	114	67	JOA ^ 9.4, VAS ^ 38	28	NR	NR	NR	6 durotomies and 3 facet fractures
Rosen, 2005	57	80	VAS ^ 2.4, ODI ^ 21, SF-36 ^ 22	10	NR	NR	2.3	None
Ikuta, 2006	37	69	JOA ^ 9.4, VAS ^ 43, RMDQ	38	NR	NR	NR	1 durotomy
Asgarzadie, 2007	48	64	ODI ^ 20, SF36 ^ 0.6	48	25	55	1.5	4% durotomies
Pao, 2007	53	62	JOA ^ 14.8, ODI ^ 47.6	15	104.5	126.7	NR	5 durotomies and 1 instability
Wada, 2008	15	72	JOA ^ 6.3, dural CSA ^ 408%	18	60	144	NR	1 EDH and 1 repeat operation
Yagi, 2009	20	73	JOA, VAS	18	37	71.1	3	Open: 2 instability. MEDS: none
Xu, 2009	32	65	MacNab: 21 Excellent, 11 Good	12	150	70	7	2 durotomies

spondylolisthesis was not present in the MEDS group but two patients in the open laminectomy group developed new spondylolisthesis. Yagi's group was able to demonstrate the efficacy and safety of MEDS compared to open laminectomy in a prospective, randomized trial [21].

Pao et al. prospectively operated on 60 patients over two years with MEDS for multilevel lumbar stenosis. 13 patients had spondylolisthesis and 4 patients had scoliosis. Exclusion criteria included primary mechanical low back pain or spinal instability as defined by dynamic X-rays. The mean operative time was 126.7 mins and the EBL was 104.5 cc. Outcomes were measured by JOA, ODI, and patient satisfaction surveys. Preoperative ODI score was 64.3 and postoperative ODI was 16.7. Preoperative JOA score was 9.4 and postoperative JOA was 24.2. Overall, 85% of patients were satisfied with their outcome. Follow-up was on average 15 months in 53 patients. 5 patients had non-clinically significant CSF leaks and 2 patients had wrong level surgeries. Postoperative progression of spondylolisthesis was not seen but one patient had new spondylolisthesis postop with evidence of excessive facet resection. Pao's group showed that MED approach in patients with spondylolisthesis or scoliosis can still be performed safely without introducing additional spinal instability or the necessity for fusion after decompression [45].

Wada et al. retrospectively evaluated 15 patients with an average age of 72 years who were treated for lumbar stenosis with MEDS. The preoperative JOA score was 17.0 and the postoperative score was 23.3. The mean operative time was 144 mins and the mean EBL was 60.2cc. The mean dural sac diameter was 32.7 mm^2 preoperatively and 137.6 mm^2 postoperatively, a change in diameter of 408% [46].

Xu et al. reviewed 32 patients treated for lumbar spinal stenosis with bilateral decompression via unilateral fenestration by a mobile microendoscopic decompression technique. The mean operative time was 70 mins and EBL 150 cc. They had 2 patients with durotomies but no symptomatic CSF leaks. 21 patients had excellent results and 11 patients had good results by the MacNab scale [47].

4. Discussion

The etiology of lumbar stenosis includes hypertrophy of ligaments, osteophyte overgrowth, hyperplasia of facet joints, congenital stenosis, disc herniation, spondylolisthesis, and tumors or infections. The pathophysiology of spinal stenosis causing neurologic symptoms is likely from a combination of anatomic compression of nerve roots as well as impaired blood flow primarily to the nerve root. While this debilitating condition has been treated successfully in the past with open laminectomies, MISS approaches are rapidly becoming the “standard” technique used by spine surgeons.

The history of MISS for spine surgery started with cadaveric models. Roh et al. in 2000 demonstrated the feasibility of a microendoscopic foraminotomy approach for foraminal stenosis in cadavers [24]. Guiot et al. compared the biomechanical and radiographic outcomes of four different techniques: unilateral MEDS for bilateral decompression, unilateral open laminotomy for bilateral decompression, bilateral MEDS for bilateral decompression, and bilateral open laminotomy for bilateral decompression. Their results showed excellent visualization and radiographic evidence of decompressed neural elements (Figure 2). The unilateral MEDS approach achieved similar outcomes with the least disruption of native anatomic structures [25]. This technique has since been translated to the clinical arena with excellent outcomes. In 2002, Khoo and Fessler compared MEDS to open laminectomy with a significant decrease in operative blood loss (68 cc versus 193 cc), postoperative narcotic requirement, and length of hospital stay (42 hr versus 94 hr) in patients treated for lumbar stenosis [29]. A review by O'Toole et al. showed that the rate of surgical site infections in 1338 MISS operations was 0.22% [48].

Historically, open laminectomies achieved a success rate of 64% of patients as defined by improved functional outcomes and patient satisfaction [3]. A Cochrane review in 2005 showed the efficacy of open laminectomies to be around 64–83% [2]. However, complications from open laminectomies also included durotomies as high as 18% of patients [3]. The Maine Lumbar Stenosis [4, 49] and SPORT trial [5] showed similar efficacy with laminectomies for lumbar stenosis. The trial patients had the greatest improvements within the first three months of surgery, but control of low back pain gradually trended back toward the medical management group over long-term follow-up (4–10 yrs). However, the patients' improvement in radiating leg pain and functional status was still statistically significant compared to medical management after long-term follow-up.

Potential repercussions from aggressive decompression of the native anatomic structures include increased blood loss, increased postoperative narcotic requirement, prolonged hospital stay, increased epidural scar formation, intraspinal facet cyst formation, chronic low back pain, and long-term spinal segmental instability [47, 50].

Postoperative, long-term spinal instability is a real concern in patients undergoing laminectomy for lumbar stenosis, especially if the patients have preoperative spondylolisthesis. Review of the literature shows that patients with preoperative spondylolisthesis have a higher rate (40–100%) of postoperative progression of instability on dynamic X-rays at long-term follow-up [7, 11, 12, 14, 51–54]. Bridwell et al. evaluated 44 patients with preoperative spondylolisthesis divided into three treatment groups: (1) decompression, (2) decompression with arthrodesis, (3) decompression with arthrodesis and instrumentation. The rate of postoperative progression of spondylolisthesis with an average follow-up of 38 months was as follows: decompression: 44%, decompression with arthrodesis: 70%, and decompression with arthrodesis and instrumentation: 4.1% [55]. Recent guidelines by the American Association of Neurological Surgery and the Congress of Neurological Surgery in 2005 recommended spinal fusion in patients undergoing lumbar decompression with stenosis and preoperative spondylolisthesis [56, 57]. Theoretically, maintenance of the posterior tension band with a MISS approach through tubular

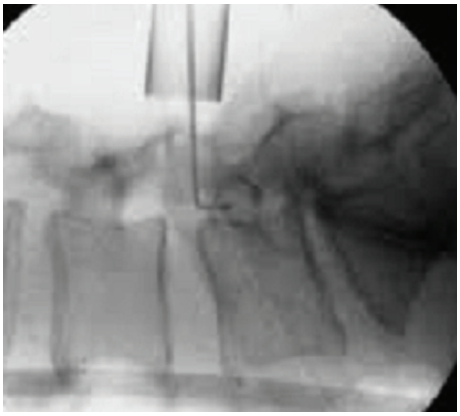


Figure 2: Minimally invasive decompression of lumbar stenosis with fluoroscopy confirmed placement of tubular retractors.

retractors would decrease the probability of developing postoperative spinal instability.

This concern was addressed through biomechanical models with cadaver lumbar specimens showing the clinical importance of maintaining an intact posterior tension band and facet joints. Abumi et al. showed a proportional increase in spinal instability with the percentage of lumbar facetectomy. Radiographic evidence of progression of spondylolisthesis was present if greater than 50% of the facet joint was resected at any one level [58]. Hindle et al. demonstrated significant loading forces absorbed by the supraspinous and interspinous ligaments during flexion forces [59]. Similarly, Goel et al. showed that the supraspinous ligament supported the greatest load to flexion forces in cadaver models [60].

Hamasaki et al. performed a biomechanical evaluation of cadaver lumbar specimens and "stability" against stress when graded parts of the posterior elements are removed in systematic fashion. Eight lumbar spine cadavers underwent segmental decompression from various techniques and were compared to an intact cadaver lumbar spine. They evaluated multiple MISS approaches: unilateral decompression, bilateral decompression via unilateral approach, bilateral decompression with partial medial facetectomies, and bilateral decompression with facetectomies. They discovered that a unilateral MISS approach for bilateral decompression with intact facets maintains up to 80% of the native anatomic "stiffness" compared to large bilateral decompressions with facetectomies [61].

There are specific situations when an MISS approach may have better long-term outcomes than in open laminectomy cases. In patients with preoperative spondylolisthesis, an MISS approach may minimize the likelihood of postoperative progression to spinal instability. Postoperative spinal instability has always been a major concern after an open laminectomy, especially if the patient has preoperative spondylolisthesis. The current surgical management for spondylolisthesis remains controversial as authorities are divided between simple laminectomies or to augment the decompression with instrumentation and arthrodesis [7, 11, 12, 14, 51–55]. Herkowitz and Kurz showed better clinical outcomes in patients with spondylolisthesis treated with lumbar decompression and arthrodesis instead of only decompression. In the arthrodesis group 36% of patients developed pseudoarthrosis, but they all finished with excellent clinical outcomes [9]. Subsequently, Fischgrund et al. compared patients with spondylolisthesis treated by lumbar decompression with arthrodesis versus lumbar decompression with arthrodesis and instrumentation. Their results showed improved fusion rates in patients with instrumentation (82% in instrumented cases versus 45% in noninstrumented cases), but overall clinical outcomes were similar between the two groups over a two-year period [8]. Kornblum et al. performed a five-year follow-up of patients undergoing lumbar decompression with arthrodesis to evaluate the clinical significance of pseudoarthrosis. They found that 85% of patients who had solid fusion had an excellent or good outcome compared to only 56% of patients who had a pseudoarthrosis. These studies strongly suggest that patients with spondylolisthesis who have open laminectomies should also have concomitant arthrodesis with instrumentation to improve their fusion rate and clinical outcomes [7, 10, 12, 14].

The subsequent question to these studies is if maintaining the posterior tension band and contralateral facet via an MISS approach is sufficient to prevent progression of spondylolisthesis. Ikuta et al. evaluated 37 patients treated for lumbar spondylolisthesis by MEDS without concomitant fusion or instrumentation. All 37 patients had statistically significant improvement in their functional outcome scores after a mean follow-up of 38months. On radiographic imaging, the change in dynamic sagittal angle was from 8.5 degrees to 6.6 degrees and the "percent slip" changed from 14.1% to 15.7%. The authors noted that 19% of their patients developed "postoperative spinal instability" on imaging, including one patient who required subsequent fusion [43]. However, when compared to the natural history of progression in spondylolisthesis, the 19% of patients showing progression is actually an encouraging sign. Matsunaga et al. documented the natural history of lumbar spondylolisthesis with 30% of patients eventually progressing to spinal instability and needing surgical intervention [13]. In the senior author's experience, only a single patient (0.45%) required subsequent fusion in 215 consecutively treated patients with an average follow-up of 4.5 years (Smith and Fessler, in submission). This suggests that MEDS in patients with lumbar stenosis and spondylolisthesis is no worse than the natural history of progression to spinal instability.

The additional structural stability provided by the posterior tension band and contralateral facet cannot be understated. As the aforementioned biomechanical studies have shown, the supraspinous and interspinous ligaments play significant roles in axial load bearing and flexion of the spine. Potentially, maintenance of these ligaments would help reduce the incidence of iatrogenic spondylolisthesis. In addition, Bresnahan et al. used a finite element model to demonstrate the effects of graded posterior element resection on spinal stability. Their results indicate that removal of the posterior bony and ligamentous elements produces increased laxity in segmental motion in open laminectomies. However,

in MISS approaches, the overall spinal stability is relatively unchanged [17, 22]. Thus, a unilateral MISS approach that splits the paravertebral muscles without dissection, maintains the posterior tension band and contralateral facet, but decompresses the bilateral laminae and hypertrophic ligamentum flavum would be an ideal procedure.

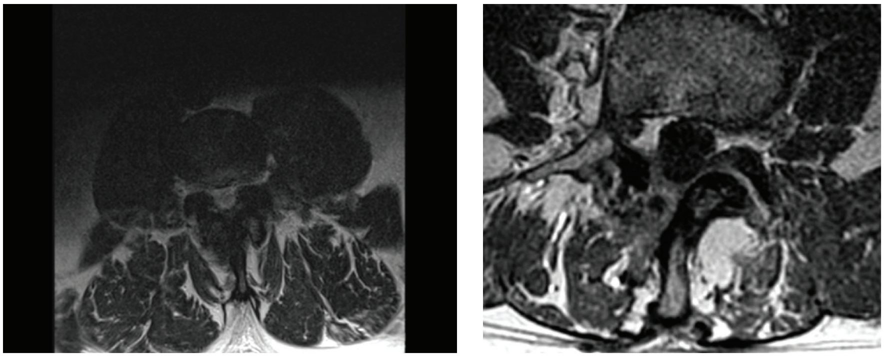
Not only would the muscle splitting procedure of an MISS approach minimize iatrogenic destruction of stabilizing structures, but it would also help to decrease the incidence of chronic low back pain. Bresnahan et al. showed in an MRI study that both open laminectomies and MEDS show significant increases in thecal sac diameter after decompression (Figure 3) (Congress of Neurological Surgeons, 2011). Their data also showed a mean decrease in the cross-sectional area of the paraspinal muscles of 18% after open laminectomy when compared to MEDS [17]. Previous authors have theorized the etiology of chronic low back pain after open laminectomy as a result of prolonged dissection and retraction of the multifidus muscle [62]. The pathophysiology of the pain is potentially from the impaired blood flow to the muscle during retraction as well as traction injury itself to the dorsal superficial nerves supplying innervations to the multifidus muscle [18, 63–65]. Follow-up studies of MEDS have shown a decreased incidence of chronic low back pain when compared to the open laminectomy patients [20, 62].

Despite many of the benefits from an MISS approach to lumbar stenosis, there remains a high rate of initial complications related to the steep learning curve of a new surgical technique [66]. Ikuta et al. reported on complications related to MEDS in a retrospective review of 114 consecutive patients over four years. Complication outcomes included durotomy, nerve root injury, inferior facet fracture, wrong level surgery, infections, or neurological deficits. 9 patients had intraoperative complications: 6 durotomies and 3 inferior facet fractures. There were no symptomatic clinical CSF leaks or wound infections. The rate of neurological complications in the first 34 patients was 18%, which decreased to 6.3% in the latest 80 patients. The JOA score improved by 9.4 and the VAS decreased by 38 after MEDS. 12 patients suffered "neurologic complications" after surgery with the majority of the patients suffering from increased pain from preoperative pain or new postoperative pain. The 12 patients were treated with medications and gradually had improved symptoms. Only one patient had a repeat surgery for postoperative instability [67].

As a follow-up to the surgical complications associated with MEDS, Ikuta et al. prospectively followed 30 patients with radiographic imaging to document the incidence of postoperative spinal epidural hematomas. The overall incidence of symptomatic spinal epidural hematomas requiring reoperation was 0.2% in a review of 14,932 spine surgeries [68–71]. In Ikuta's series of 30 patients undergoing MEDS over nine months, postoperative patients had MRI T2 imaging of the lumbar spine at 1 week, 3 months, and 1 year. Spinal EDH was defined as a cross-sectional EDH greater than 100 mm^2 and a dural sac of less than 75 mm^2. At the one-week review, 10 patients (33%) had radiographic evidence of spinal EDH compared to the 20 patients without spinal EDH. The two groups had similar preoperative profiles with similar levels of decompression. All 10 patients with spinal EDH had complete resolution of their symptoms within 3 weeks. At the 3-month MRI interval, there was radiographic improvement in the spinal EDH. At the 1-year MRI interval, there was complete resolution of radiographic EDH, but there were a few patients with a low-signal intensity band surrounding the thecal sac with associated stenosis despite adequate bony decompression. In addition, patients with postoperative spinal EDH had worse functional outcomes by the VAS, JOA, and RDMQ scores when compared to patients without spinal EDH. Thus, the authors have recommended meticulous intraoperative hemostasis, tight blood pressure regulation, and consideration of an intraoperative wound drain. While MISS approaches should theoretically limit the volume of dead space for hematoma collection after surgery, meticulous hemostasis is essential for successful outcomes in MEDS for lumbar stenosis [72].

While the main philosophy of MISS approaches is to preserve the majority of the native supportive anatomy, there are also many other beneficial results to MISS. In the majority of the MEDS articles reviewed, the authors have shown rapid improvement in their surgical skills after the initial steep learning curve and associated complications arising from a novel surgical technique. Shih et al. showed similar rates of clinical complications when comparing the open laminectomy to MEDS [73]. Since then, the authors have reported overall decreases in operative time, EBL, length of hospitalization, use of narcotics, incidence of symptomatic CSF leaks, incidence of wound infections, and minimal progression of postoperative spinal spondylolisthesis. In the senior author's experience, unintentional durotomies in MEDS have decreased with the use of a protective sleeve drill bit and preservation of the underlying ligamentum flavum during bony decompression (Figure 4). The use of a retractable, single-sided guard on the pneumatic drill bit protects the dura from inadvertent injury on one side while allowing visualization of the drill bit tip from the other side (Figure 4, the drill-bit used is a variant of the AM8 standard drill (Midas Rex, Medtronic). In MEDS, the ligamentum flavum is kept intact until the bony decompression with the drill and Kerrison rongeurs is completed [40]. The senior author recently showed a 4.5% incidence of durotomies in obese patients undergoing MEDS for lumbar stenosis [74].

Another subpopulation of patients that would potentially benefit from MISS approaches to spinal pathology would be the elderly or medically frail patients. Previously published data on complication rate in open laminectomies for patients older than 75 years was 18% [75, 76]. Jansson et al. discovered a four times increase in perioperative mortality in patients older than 80 years undergoing open laminectomy for lumbar stenosis [77]. In contrast, Rosen et al. reported their success in treating elderly patients with MEDS for lumbar stenosis with minimal complications. They evaluated 57 patients with an average age of 80.8 years with multiple medical comorbidities. The elderly population demonstrated improved and sustained VAS, ODI, and SF-36 scores that reached statistical significance. Rosen et al. showed no operative complications and the overall minor complication



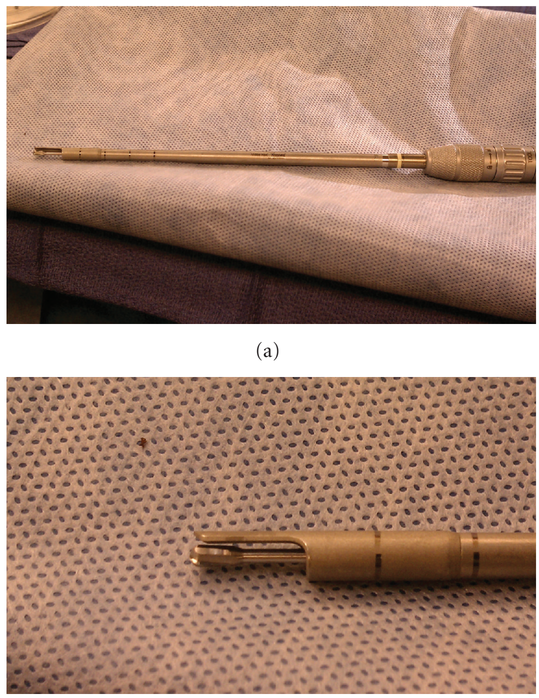
(a) (b)

Figure 3: Preoperative (a) and postoperative (b) cross-sectional MRI of lumbar spine demonstrating significant enlargement of thecal sac.

rate was 2% [33]. It is our experience that minimally invasive techniques may significantly decrease morbidity in the elderly, primarily due to decreases in blood loss, soft-tissue injury, and physiological stress.

Another subpopulation of patients that may benefit from MISS approaches would be the obese patients. Obese patients tend to have longer operative times, increased blood loss, larger incisions and soft-tissue dissection for exposure, and increased perioperative complications [78]. Some authors have quoted obesity-related complications to range from 36–67% higher than a normal BMI patient [78–80]. Kalanithi et al. reported an absolute increase in length of hospitalization (2 extra days) and perioperative complications (6.7%) in obese patients undergoing spinal surgery in California. The majority of their complications were from wound infections and pulmonary disease [81]. In contrast, MISS approaches would employ a small incision with minimal wound exposure and decreased soft-tissue trauma. Theoretically, there would be a decreased "potential space" for infection with overall decreased surgical trauma. Senker et al. treated 72 patients with an MISS approach for a transforaminal lumbar interbody fusion and decompression. 3 subgroups were created: normal BMI, overweight, and obese. With an MISS approach, Senker et al. did not find any statistical difference between the three groups in complication rate, operative time, EBL, or hospital stay [82]. Smith et al. compared 60 "obese" BMI patients to 51 "normal" BMI patients treated with MEDS for lumbar stenosis and found similar outcomes in mean operative time, EBL, length of hospital stay, or perioperative complications [74]. Thus, obese patients who may have increased comorbidities and perioperative complications from an open surgical approach may have improved outcomes with MISS.

Technological advances have opened new doors for MISS approaches in treating spinal pathologies. While the MISS technique was originally designed for microdiscectomy, the MISS philosophy has expanded in treating many diseases from different angles with similar or improved outcomes. MISS approaches are now feasible for disc herniations, central canal/foraminal stenosis, extraforaminal stenosis [83], intradural or intramedullary spinal tumors, spinal fusion, and deformity correction.



(a)

(b)

Figure 4: (a) Retractable, single-sided guard on the pneumatic drill bit protects the dura from inadvertent injury on one side while allowing visualization of the drill bit tip from the other side. (b) Zoomed-in view of the drill-bit that is a variant of the AM8 standard drill (Midas Rex, Medtronic).

5. Conclusion

There continue to be rapid improvements in MISS technology, enabling innovative surgical approaches to traditional spinal disease. There is a continuous trend toward minimally

invasive surgical approaches in many different surgical subspecialties. This paradigm shift of "less is more" has flourished in MISS approaches for discectomies, foraminotomies, decompression for stenosis, instrumentation and fusion, spinal tumor resection, and deformity correction [84]. Review of the recent literature shows the efficacy of MEDS for lumbar stenosis in patient satisfaction and functional outcomes. Hopefully, future studies will demonstrate the ultimate benefit of MEDS: preservation of native anatomic support structures leading to a decreased incidence of iatrogenic spinal instability.

Abbreviations

BMI:	Body mass index
CSA:	Cross-sectional area
EDH:	Epidural hematoma
MEDS:	Microendoscopic decompression of stenosis
MISS:	Minimally invasive spine surgery
MRI:	Magnetic resonance imaging
ODI:	Oswestry Disability Index
RMDQ:	Roland Morris Disability Questionnaire
SF-36:	Short Form-36
SPORT:	Spine Patient Outcomes Research Trial
VAS:	Visual Analog Scale pain scores.

References

[1] R. K. Osenbach, "Lumbar laminectomy," in *Atlas of Neurosurgical Techniques: Spine and Peripheral Nerves*, L. Sekhar and R. G. Fessler, Eds., vol. 2, Thieme, 1st edition, 2006.

[2] J. N. A. Gibson and G. Waddell, "Surgery for degenerative lumbar spondylosis: updated Cochrane review," *Spine*, vol. 30, no. 20, pp. 2312–2320, 2005.

[3] J. A. Turner, M. Ersek, L. Herron, and R. Deyo, "Surgery for lumbar spinal stenosis: attempted meta-analysis of the literature," *Spine*, vol. 17, no. 1, pp. 1–8, 1992.

[4] S. J. Atlas, R. A. Deyo, R. B. Keller et al., "The Maine Lumbar Spine Study, part III: 1-Year outcomes of surgical and nonsurgical management of lumbar spinal stenosis," *Spine*, vol. 21, no. 15, pp. 1787–1795, 1996.

[5] J. N. Weinstein, T. D. Tosteson, J. D. Lurie et al., "Surgical versus nonoperative treatment for lumbar spinal stenosis four-year results of the spine patient outcomes research trial," *Spine*, vol. 35, no. 14, pp. 1329–1338, 2010.

[6] Y. Chang, D. E. Singer, Y. A. Wu, R. B. Keller, and S. J. Atlas, "The effect of surgical and nonsurgical treatment on longitudinal outcomes of lumbar spinal stenosis over 10 years," *Journal of the American Geriatrics Society*, vol. 53, no. 5, pp. 785–792, 2005.

[7] H. Bassewitz and H. Herkowitz, "Lumbar stenosis with spondylolisthesis: current concepts of surgical treatment," *Clinical Orthopaedics and Related Research*, no. 384, pp. 54–60, 2001.

[8] J. S. Fischgrund, M. Mackay, H. N. Herkowitz, R. Brower, D. M. Montgomery, and L. T. Kurz, "Degenerative lumbar spondylolisthesis with spinal stenosis: a prospective, randomized study comparing decompressive laminectomy and arthrodesis with and without spinal instrumentation," *Spine*, vol. 22, no. 24, pp. 2807–2812, 1997.

[9] H. N. Herkowitz and L. T. Kurz, "Degenerative lumbar spondylolisthesis with spinal stenosis: a prospective study comparing decompression with decompression and intertransverse process arthrodesis," *Journal of Bone and Joint Surgery*, vol. 73, no. 6, pp. 802–808, 1991.

[10] M. B. Kornblum, J. S. Fischgrund, H. N. Herkowitz, D. A. Abraham, D. L. Berkower, and J. S. Ditkoff, "Degenerative lumbar spondylolisthesis with spinal stenosis: a prospective long-term study comparing fusion and pseudarthrosis," *Spine*, vol. 29, no. 7, pp. 726–733, 2004.

[11] S. M. Mardjetko, P. J. Connolly, and S. Shott, "Degenerative lumbar spondylolisthesis: a meta-analysis of literature 1970–1993," *Spine*, vol. 19, supplement 20, pp. 2256S–2265S, 1994.

[12] C. R. Martin, A. T. Gruszczynski, H. A. Braunsfurth, S. M. Fallatah, J. O'Neil, and E. K. Wai, "The surgical management of degenerative lumbar spondylolisthesis: a systematic review," *Spine*, vol. 32, no. 16, pp. 1791–1798, 2007.

[13] S. Matsunaga, T. Sakou, Y. Morizono, A. Masuda, and A. M. Demirtas, "Natural history of degenerative spondylolisthesis: pathogenesis and natural course of the slippage," *Spine*, vol. 15, no. 11, pp. 1204–1210, 1990.

[14] D. K. Sengupta and H. N. Herkowitz, "Degenerative spondylolisthesis: review of current trends and controversies," *Spine*, vol. 30, supplement 6, pp. S71–S81, 2005.

[15] B. B. Pradhan, J. A. Nassar, R. B. Delamarter, and J. C. Wang, "Single-level lumbar spine fusion: a comparison of anterior and posterior approaches," *Journal of Spinal Disorders and Techniques*, vol. 15, no. 5, pp. 355–361, 2002.

[16] T. Sihvonen, A. Herno, L. Paljarvi, O. Airaksinen, J. Partanen, and A. Tapaninaho, "Local denervation atrophy of paraspinal muscles in postoperative failed back syndrome," *Spine*, vol. 18, no. 5, pp. 575–581, 1993.

[17] L. Bresnahan, R. G. Fessler, and R. N. Natarajan, "Evaluation of change in muscle activity as a result of posterior lumbar spine surgery using a dynamic modeling system," *Spine*, vol. 35, no. 16, pp. E761–E767, 2010.

[18] T. Motosuneya, T. Asazuma, T. Tsuji, H. Watanabe, Y. Nakayama, and K. Nemoto, "Postoperative change of the cross-sectional area of back musculature after 5 surgical procedures as assessed by magnetic resonance imaging," *Journal of Spinal Disorders and Techniques*, vol. 19, no. 5, pp. 318–322, 2006.

[19] J. Rantanen, M. Hurme, B. Falck et al., "The lumbar multifidus muscle five years after surgery for a lumbar intervertebral disc herniation," *Spine*, vol. 18, no. 5, pp. 568–574, 1993.

[20] R. Gejo, H. Matsui, Y. Kawaguchi, H. Ishihara, and H. Tsuji, "Serial changes in trunk muscle performance after posterior lumbar surgery," *Spine*, vol. 24, no. 10, pp. 1023–1028, 1999.

[21] M. Yagi, E. Okada, K. Ninomiya, and M. Kihara, "Postoperative outcome after modified unilateral-approach microendoscopic midline decompression for degenerative spinal stenosis: clinical article," *Journal of Neurosurgery: Spine*, vol. 10, no. 4, pp. 293–299, 2009.

[22] L. Bresnahan, A. T. Ogden, R. N. Natarajan, and R. G. Fessler, "A biomechanical evaluation of graded posterior element removal for treatment of lumbar stenosis: comparison of a minimally invasive approach with two standard laminectomy techniques," *Spine*, vol. 34, no. 1, pp. 17–23, 2009.

[23] A. T. Ogden, L. Bresnahan, J. S. Smith, R. Natarajan, and R. G. Fessler, "Biomechanical comparison of traditional and minimally invasive intradural tumor exposures using finite element analysis," *Clinical Biomechanics*, vol. 24, no. 2, pp. 143–147, 2009.

[24] S. W. Roh, D. H. Kim, A. C. Cardoso, and R. G. Fessler, “Endoscopic foraminotomy using MED system in cadaveric specimens,” *Spine*, vol. 25, no. 2, pp. 260–264, 2000.

[25] B. H. Guiot, L. T. Khoo, and R. G. Fessler, “A minimally invasive technique for decompression of the lumbar spin,” *Spine*, vol. 27, no. 4, pp. 432–438, 2002.

[26] R. G. Fessler and L. T. Khoo, “Minimally invasive cervical microendoscopic foraminotomy: an initial clinical experience,” *Neurosurgery*, vol. 51, supplement 5, pp. 37–45, 2002.

[27] K. T. Foley, L. T. Holly, and J. D. Schwender, “Minimally invasive lumbar fusion,” *Spine*, vol. 28, supplement 15, pp. S26–S35, 2003.

[28] R. E. Isaacs, V. K. Podichetty, P. Santiago et al., “Minimally invasive microendoscopy-assisted transforaminal lumbar interbody fusion with instrumentation,” *Journal of Neurosurgery: Spine*, vol. 3, no. 2, pp. 98–105, 2005.

[29] L. T. Khoo and R. G. Fessler, “Microendoscopic decompressive laminotomy for the treatment of lumbar stenosis,” *Neurosurgery*, vol. 51, supplement 5, pp. 146–154, 2002.

[30] S. Palmer, R. Turner, and R. Palmer, “Bilateral decompression of lumbar spinal stenosis involving a unilateral approach with microscope and tubular retractor system,” *Journal of Neurosurgery*, vol. 97, supplement 2, pp. 213–217, 2002.

[31] R. G. Fessler, J. E. O’Toole, K. M. Eichholz, and M. J. Perez-Cruet, “The development of minimally invasive spine surgery,” *Neurosurgery Clinics of North America*, vol. 17, no. 4, pp. 401–409, 2006.

[32] F. Asgarzadie and L. T. Khoo, “Minimally invasive operative management for lumbar spinal stenosis: overview of early and long-term outcomes,” *Orthopedic Clinics of North America*, vol. 38, no. 3, pp. 387–399, 2007.

[33] D. S. Rosen, J. E. O’Toole, K. M. Eichholz et al., “Minimally invasive lumbar spinal decompression in the elderly: outcomes of 50 patients aged 75 years and older,” *Neurosurgery*, vol. 60, no. 3, pp. 503–509, 2007.

[34] P. Park and K. T. Foley, “Minimally invasive transforaminal lumbar interbody fusion with reduction of spondylolisthesis: technique and outcomes after a minimum of 2 years’ follow-up,” *Neurosurgical Focus*, vol. 25, no. 2, article E16, 2008.

[35] D. S. Rosen, S. D. Ferguson, A. T. Ogden, D. Huo, and R. G. Fessler, “Obesity and self-reported outcome after minimally invasive lumbar spinal fusion surgery,” *Neurosurgery*, vol. 63, no. 5, pp. 956–960, 2008.

[36] J. S. Smith, A. T. Ogden, and R. G. Fessler, “Minimally invasive posterior thoracic fusion,” *Neurosurgical Focus*, vol. 25, no. 2, article E9, 2008.

[37] J. E. O’Toole, K. M. Eichholz, and R. G. Fessler, “Surgical site infection rates after minimally invasive spinal surgery: clinical article,” *Journal of Neurosurgery*, vol. 11, no. 4, pp. 471–476, 2009.

[38] C. Lawton, Z. A. Smith, A. Barnawi, and R. G. Fessler, “The surgical technique of minimally invasive transforaminal lumbar interbody fusion,” *Journal of Neurosurgical Sciences*, vol. 55, no. 3, pp. 259–264, 2011.

[39] L. T. Khoo, Z. A. Smith, F. Asgarzadie et al., “Minimally invasive extracavitary approach for thoracic discectomy and interbody fusion: 1-Year clinical and radiographic outcomes in 13 patients compared with a cohort of traditional anterior transthoracic approaches—clinical article,” *Journal of Neurosurgery: Spine*, vol. 14, no. 2, pp. 250–260, 2011.

[40] L. T. Khoo and R. G. Fessler, “Microendoscopic decompressive laminotomy for the treatment of lumbar stenosis,” *Neurosurgery*, vol. 51, supplement 5, pp. S146–S154, 2002.

[41] M. Y. Wang, J. A. Bravo-Ricoy, R. Casal-Moro, M. Hernández-Blanco, and F. J. Jorge-Barreiro, “Midterm outcome after microendoscopic decompressive laminotomy for lumbar spinal stenosis: 4-Year prospective study—commentary,” *Neurosurgery*, vol. 65, no. 1, pp. 100–110, 2009.

[42] K. Ikuta, J. Arima, T. Tanaka et al., “Short-term results of microendoscopic posterior decompression for lumbar spinal stenosis. Technical note,” *Journal of Neurosurgery: Spine*, vol. 2, no. 5, pp. 624–633, 2005.

[43] K. Ikuta, O. Tono, and M. Oga, “Clinical outcome of microendoscopic posterior decompression for spinal stenosis associated with degenerative spondylolisthesis—minimum 2-year outcome of 37 patients,” *Minimally Invasive Neurosurgery*, vol. 51, no. 5, pp. 267–271, 2008.

[44] M. Rahman, L. E. Summers, B. Richter, R. I. Mimran, and R. P. Jacob, “Comparison of techniques for decompressive lumbar laminectomy: the minimally invasive versus the ”classic” open approach,” *Minimally Invasive Neurosurgery*, vol. 51, no. 2, pp. 100–105, 2008.

[45] J. L. Pao, W. C. Chen, and P. Q. Chen, “Clinical outcomes of microendoscopic decompressive laminotomy for degenerative lumbar spinal stenosis,” *European Spine Journal*, vol. 18, no. 5, pp. 672–678, 2009.

[46] K. Wada, K. Sairyo, T. Sakai, and N. Yasui, “Minimally invasive endoscopic bilateral decompression with a unilateral approach (endo-BiDUA) for elderly patients with lumbar spinal canal stenosis,” *Minimally Invasive Neurosurgery*, vol. 53, no. 2, pp. 65–68, 2010.

[47] B. S. Xu, Q. S. Tan, Q. Xia, N. Ji, and Y. C. Hu, “Bilateral decompression via unilateral fenestration using mobile microendoscopic discectomy technique for lumbar spinal stenosis,” *Orthopedic Surgery*, vol. 2, no. 2, pp. 106–110, 2010.

[48] J. E. O’Toole, K. M. Eichholz, and R. G. Fessler, “Surgical site infection rates after minimally invasive spinal surgery: clinical article,” *Journal of Neurosurgery: Spine*, vol. 11, no. 4, pp. 471–476, 2009.

[49] S. J. Atlas, R. B. Keller, Y. A. Wu, R. A. Deyo, and D. E. Singer, “Long-term outcomes of surgical and nonsurgical management of lumbar spinal stenosis: 8 to 10 year results from the Maine lumbar spine study,” *Spine*, vol. 30, no. 8, pp. 936–943, 2005.

[50] K. Ikuta, O. Tono, and M. Oga, “Prevalence and clinical features of intraspinal facet cysts after decompression surgery for lumbar spinal stenosis: clinical article,” *Journal of Neurosurgery: Spine*, vol. 10, no. 6, pp. 617–622, 2009.

[51] D. K. Sengupta, “Point of view: dynamic stabilization in addition to decompression for lumbar spinal stenosis with degenerative spondylolisthesis,” *Spine*, vol. 31, no. 4, p. 450, 2006.

[52] C. K. Lee, “Lumbar spinal instability (olisthesis) after extensive posterior spinal decompression,” *Spine*, vol. 8, no. 4, pp. 429–433, 1983.

[53] K. E. Johnsson, S. Willner, and K. Johnsson, “Postoperative instability after decompression for lumbar spinal stenosis,” *Spine*, vol. 11, no. 2, pp. 107–110, 1986.

[54] V. Surin, E. Hedelin, and L. Smith, “Degenerative lumbar spinal stenosis. Results of operative treatment,” *Acta Orthopaedica Scandinavica*, vol. 53, no. 1, pp. 79–85, 1982.

[55] K. H. Bridwell, T. A. Sedgewick, M. F. O’Brien, L. G. Lenke, and C. Baldus, “The role of fusion and instrumentation in the treatment of degenerative spondylolisthesis with spinal stenosis,” *Journal of Spinal Disorders*, vol. 6, no. 6, pp. 461–472, 1993.

[56] D. K. Resnick, T. F. Choudhri, A. T. Dailey et al., "Guidelines for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 10: fusion following decompression in patients with stenosis without spondylolisthesis," *Journal of Neurosurgery: Spine*, vol. 2, no. 6, pp. 686–691, 2005.

[57] D. K. Resnick, T. F. Choudhri, A. T. Dailey et al., "Guidelines for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 9: fusion in patients with stenosis and spondylolisthesis," *Journal of Neurosurgery: Spine*, vol. 2, no. 6, pp. 679–685, 2005.

[58] K. Abumi, M. M. Panjabi, K. M. Kramer, J. Duranceau, T. Oxland, and J. J. Crisco, "Biomechanical evaluation of lumbar spinal stability after graded facetectomies," *Spine*, vol. 15, no. 11, pp. 1142–1147, 1990.

[59] R. J. Hindle, M. J. Pearcy, and A. Cross, "Mechanical function the human lumbar interspinous and supraspinous ligaments," *Journal of Biomedical Engineering*, vol. 12, no. 4, pp. 340–344, 1990.

[60] V. K. Goel, S. J. Fromknecht, and K. Nishiyama, "The role of lumbar spinal elements in flexion," *Spine*, vol. 10, no. 6, pp. 516–523, 1985.

[61] T. Hamasaki, N. Tanaka, J. Kim, M. Okada, M. Ochi, and W. C. Hutton, "Biomechanical assessment of minimally invasive decompression for lumbar spinal canal stenosis: a cadaver study," *Journal of Spinal Disorders and Techniques*, vol. 22, no. 7, pp. 486–491, 2009.

[62] G. Datta, K. K. Gnanalingham, D. Peterson et al., "Back pain and disability after lumbar laminectomy: is there a relationship to muscle retraction?" *Neurosurgery*, vol. 54, no. 6, pp. 1413–1420, 2004.

[63] S. J. Hyun, Y. B. Kim, Y. S. Kim et al., "Postoperative changes in paraspinal muscle volume: comparison between paramedian interfascial and midline approaches for lumbar fusion," *Journal of Korean Medical Science*, vol. 22, no. 4, pp. 646–651, 2007.

[64] D. Y. Kim, S. H. Lee, K. C. Sang, and H. Y. Lee, "Comparison of multifidus muscle atrophy and trunk extension muscle strength: percutaneous versus open pedicle screw fixation," *Spine*, vol. 30, no. 1, pp. 123–129, 2005.

[65] Y. Kawaguchi, H. Matsui, and H. Tsuji, "Back muscle injury after posterior lumbar spine surgery: a histologic and enzymatic analysis," *Spine*, vol. 21, no. 8, pp. 941–944, 1996.

[66] M. J. Perez-Cruet, R. G. Fessler, and N. I. Perin, "Review: complications of minimally invasive spinal surgery," *Neurosurgery*, vol. 51, supplement 5, pp. 26–36, 2002.

[67] K. Ikuta, O. Tono, T. Tanaka et al., "Surgical complications of microendoscopic procedures for lumbar spinal stenosis," *Minimally Invasive Neurosurgery*, vol. 50, no. 3, pp. 145–149, 2007.

[68] J. N. Awad, K. M. Kebaish, J. Donigan, D. B. Cohen, and J. P. Kostuik, "Analysis of the risk factors for the development of post-operative spinal epidural haematoma," *Journal of Bone and Joint Surgery*, vol. 87, no. 9, pp. 1248–1252, 2005.

[69] L. Di Lauro, R. Poli, M. Bortoluzzi, and G. Marini, "Paresthesias after lumbar disc removal and their relationship to epidural hematoma. Report of two cases," *Journal of Neurosurgery*, vol. 57, no. 1, pp. 135–136, 1982.

[70] J. J. Shin, S. U. Kuh, and Y. E. Cho, "Surgical management of spontaneous spinal epidural hematoma," *European Spine Journal*, vol. 15, no. 6, pp. 998–1004, 2006.

[71] M. T. Lawton, R. W. Porter, J. E. Heiserman, R. Jacobowitz, V. K. H. Sonntag, and C. A. Dickman, "Surgical management of spinal epidural hematoma: relationship between surgical timing and neurological outcome," *Journal of Neurosurgery*, vol. 83, no. 1, pp. 1–7, 1995.

[72] K. O. Ikuta, O. Tono, T. Tanaka et al., "Evaluation of postoperative spinal epidural hematoma after microendoscopic posterior decompression for lumbar spinal stenosis: a clinical and magnetic resonance imaging study," *Journal of Neurosurgery: Spine*, vol. 5, no. 5, pp. 404–409, 2006.

[73] P. Shih, A. P. Wong, T. R. Smith, A. I. Lee, and R. G. Fessler, "Complications of open compared to minimally invasive lumbar spine decompression," *Journal of Clinical Neuroscience*, vol. 18, no. 10, pp. 1360–1364, 2011.

[74] Z. A. Smith, "Obesity and patient outcomes following lumbar microendoscopic decompression of stenosis—outcomes and complications in 111 consecutively treated patients," Northwestern Memorial Hospital, Northwestern University, Chicago, Ill, USA, p. 19, 2012.

[75] R. A. Deyo, D. C. Cherkin, J. D. Loeser, S. J. Bigos, and M. A. Ciol, "Morbidity and mortality in association with operations on the lumbar spine. The influence of age, diagnosis, and procedure," *Journal of Bone and Joint Surgery*, vol. 74, no. 4, pp. 536–543, 1992.

[76] L. Y. Carreon, R. M. Puno, J. R. Dimar, S. D. Glassman, and J. R. Johnson, "Perioperative complications of posterior lumbar decompression and arthrodesis in older adults," *Journal of Bone and Joint Surgery*, vol. 85, no. 11, pp. 2089–2092, 2003.

[77] K. Å. Jansson, P. Blomqvist, F. Granath, and G. Németh, "Spinal stenosis surgery in Sweden 1987–1999," *European Spine Journal*, vol. 12, no. 5, pp. 535–541, 2003.

[78] N. Patel, B. Bagan, S. Vadera et al., "Obesity and spine surgery: relation to perioperative complications," *Journal of Neurosurgery: Spine*, vol. 6, no. 4, pp. 291–297, 2007.

[79] R. Vaidya, J. Carp, S. Bartol, N. Ouellette, S. Lee, and A. Sethi, "Lumbar spine fusion in obese and morbidly obese patients," *Spine*, vol. 34, no. 5, pp. 495–500, 2009.

[80] S. Yadla, J. Malone, P. G. Campbell et al., "Obesity and spine surgery: reassessment based on a prospective evaluation of perioperative complications in elective degenerative thoracolumbar procedures," *Spine Journal*, vol. 10, no. 7, pp. 581–587, 2010.

[81] P. S. Kalanithi, R. Arrigo, and M. Boakye, "Morbid obesity increases cost and complication rates in spinal arthrodesis," *Spine*, vol. 37, no. 11, pp. 982–988, 2012.

[82] W. Senker, C. Meznik, A. Avian, and A. Berghold, "Perioperative morbidity and complications in minimal access surgery techniques in obese patients with degenerative lumbar disease," *European Spine Journal*, vol. 20, no. 7, pp. 1182–1187, 2011.

[83] M. Yoshimoto, T. Takebayashi, S. Kawaguchi et al., "Minimally invasive technique for decompression of lumbar foraminal stenosis using a spinal microendoscope: technical note," *Minimally Invasive Neurosurgery*, vol. 54, no. 3, pp. 142–146, 2011.

[84] Z. Smith and R. G. Fessler, "Concept and paradigm changes in spine surgery—minimally invasive spine surgery as the modern standard of care," In press.

Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 173685, 6 pages
doi:10.1155/2012/173685

Clinical Study

Percutaneous Iliac Screws for Minimally Invasive Spinal Deformity Surgery

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Received 6 May 2012; Accepted 10 May 2012

Academic Editor: Zachary A. Smith

Introduction. Adult spinal deformity (ASD) surgeries carry significant morbidity, and this has led many surgeons to apply minimally invasive surgery (MIS) techniques to reduce the blood loss, infections, and other peri-operative complications. A spectrum of techniques for MIS correction of ASD has thus evolved, most recently the application of percutaneous iliac screws. *Methods*. Over an 18 months 10 patients with thoracolumbar scoliosis underwent MIS surgery. The mean age was 73 years (70% females). Patients were treated with multi-level facet osteotomies and interbody fusion using expandable cages followed by percutaneous screw fixation. Percutaneous iliac screws were placed bilaterally using the obturator outlet view to target the ischial body. *Results*. All patients were successfully instrumented without conversion to an open technique. Mean operative time was 302 minutes and the mean blood loss was 480 cc, with no intraoperative complications. A total of 20 screws were placed successfully as judged by CT scanning to confirm no bony violations. Complications included: two asymptomatic medial breaches at T10 and L5, and one patient requiring delayed epidural hematoma evacuation. *Conclusions*. Percutaneous iliac screws can be placed safely in patients with ASD. This MIS technique allows for successful caudal anchoring to stress-shield the sacrum and L5-S1 fusion site in long-segment constructs.

1. Introduction

Surgery to correct adult spinal deformity (ASD) is a growing field. The ever-aging American population is presenting to spinal surgeons increasingly with high expectations of continued quality of life well into the seventh, eighth, and ninth decades of life. However, while surgical treatment of ASD is the only viable option for patients failing conservative measures, the surgical interventions are associated with relatively high morbidity and mortality rates. Indeed, in a series reported from Johns' Hopkins consisting of 361 patients, the 30-day mortality rate was found to be 2.4% [1]. In a more series by Smith et al., multicenter data from the Spinal Deformity Study Group demonstrated that even in expert centers 26.2% of patients suffered a minor complication and 15.5% suffered a major complication [2].

Several factors contribute to these high complication rates, including reduced bone mass and weaker fixation points, a higher associated rate of medical comorbidites, patient deconditioning due to immobility, and a rigid and nonflexible deformity [3, 4]. In addition, the surgical enterprise necessary to correct ASD is typically a long-segment fusion with instrumentation and osteotomies. Therefore, in this population, a major surgical intervention is being applied in a highly compromised patient population [5, 6].

To combat these challenges, modern surgeons have begun to apply minimally invasive surgery (MIS) techniques to address ASD [7–9]. MIS techniques have been associated with reduced intraoperative blood loss, lower infection rates, and quicker mobilization, all of which would be highly desirable in the ASD population [10]. While the early MIS fusion experience has focused on one- and two-level procedures for degenerative spinal disease, a variety of techniques have been developed more recently for use in ASD.

One major advance in spinal fixation has been the application of iliac fixation. Pelvic fixation is an important tool in the armamentarium of the modern spinal surgeon, as screws or bolts of a large diameter and length can be placed safely for caudal anchoring and extend anterior to the spine

in the sagittal plane and lateral to it in the coronal plane. Iliac fixation is useful in ASD for long instrumentation constructs, sagittal and coronal deformity corrections, and stabilization of low sacropelvic instability [11–13].

We previously published a technique for percutaneous iliac screw fixation [14]. This paper builds upon that experience with the application of this technique in the setting of ASD.

2. Methods

2.1. Patient Population. A consecutive series of 10 patients were treated over an 18-month period at a single institution. All patients underwent MIS treatment of ASD using expandable interbody cage placement and percutaneous pedicle and iliac screws. ASD was defined as a Cobb angle greater than 20°. All deformities were rigid with less than 10° of motion in the coronal or sagittal planes across the deformity segments on flexion, extension, and lateral bending films. All patients had also failed conservative measures and had severe back and/or back and leg pain with distance limited gait. The accuracy of iliac screw insertion was examined using postoperative spiral CT scanning to confirm that screws were entirely within the bony confines.

2.2. Surgical Technique. Patients were positioned prone on the Jackson table so that the pelvis would not be obscured on fluoroscopic imaging by the base of the operating table. Pre-operative imaging, including 3 D reconstructed CT scans of the pelvis, was helpful for planning screw placement trajectories and to validate the fluoroscopic data in the operating room. Iliac cannulation is performed prior to pedicle screw cannulation to maximize the ability to image the pelvis. In addition, the decompression, osteotomies, and interbody fusion are accomplished prior to screw placement. For each side of the iliac crest, the fluoroscope is angled in the sagittal and coronal planes in the obturator outlet view so that the X-ray beams are approximately parallel to both the inner and outer tables of the ilium (Figure 1). The "teardrop" that is visualized is the safe corridor and placement of instrumentation within this two-dimensional space ensures safe screw placement, even with 80 mm long screws (Figure 2).

A 1.5 cm incision is then made overlying the posterior superior iliac spine of the pelvis (PSIS). A Jamshidi needle is then docked onto the most superficial aspect of the PSIS and "walked" ventromedially, with care not to enter into the sacroiliac joint. However, the exact starting point along the superinferior plane of the PSIS can vary according to the specific screw trajectory desired, as multiple acceptable paths are acceptable. A drill or osteotome can be used to create a bony depression to better seat the screw or bolt head to minimize hardware prominence (Figure 3). After entering 55–75 mm, the Jamshidi needle is then replaced internally with a K-wire and then removed. Cannulated cancellous screw taps are then placed over the K-wire followed by final screw insertion.

Pedicle screw cannulation and placement then proceed followed by rod insertion and hookup (Figure 4). Since the

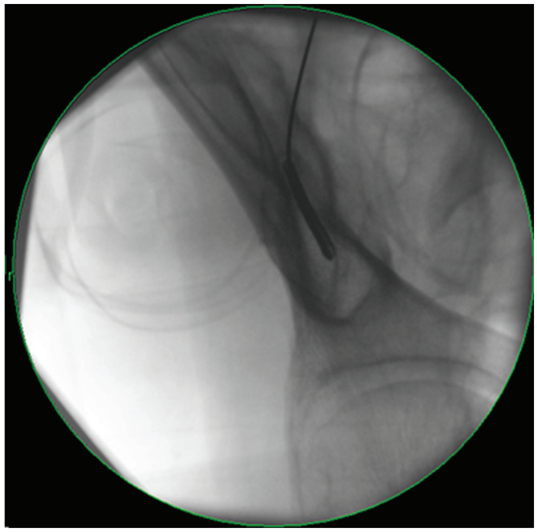


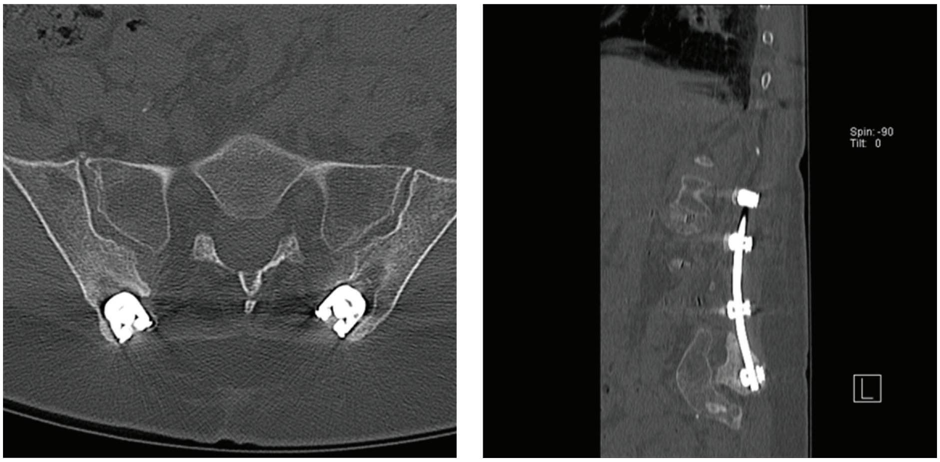
Figure 1: Obturator outlet view showing the "teardrop" target for iliac screw placement. Cannulation of this space provides a safe corridor completely within the bony confines.

Figure 2: Cannulated 8 mm diameter by 80 mm long screws for iliac fixation and cannulated cancellous bone probe.

iliac screws will be more dorsal and lateral than pedicle screws, the appropriate rod bending in two planes facilitates screw-rod mating. In addition, starting the S1 screws high and the iliac screws low provides more distance between the screw heads, making the connection easier (Figure 5). Bending the rods while attached to the rod holder facilitates this two-plane bending when using a French bender. The exact amount of curvature to place in the rods is based upon the surgeon's judgement of preoperative curvature, desired degree of correction, and flexibility in the spine after decompression and osteotomies.

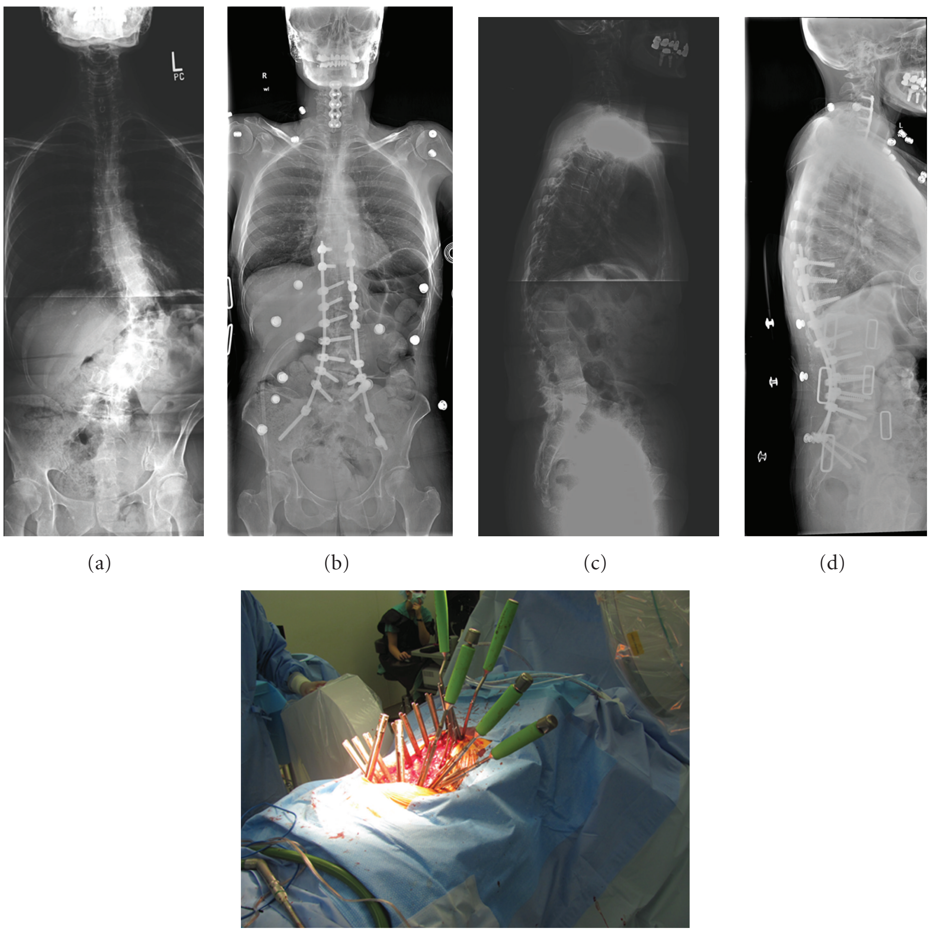
3. Results

The series was consecutive with no patients lost to followup, and in no case was conversion to a traditional open technique necessary. A total of 10 patients (7 women and 3 men) were treated using this technique (Table 1). Their mean age was 73 years, with a range of 62 to 80. The average BMI was 28. A total of 69 segmental levels were treated (mean = 6.9), with



(a) (b)

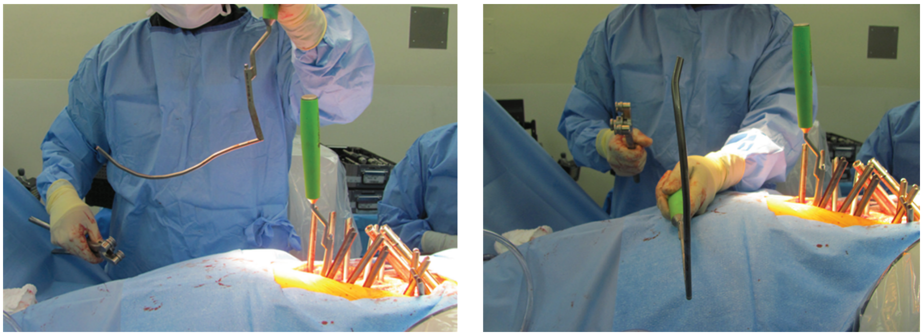
Figure 3: Recession of the iliac screw saddles into the bone to avoid hardware prominence as seen on this postoperative (a) axial and (b) sagittal reconstruction CT scan.



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

(e)

Figure 4: Case example showing a T9 to Iliac MIS fusion with interbody grafts at L2-S1. (a) and (b) Pre- and postoperative AP, and (c) and (d) Pre- and postoperative lateral 36” X-Ray images. (e) Intraoperative view.



(a) (b)

Figure 5: Two plane rods bending in the (a) sagittal and (b) coronal planes to facilitate connection to the more laterally located iliac screw saddles.

Table 1

Patient	Sex	Age	Operative procedure	Complications	Time	EBL	LOS	Dispo	Iliac screws	CT confirmation of iliac screw placement
JB	M	68	L1-iliac MIS instrumented fusion with L2-S1 MIS TLIF	None	360	800	4	Home	65 mm × 8 mm	Yes, correct position
DK	F	75	T10-iliac MIS instrumented fusion with L2-S1 MIS TLIF	None	320	500	5	Home	80 mm × 8 mm	Yes, correct position
HS	F	78	T9-iliac MIS instrumented fusion with L1-S1 MIS TLIF	None	340	550	7	Home	65 mm × 8 mm	Yes, correct position
JL	F	72	T9-iliac MIS instrumented fusion with L1–5 MIS TLIF	None	300	450	6	Home	80 mm × 8 mm	Yes, correct position
KF	F	62	T11-iliac MIS instrumented fusion with L5-S1 MIS TLIF	None	265	250	5	Home	65 mm × 8 mm	Yes, correct position
ES	F	76	T10-iliac MIS instrumented fusion with L2-S1 MSI TLIF	T10 and L5 screw breaches	310	500	8	Rehab	80 mm × 8 mm	Yes, correct position
RS	F	75	T12-iliac MIS instrumented fusion with L2-S1 MSI TLIF	None	310	400	4	Rehab	65 mm × 8 mm	Yes, correct position
BP	M	80	L2-iliac MIS instrumented fusion with L2-S1 MIS TLIF	None	280	450	5	Home	80 mm × 8 mm	Yes, correct position
SR	F	66	T9-iliac MIS instrumented fusion with L1–5 MIS TLIF	Epidural hematoma requiring laminectomy for evacuation	300	500	7	Rehab	65 mm × 8 mm	Yes, correct position
RL	M	78	L2-iliac MIS instrumented fusion with L2-S1 MIS TLIF	None	240	395	5	Home	80 mm × 8 mm	Yes, correct position

a range of 4–9. A total of 20 percutaneous iliac screws were placed. The mean operative time was 302 minutes from skin-to-skin, and the mean intraoperative blood loss as measured by the perfusionist was 480 cc. Length of acute care stay averaged 5.6 days (range of 4–7) after surgery. Three of the 10 patients were discharged to an inpatient rehabilitation facility, and the rest were discharged to home. 65 mm × 8 mm screws were used in 5 patients, and 80 mm × 8 mm screws were used in 5 patients. All patients had interbody allograft cages placed at the L5/S1 level.

Early radiographic outcomes were determined using pre- and postoperative 36” standing X-rays at last followup. The mean preoperative Cobb angle was 35° which improved to a mean of 8.0°, reflecting an average of 27° of improvement. The mean preoperative global lumbar lordosis as measured between L1 and S1 was 27° which improved to a mean of 48°, reflecting an average of 21° of improvement. All 20 iliac screws were placed successfully as judged by postoperative CT scanning.

There were no intraoperative complications. However, one patient had two asymptomatic medial screw breaches at T10 and L5. This patient did not undergo reoperation as there was no neurological impairment. A second patient developed a symptomatic epidural hematoma on postoperative day number 6. This was evacuated emergently with neurological recovery.

4. Discussion

Due to the many benefits of MIS surgery, it has the potential to improve the outcomes of surgery for ASD. Because these patients are often medically compromised, a reduction in infection rates, intraoperative blood loss, and quicker mobilization may have a significant impact on their recovery. While in the past MIS surgeons focused primarily on short segment fusions for degenerative disease [10], there is increasing interest in using MIS techniques for ASD. However, the concept that is emerging for MIS deformity surgery is that the goals and standards being developed for open deformity surgery must also be met with MIS surgery.

In this paper we describe our initial experience with percutaneous iliac screws for treating ASD. While the series is of limited size, radiographic evaluation demonstrated safe iliac screw placement using a relatively straightforward technique that did not require specialized equipment is possible. Using a single C-arm and the obturator outlet view, standard size iliac screws could be placed safely and efficiently. While image guidance can be helpful in many settings, navigation systems are expensive, prone to error, and require additional setup time. Thus, we have chosen to continue using a simplified C-arm method for screw placement. The introduction of commercially available cannulated iliac screws has also helped to make this procedure widely accessible to surgeons and renders the procedure as accessible as open screw placement. It should however be remembered that screw misplacement with any surgical technique can result in sciatic nerve injury, major vessel disruption, pelvic fracture, or retroperitoneal hematoma formation, and these risks are higher in the ASD population.

When applying this technique, many of the considerations for open surgery are relevant to the MIS setting. For example, strict attention needs to be placed to screw head positioning. It is critical to recess the iliac screw heads to reduce complaints of hardware prominence. This can be accomplished by using the drill or osteotome to created an opening in the posterior cortical wall of the ilium. In additional, starting the screw below the PSIS keeps the saddle low. With regard to hardware connections, placing the iliac screw heads medial and the pedicle screws lateral keeps the screw saddles in a single plane and facilitates rod-screw mating. However, despite these efforts, multiple-rod plane bending is often necessary as lateral offset connectors cannot be applied using a truly percutaneous method.

It should also be noted that in this series the screws were either 65 or 80 mm in length. Open deformity surgeons commonly use longer screws to obtain superior fixation. In this series, we generally did not treat cases of severe scoliosis (>60°) or major kyphosis, and the series also did not include serious revisions and thus have had success with the shorter iliac screws. Furthermore, maintenance of the soft tissue envelope and posterior tension band with MIS surgery preserves the spine’s native integrity and thus may obviate the need for these longer screws. Ultimately, the placement of screws greater than 100 mm in length should be feasible but will be yet another area requiring validation in the clinical setting.

While MIS surgery for ASD has not been able to completely replace open, conventional methods, the expanding spectrum of MIS techniques has allowed the modern MIS surgeon to perform ever more complex surgeries in this patient population. Percutaneous iliac screws represent one such advance to allow for successful caudal anchoring of long-segment spinal fixation constructs.

Conflict of Interests

The author is a consultant and receives royalty payments from DePuy Spine, Inc.

References

[1] D. B. Pateder, R. A. Gonzales, K. M. Kebaish, D. B. Cohen, J. Y. Chang, and J. P. Kostuik, “Short-term mortality and its association with independent risk factors in adult spinal deformity surgery,” *Spine*, vol. 33, no. 11, pp. 1224–1228, 2008.

[2] J. S. Smith, C. I. Shaffrey, S. D. Glassman et al., “Risk-benefit assessment of surgery for adult scoliosis: an analysis based on patient age,” *Spine*, vol. 36, no. 10, pp. 817–824, 2011.

[3] M. G. Fehlings and G. M. Ibrahim, “Spinal deformity,” *Journal of Neurosurgery*, vol. 13, no. 6, pp. 663–664, 2010.

[4] P. V. Mummaneni, S. S. Dhall, S. L. Ondra, V. P. Mummaneni, and S. Berven, “Pedicle subtraction osteotomy,” *Neurosurgery*, vol. 63, no. 3, pp. A171–A176, 2008.

[5] S. Bess, O. Boachie-Adjei, D. Burton et al., “Pain and disability determine treatment modality for older patients with adult scoliosis, while deformity guides treatment for younger patients,” *Spine*, vol. 34, no. 20, pp. 2186–2190, 2009.

[6] J. S. Smith, C. I. Shaffrey, S. Berven et al., “Improvement of back pain with operative and nonoperative treatment in adults with scoliosis,” *Neurosurgery*, vol. 65, no. 1, pp. 86–93, 2009.

[7] N. Anand, E. M. Baron, G. Thaiyananthan, K. Khalsa, and T. B. Goldstein, "Minimally invasive multilevel percutaneous correction and fusion for adult lumbar degenerative scoliosis: a technique and feasibility study," *Journal of Spinal Disorders and Techniques*, vol. 21, no. 7, pp. 459–467, 2008.

[8] K. M. Scheufler, D. Cyron, H. Dohmen, and A. Eckardt, "Less invasive surgical correction of adult degenerative scoliosis, part I: technique and radiographic results," *Neurosurgery*, vol. 67, no. 3, pp. 696–710, 2010.

[9] M. Y. Wang and P. V. Mummaneni, "Minimally invasive surgery for thoracolumbar spinal deformity: initial clinical experience with clinical and radiographic outcomes," *Neurosurgical Focus*, vol. 28, no. 3, pp. 1–8, 2010.

[10] J. D. Schwender, L. T. Holly, D. P. Rouben, and K. T. Foley, "Minimally invasive transforaminal lumbar interbody fusion (TLIF): technical feasibility and initial results," *Journal of Spinal Disorders and Techniques*, vol. 18, no. 1, pp. S1–S6, 2005.

[11] C. Bellabarba, T. A. Schildhauer, A. R. Vaccaro, and J. R. Chapman, "Complications associated with surgical stabilization of high-grade sacral fracture dislocations with spinopelvic instability," *Spine*, vol. 31, no. 11, pp. S80–S88, 2006.

[12] S. Fujibayashi, M. Neo, and T. Nakamura, "Palliative dual iliac screw fixation for lumbosacral metastasis: technical note," *Journal of Neurosurgery*, vol. 7, no. 1, pp. 99–102, 2007.

[13] C. R. Lippman, S. A. Salehi, J. C. Liu, and S. L. Ondra, "Salvage technique of posterior iliac bolt placement in long-segment spinal constructs with a previous posterior iliac crest harvest: technical note," *Neurosurgery*, vol. 58, no. 1, supplement, pp. ONS-E178–ONS-E179, 2006.

[14] M. Y. Wang, S. C. Ludwig, D. G. Anderson, and P. V. Mummaneni, "Percutaneous iliac screw placement: description of a new minimally invasive technique," *Neurosurgical Focus*, vol. 25, no. 2, article E17, pp. 1–5, 2008.

Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 213791, 10 pages
doi:10.1155/2012/213791

Review Article

Minimally Invasive Thoracic Corpectomy: Surgical Strategies for Malignancy, Trauma, and Complex Spinal Pathologies

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Received 16 March 2012; Accepted 7 June 2012

Academic Editor: Nicholas Slimack

The rapid expansion of minimally invasive techniques for corpectomy in the thoracic spine provides promise to redefine treatment options in this region. Techniques have evolved permitting anterior, lateral, posterolateral, and midline posterior corpectomy in a minimally invasive fashion. We review the numerous techniques that have been described, including thoracoscopy, tubular retraction, and various instrumentation techniques. Minimally invasive techniques are compared to their open predecessors from a technical and complication standpoint. Advantages and disadvantages of different approaches are also considered, with an emphasis on surgical strategies and nuance.

1. Background

The unique anatomy and structural support in the thoracic spine create challenges for practitioners attempting surgery in the region. Due to the inherent rigidity of the region granted by the rib cage, spondylotic changes are significantly less common than in the cervical and lumbar spine [1]. The most common pathologies in the thoracic spine requiring corpectomy are tumors, trauma, and infection [2–4]. Treating these pathologies can require significant anterior reconstruction, made challenging due to the ribs and other adjacent critical structures including the lungs, pleura, aorta, and mediastinum [5]. Obtaining adequate exposure for corpectomy is critical due to the relative intolerance of the thoracic spinal cord to manipulation and mobilization [1, 3, 6]. Additionally, the numerous comorbidities usually present in these patients often preclude the systemic stress of open surgery [7].

Minimally invasive techniques in the cervical and lumbar spine have been clearly demonstrated to lower surgical blood loss, pain, improve wound healing, and shorten hospital stay [8–10]. In the thoracic spine, their advent is allowing surgeons to consider treatment for patients who previously would have been relegated to bracing and palliative pain relief due to risks of open surgery. Reports have emerged describing minimally invasive variants to nearly every open thoracic approach to corpectomy [3, 11–15]. We present here the treatment options described in the literature, with an emphasis on specific advantages, disadvantages, and surgical nuance (Table 1).

2. Transthoracic

Thoracotomy to access the anterior thoracic spine was first described in the 1950s [16]. Used initially primarily in the treatment of thoracic disc herniation, it found significant popularity in the 1970s and 1980s in response to the disappointing results for laminectomy for decompression and discectomy, due to poor outcomes associated with manipulation of the thoracic spinal cord [1, 6, 17–19]. Surgery involves placing patients in the lateral position, making a lengthy incision laterally along the associated rib, performing thoracotomy, and retracting the lung anteriorly. The parietal pleura is then split close to the rib head, allowing visualization of the costovertebral joint. The costovertebral ligaments and rib head are removed creating anterolateral visualization of the vertebral body, allowing discectomy and corpectomy. Closure includes leaving a chest tube,

Table 1: Advantages and limitations of various minimally invasive approaches.

MIS approach	Selected authors	Advantages	Limitations
Anterior (thoracoscopic)	Dickman et al.	Complete decompression of canal	Pleural entry/chest tube
	Mack et al.	Easy graft insertion	Ventral to dorsal working pattern
	Ragel et al.	Anterolateral screw-plate fixation	High complication rates
Anterolateral (retropleural)	Uribe et al.	Complete decompression of canal	Extensive retropleural dissection
	Scheufler et al.	Anterolateral screw-plate fixation	Difficult working angle
	Kasliwal et al.	Extra-coelomic working corridor	High rate of pleural violation
Posterolateral (lateral extracavitary)	Kim et al.	Clear visualization of thecal sac	Significant blood loss/OR time
	Khoo et al.	Anterior stabilization	Unilateral decompression
	Mussachio et al.	Preservation of posterior tension band	Second incision for percutaneous stabilization
Posterior (transpedicular)	Chou et al.	Single incision	Difficult to place interbody graft
	Deutsch et al.	Circumferential decompression	Thecal sac between surgeon and body
		Decreased blood loss/pain	Dorsal to ventral working pattern (aorta, etc.)

typically for three days of recumbent drainage [1, 17, 18]. While early reports showed good associated outcomes, surgical morbidity quickly prompted surgeons to explore other approaches [2, 5]. Approach related complications include pulmonary contusion, atelectasis, pleural effusion, chylothorax, and hemothorax [5, 7].

Video-assisted thoracoscopy has allowed surgeons to avoid much of the incision- and dissection-related morbidity associated with thoracotomy [11, 20, 21]. Similar to thoracotomy, the patient is intubated with a double endotracheal tube with deflation of the ipsilateral lung, in a lateral position. Four thoracoscopic ports are placed via 2-centimeter incisions over the intercostal space, spaced widely throughout the chest, centered over the level of interest. The thoracoscope is typically a 10 mm fixed endoscope, with angled options available. Because the working distance to the spine ranges from 14 to 30 mm, specific adaptations of common surgical instruments are required, including drills, soft tissue dissectors, hemostatic agents, and spinal tools. Similarly to open thoracotomy, the appropriate costovertebral joint is identified, with subsequent opening of the pleura, removal of the rib head, discectomy, corpectomy, and reconstruction [11, 22] Closure consists of copious irrigation, inspection of the ipsilateral lung, followed by placement of chest tubes [11, 23–25].

Yanni et al. recently described a variation of this approach, focused on alleviating the challenge of manually holding the endoscope [26]. They conducted a similar exposure with port placement, but once the exposure was complete, they utilized one of the ports to place a tubular retractor against the spine, under direct visualization with the endoscope. This allowed them direct lateral exposure comparable to the technique commonly used in the lumbar spine.

The advent of thoracoscopy has allowed spine surgeons to reconsider the anterolateral approach to the thoracic spine [21]. Existing series suggest that the technique is feasible, and it appears to be as successful as open surgery in allowing decompression and instrumentation [21, 23]. Anterior visualization allows surgeons to perform complete corpectomy, visualizing the posterior longitudinal ligament, the entire anterior spinal cord, ipsilateral pedicle and foramen. The exposure allows a wide variety of grafts to be inserted, with the benefit of screw-plate fixation. Above T11, the surgeon can choose a right- or left-sided approach based on specific patient anatomy, to concentrate on visualization of affected critical structures including the azygos vein, aorta, thoracic duct, and artery of Adamkiewicz. T11 and T12 should be approached from the left to avoid the liver, and require caudal retraction of the hemidiaphragm [1, 11].

Significant limitations persist, however, in the utilization of thoracoscopy. A steep learning curve has been described for surgeons beginning to undertake the technique [11, 27]. Intraoperative utilization of the multiple ports along with the endoscope can be facilitated by the use of fixed table based systems, but often can require significant assistant support. Introduction of a tubular retraction system may overcome this challenge, however [11, 26]. Working in a ventral-to-dorsal direction limits visualization of the posterior longitudinal ligament and thecal sac, and forces the surgeon to continuously estimate the distance between the working instrument and the spinal cord [3]. Additionally, patients with significant lung pathology limiting single lung ventilation or pleural adhesions are contraindicated from thoracoscopy [11].

Despite the disadvantages, thoracoscopy has been shown to reduce the incidence of pulmonary morbidity, intercostal neuralgia, and shoulder girdle dysfunction versus open thoracotomy [8, 23, 28]. Patients suffer significantly less pain and incisional morbidity in thoracoscopic cases, with a lower rate of postthoracotomy pain syndrome [21]. Overall complication rates have been quoted to be significantly lower than those reported for thoracotomy, which ranges from 9 to 11.5% incidence of major complication [5, 7]. Nevertheless, the rate of complications including atelectasis, pneumothorax, hemothorax, and pleural effusion are still

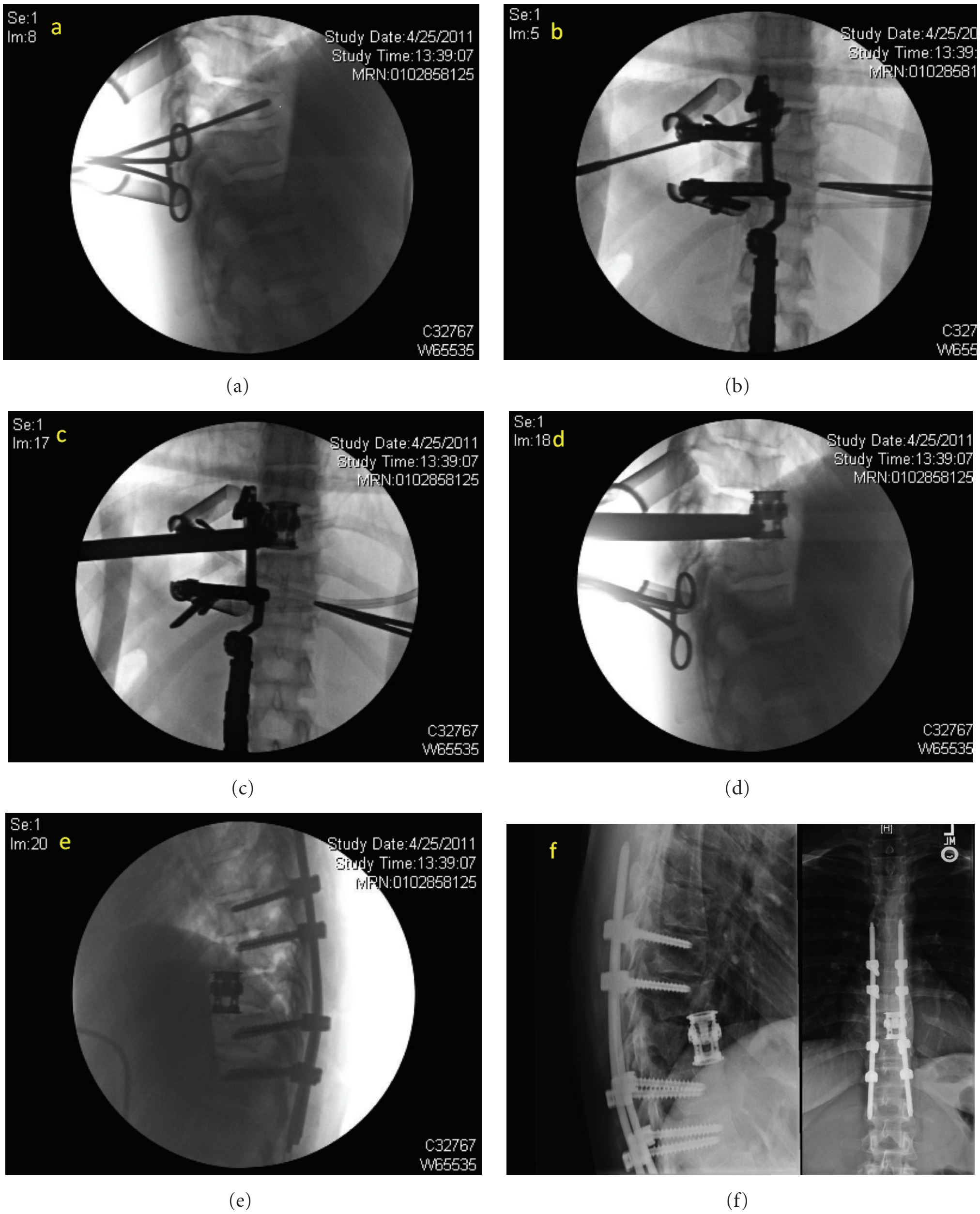
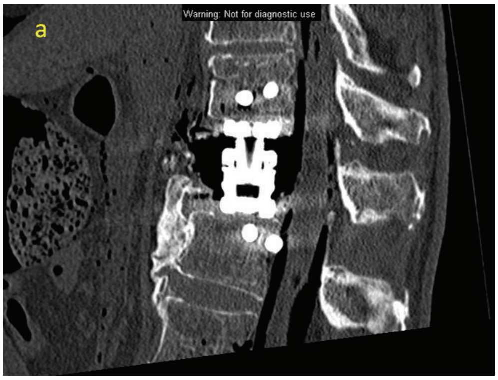


Figure 1: 24-year-old female who suffered a traumatic T9 fracture and underwent MIS lateral extracavitary T9 corpectomy with T7-T11 posterior segmental instrumentation—Sequential intraoperative and postoperative images ((a)–(f)).

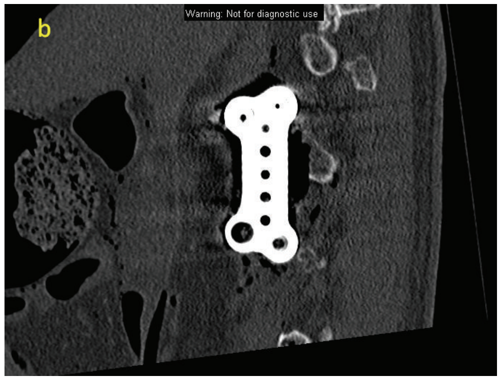
considerable, ranging from 14.1 to 29.4% [11, 29, 30]. Additionally, the burden of chest tube placement can still cause significant pain and limitation of postoperative patient mobilization.

3. Retropleural

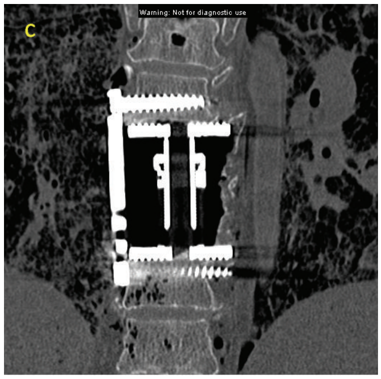
McCormick and Moskovitch described the retropleural approach to the anterolateral thoracic spine in the early 1990s as a method to avoid the morbidity associated with thoracotomy [31, 32]. Employing a retropleural approach allows for a ventral decompression without requiring entrance into the pleural cavity. McCormick's report described 15 patients undergoing treatment ranging from discectomy to two-level corpectomy. In his surgical technique, a 12 cm incision is performed from the posterior axillary line to 4 cm lateral of midline, with exposure and removal of 8–10 cm of the rib. The endothoracic fascia is incised and dissected off of the parietal pleura, leaving a plane with only slight areolar tissue, which is dissected until the endothoracic fascia is opened over the rib head. The costovertebral ligaments and proximal rib head are taken down to expose the vertebral body, facilitating corpectomy and reconstruction. Pleural



(a)



(b)



(c)

Figure 2: Cadaveric MIS lateral extracavitary corpectomy-coronal (a), and sagittal images of the plate (b) and cage (c) construct.

tears are repaired primarily, and a chest tube is not required unless a significant tear is encountered. In the series of fifteen patients, adequate decompression and reconstruction were performed in all cases, although four patients did require chest tube placement.

The significant exposure-related morbidity of this approach has limited its appeal and usage. Recent descriptions of a minimally invasive retropleural approach, however, have reopened the anterolateral corridor for corpectomy. Scheufler described a minimally invasive variant of the retropleural approach in 38 patients [33]. He made a 5-6 cm incision laterally, removed an 8–10 cm segment of the rib, and dissected between the endothoracic fascia and pleura towards the rib head. He then placed retracting blades in a 360-degree fashion and performed anterolateral corpectomy. Four out of thirty-eight patients ultimately required chest tube drainage, and all patients had adequate decompression and insertion of instrumentation.

Uribe et al. furthered this approach by describing a tubular retractor based retropleural approach in a cadaveric series and a small patient series [12]. By using tubular dilators to perform the retropleural dissection, their series most closely adheres to MIS principals. They perform a 6 cm incision, remove 5 cm of underlying rib, and dissect free the retropleural plane towards the ribhead. Sequential tubular dilators are inserted, finishing with an expandable table-based retractor. Corpectomy is performed in a pedicle-to-pedicle fashion, with an anterior shell of bone and the ALL (anterior longitudinal ligament) preserved to protect thoracic contents. Reconstruction is performed with an expandable cage and autograft, with ventrolateral screw-plate fixation. A midline posterior incision is then performed, and posterior percutaneous screws are placed for reinforcement. One of their four reported cases required chest tube placement, and there were no perioperative complications. Kasliwal and Deutsch also described a similar approach for thoracic discectomy, utilizing a 2 cm incision to place an expandable tubular retraction system through a retropleural corridor in 7 patients [34]. A case report from Keshavarzi et al. also utilized this approach [35].

Advantages of this approach include excellent anterior column reconstruction and little risk to the spinal cord. However, a significant challenge, particularly at the thoracolumbar junction, is manipulation of the diaphragm [36]. Dakwar and colleagues performed an anatomic study on 9 cadavers, examining the variants of diaphragmatic insertion points. They noted that while the diaphragmatic insertion is released with partial rib resection and mobilization of the pleura, by pursuing tubular dilation, the fibers of the diaphragm are not being cut. Thus, there is no need for repair of the diaphragm during closure [36]. However, other challenges associated with the retropleural approach

include risk to the lumbar plexus, the mechanical difficulty of decompressing the canal from this angle, and risk to the segmental arteries.

4. Posterolateral

The lateral extracavitary approach was first described by Capener in 1954, and modified by Larson et al. [37, 38]. It has since been modified and popularized by numerous modern spine surgeons [39–42]. It provides a posterolateral, oblique approach to the vertebral body and spinal canal without entering the pleural cavity or retropleural dissection. The common description of the procedure describes a hockey stick incision, with the short limb extending 8 cm laterally of midline, in either prone or 3/4 prone position. The thoracodorsal fascia is exposed and the erector spinae muscles are elevated off the ribs. The rib is dissected free, cut 6–10 cm laterally, and removed after disarticulation of the costovertebral joint. With minimal retraction, discectomy and corpectomy can be performed under direct visualization, although the contralateral edge of the vertebral body and pedicle are not visualized. A wide variety of grafts can be introduced, and standard posterior pedicle screw/rod fixation achieved. A chest tube is only required in case of pleural violation [38–44].

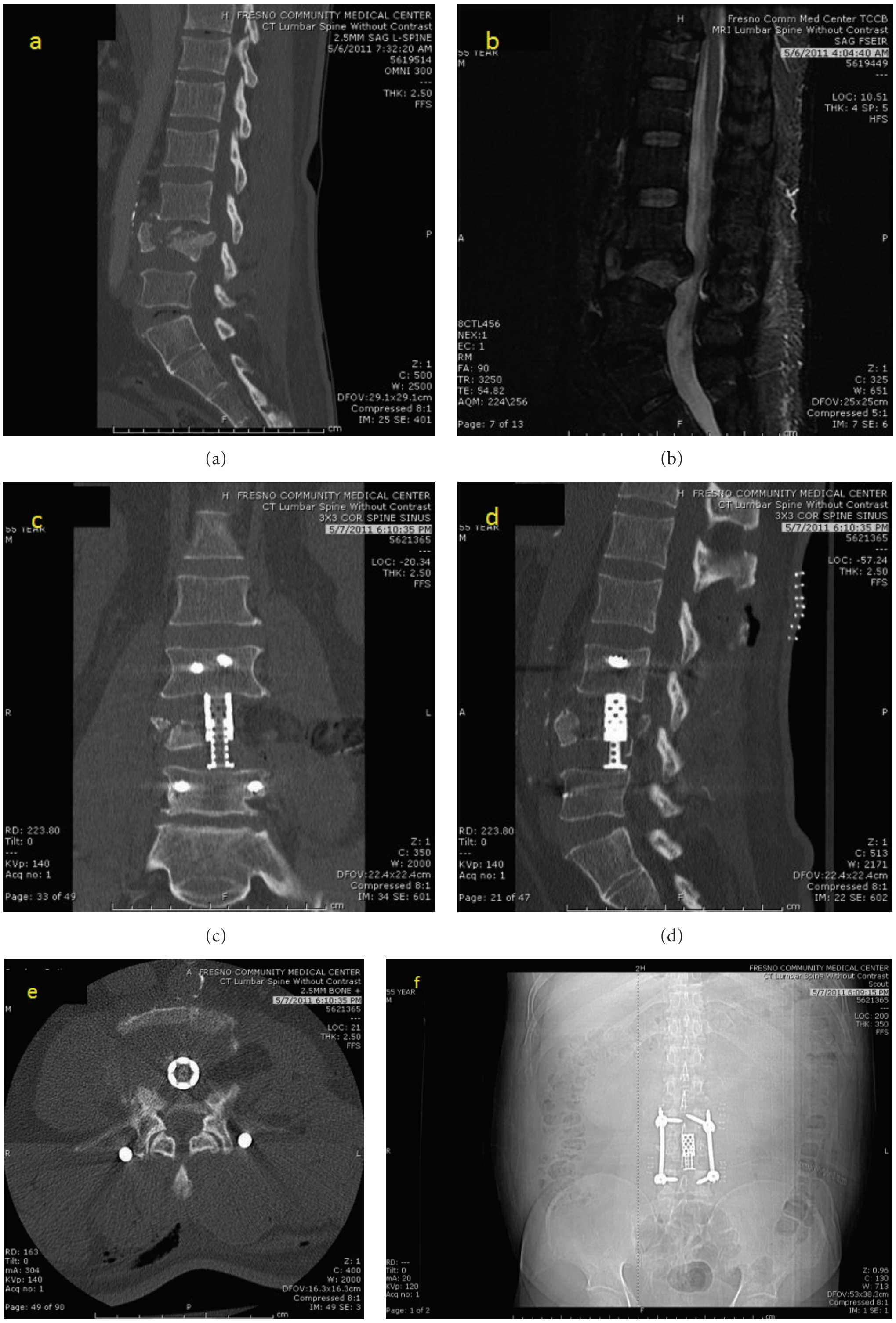
Given the extensive muscle dissection required for the lateral extracavitary approach, the application of MIS techniques may provide distinct advantages. The first description of minimally invasive posterolateral corpectomy was published by Kim et al. in a series of cadaveric procedures and a small series of patients [3]. They started with a four cm long incision four cm laterally from midline. A K wire (Kirschner wire) was docked on the ipsilateral facet near the pedicle, followed by dilators and an expandable tubular retractor. The proximal rib was removed, followed by removal of the costovertebral ligaments, rib head, intercostal vessels, and ipsilateral pedicle. Discectomy and corpectomy were performed with preservation of the ventral body, ALL, and contralateral vertebral margins. Titanium mesh, autograft, or expandable cages were used for reconstruction, and vertebral body screws and rods were sometimes used for supplementation. Posterior percutaneous screws and rods were typically placed through a second incision. An average of 79.2% corpectomy was performed in the cadaveric cases, although the contralateral side was unable to be decompressed. Average estimated blood loss was 495 mL, operating room time was 5.8 hours, and hospital stay was 4.7 days in the clinical series. Satisfactory neural decompression was accomplished in all cases. Images from a representative case and cadaveric surgery are shown here (Figures 1 and 2).

Khoo et al. described their experience with removal of thoracic disks and interbody fusion utilizing a similar minimally invasive posterolateral thoracic approach in 13 patients, and compared the cohort to patients undergoing traditional transthoracic surgery [45]. They utilized a 2 cm incision and docked the K wire at the junction of the ipsilateral transverse process and pedicle. They performed diskectomy without thecal sac retraction by rotating the bed in an oblique fashion. Their one-year outcomes were equivalent to open surgery, and most patient metrics favored the minimally invasive approach. Smith et al. described their outcomes in minimally invasive posterolateral corpectomy in a recent manuscript outlining a cadaveric series and surgical management of three patients. They utilized similar technique to Kim et al. They had appropriate decompression and instrumentation in all three patients, estimated blood loss of 517 mL, and average operating room time of 4.75 hours. They were able to achieve a mean of 72% vertebral body resection in the cadaveric series, without contralateral decompression [46]. Mussachio et al. published a cadaveric study, describing another variant of the approach [13]. They introduced a first tube to perform a costotransversectomy and corpectomy on the more affected side. They then placed a contralateral tube to perform contralateral transpedicular decompression. This technique allowed circumferential decompression by pursuing contralateral transpedicular completion of the corpectomy [13].

The lateral extracavitary approach is one of the most widely validated approaches for corpectomy in the thoracic spine. Decompression and neurologic outcomes are excellent, and complications are typically minor and self-limited [39–41]. Nevertheless, muscle-dissection-related morbidity is severe, and the substantial tissue dissection and blood loss place severe systemic stress on the patient. One series described an average of 3100 mL of blood loss and 7.74 hours per case, although these numbers may have been exaggerated by a small number of complicated cases [39]. In contrast, minimally invasive posterolateral corpectomy appears to provide adequate decompression and instrumentation, with less blood loss and operative time [3]. An important advantage of this approach as opposed to midline posterior approaches is preservation of the midline posterior tension band. It also allows the ability to create longer constructs by placing percutaneous screws above and below the level of corpectomy. Nevertheless, the learning curve and patient morbidities may limit general applicability.

5. Posterior

The transpedicular approach has been extensively utilized in patients whose comorbidities limit transthoracic and lateral extracavitary approaches [47–51]. Outcomes appear favorable when compared with other open techniques, and the technique has been described for a wide range of pathology [47, 50, 52–54]. Surgery consists of midline incision two levels above and below the level of pathology, with dissection to the lateral edge of the transverse processes. The posterior elements are removed, along with the bilateral facets, demonstrating the thecal sac and pedicles. The pedicles are then taken down, exposing the vertebral body for corpectomy and adjacent level discectomy. Multiple techniques have been described for placement of an expandable cages in the transpedicular approach: including thecal sac mobilization, rib head osteotomy, rib head disarticulation, and trap-door rib head osteotomy, with thinning of the rib to



(a) (b) (c) (d) (e) (f)

Figure 3: 21-year-old who suffered a roll-over MVC and L4 burst fracture, and who underwent MIS lateral corpectomy: significant preoperative and postoperative images ((a)–(f)).

allow greenstick fracture and displacement with subsequent displacement [47, 52, 53].

Deutsch et al. performed minimally invasive transpedicular corpectomy in 8 patients with metastatic tumors [14]. They focused on patients older than 68 years of age, who were deemed to be poor candidates for open surgery, with less than one year of life expectancy, but significant neurologic deficit. They first performed a 3 cm incision

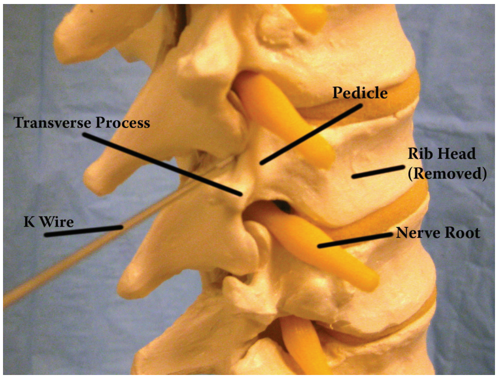


Figure 4: Saw bones image with a K wire showing the localization point for MIS lateral extracavitary corpectomy. Relevant anatomy highlighted.

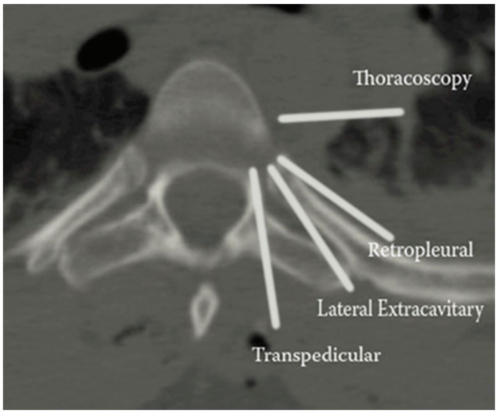


Figure 5: Axial CT image in midthoracic spine demonstrating the trajectory used in the various minimally invasive approaches for corpectomy.

above the transverse process of the more affected side. They used sequential dilators and an expandable tubular retractor to visualize the posterior elements, then took down the ipsilateral transverse process, proximal lamina, and pedicle. They were able to decompress 75% of the canal from a single side. Bilateral decompression was performed when necessary to decompress the entire anterior canal. They did not instrument as they did not feel that stability had been compromised, and given the palliative nature of the procedures [14].

Chou and Lu described minimally invasive transpedicular corpectomy with expandable cage reconstruction [15]. They describe the procedure for 8 patients and compare it to a similar open cohort. They perform a midline incision two levels above and below the level of interest, preserving the fascia. Percutaneous screws are placed two levels above and below the level of corpectomy. A midline fascial opening is performed over the level of interest, and an expandable tubular retraction system is placed. The posterior elements are removed, followed by removal of the pedicles and adjacent level diskectomy. They then perform bilateral transpedicular corpectomy. They perform a trap door rib head osteotomy, allowing expandable cage placement. They comment that removing the tubular retractor and placing a cerebellar helps to insert the cage, along with rotating the cage while inserting it between the vertebral bodies. They did not perform arthrodesis in these cases. Compared to their open cohort, they showed lower blood loss, similar operative time, and similar complication rates [15].

6. Discussion

The varying approach corridors to the thoracic spine offer different advantages and drawbacks (Figure 5). The anterior (transthoracic and thoracoscopic) approaches allows the broadest decompression of the vertebral body with the ability to visualize the entire anterior thecal sac, but presents complications associated with entering the thorax, and risks related to working adjacent to the aorta and azygos vein [5, 23, 29, 55]. Working in a ventral-to-dorsal direction forces the surgeon to constantly estimate his distance to the thecal sac [3]. Learning thoracoscopy also demands specialized training from the surgeon [11]. The retropleural approach offers a similar view to thoracoscopy without entering the pleura, but even the existing minimally invasive descriptions require at least a 6–8 cm incision, substantial rib resection, and an extensive retropleural dissection [12, 33]. This dissection is technically demanding, results in an increased risk of pleural violation and chest tube placement, and may be mechanically more awkward than the transthoracic approaches [31].

The posterolateral approach allows surgeons to use a more familiar surgical angle (Figure 4). The minimally invasive variant spares much of the muscle dissection classically associated with the lateral extracavitary approach, decreasing blood loss, and surgical time [3, 45]. The lateral angulation allows the surgeon to directly visualize the thecal sac during decompression. Nevertheless, the unilateral approach likely limits the surgeon to a maximum of 80% corpectomy, and the contralateral pedicle, PLL, and ventral thecal sac cannot be clearly visualized in cadaveric studies [3]. Also, placement of percutaneous screws is typically required for reinforcement, which requires a second, parallel incision. This technique may also require a significant learning curve for the surgeon [3, 45]. The midline transpedicular approaches use a familiar midline trajectory, with either a miniopen approach through midline fascial opening, or bilateral expandable tubular retractors [13–15]. This approach allows bilateral decompression, cage reconstruction, and posterior instrumentation through a single exposure. Nevertheless, placement of the cage still requires either significant manipulation of the rib head or thecal sac, and working with the spinal cord directly between the surgeon and the vertebral body poses clear risks for injury [15, 49]. Loss of the midline posterior tension band may also result depending on the approach.

Choice of surgical approach carries implications regarding instrumentation implementation. Anterior and anterolateral approaches will dictate anterior only instrumentation systems, while posterolateral and posterior approaches better

allow for posterior pedicle screws in the same position, with or without anterior cage reconstruction. Anterior approaches allow plating for stabilization over a wide variety of grafts, ranging from autograft to cages [11, 21]. The posterolateral approach allows for multiple types of anterior grafts as well, but supporting plate/screw systems are limited to a unilateral lateral orientation. As a result, most surgeons are performing a second incision for placement of percutaneous screws [3, 46]. The midline posterior approach is secured with percutaneous screws, with or without expandable cage grafting. In the posterior approach, supporting plating cannot be performed over the graft [15]. Studies have demonstrated that anterior-only constructs for thoracic reconstruction are feasible and appear at least as efficacious as posterior only constructs, although they may be less biomechanically sound [56, 57]. Anterior reconstruction has also been suggested to carry the advantage of correcting kyphosis and preventing secondary kyphosis [11, 57, 58].

Descriptions of minimally invasive techniques for corpectomy are currently very limited by small sample size and limited followup. While some of the series have made early attempts to compare outcomes to the more established open procedures, comparisons are made only on the basis of intraoperative data such as blood loss and feasibility of decompression and instrumentation. Long-term instrumentation outcomes, fusion rates, and patient morbidity and mortality data are still lacking at this time. Thus, continued followup will be required before these minimally invasive techniques can be held in equipoise with established open procedures. Nevertheless, surgeons should be aware of these technical possibilities, and should consider their incorporation in modern surgical practice.

7. Lumbar and Thoracolumbar Corpectomy

Comprehensive discussion of emerging techniques in lumbar and thoracolumbar corpectomy would easily command an independent paper. Nevertheless, most emerging techniques in minimally invasive lumbar corpectomy utilize similar principals to the thoracic techniques, specifically blunt tubular muscle and plane splitting, to minimize blood loss and tissue trauma. Lateral and anterior techniques in the lumbar spine and thoracolumbar junction provide similar advantages for decompression and reconstruction. We present an illustrative case of a 21-year-old male who suffered an L4 burst fracture and underwent MIS lateral corpectomy and reconstruction (Figure 3).

8. Conclusion

Minimally invasive approaches for corpectomy in the thoracic spine offer substantial exposure-related advantages compared to their open counterparts. Descriptions are new and will require larger series and greater long-term followup to become fully validated. Choice of exposure approach should be driven by a patient's specific pathology, anatomy, and medical comorbidities.

Disclousre

No financial support was received by any of the authors in conjunction with the generation of this paper.

References

[1] H. H. Bohlman and T. A. Zdeblick, "Anterior excision of herniated thoracic discs," *The Journal of Bone & Joint Surgery A*, vol. 70, no. 7, pp. 1038–1047, 1988.

[2] Z. L. Gokaslan, J. E. York, G. L. Walsh et al., "Transthoracic vertebrectomy for metastatic spinal tumors," *Journal of Neurosurgery*, vol. 89, no. 4, pp. 599–609, 1998.

[3] D. H. Kim, J. E. O'Toole, A. T. Ogden et al., "Minimally invasive posterolateral thoracic corpectomy: cadaveric feasibility study and report of four clinical cases," *Neurosurgery*, vol. 64, no. 4, pp. 746–753, 2009.

[4] T. Mückley, T. Schütz, M. H. Schmidt, M. Potulski, V. Bühren, and R. Beisse, "The role of thoracoscopic spinal surgery in the management of pyogenic vertebral osteomyelitis," *Spine*, vol. 29, no. 11, pp. E227–E233, 2004.

[5] R. G. Fessler and M. Sturgill, "Review: complications of surgery for thoracic disc disease," *Surgical Neurology*, vol. 49, no. 6, pp. 609–618, 1998.

[6] V. Logue, "Thoracic intervertebral disc prolapse with spinal cord compression," *Journal of Neurology, Neurosurgery, and Psychiatry*, vol. 15, no. 4, pp. 227–241, 1952.

[7] T. Faciszewski, R. B. Winter, J. E. Lonstein, F. Denis, and L. Johnson, "The surgical and medical perioperative complications of anterior spinal fusion surgery in the thoracic and lumbar spine in adults: a review of 1223 procedures," *Spine*, vol. 20, no. 14, pp. 1592–1599, 1995.

[8] M. J. Perez-Cruet, R. G. Fessler, and N. I. Perin, "Review: complications of minimally invasive spinal surgery," *Neurosurgery*, vol. 51, no. 5, supplement, pp. S26–S36, 2002.

[9] J. E. O'Toole, K. M. Eichholz, and R. G. Fessler, "Surgical site infection rates after minimally invasive spinal surgery," *Journal of Neurosurgery*, vol. 11, no. 4, pp. 471–476, 2009.

[10] Y. M. Ryang, M. F. Oertel, L. Mayfrank, J. M. Gilsbach, and V. Rohde, "Standard open microdiscectomy versus minimal access trocar microdiscectomy: results of a prospective randomized study," *Neurosurgery*, vol. 62, no. 1, pp. 174–182, 2008.

[11] C. A. Dickman, D. Rosenthal, D. G. Karahalios et al., "Thoracic vertebrectomy and reconstruction using a microsurgical thoracoscopic approach," *Neurosurgery*, vol. 38, no. 2, pp. 279–293, 1996.

[12] J. S. Uribe, E. Dakwar, R. F. Cardona, and F. L. Vale, "Minimally invasive lateral retropleural thoracolumbar approach: cadaveric feasibility study and report of 4 clinical cases," *Neurosurgery*, vol. 68, no. 1, supplement, pp. 32–39, 2011.

[13] M. Musacchio, N. Patel, B. Bagan, H. Deutsch, A. R. Vaccaro, and J. Ratliff, "Minimally invasive thoracolumbar costotransversectomy and corpectomy via a dual-tube technique: evaluation in a cadaver model," *Surgical Technology International*, vol. 16, pp. 221–225, 2007.

[14] H. Deutsch, T. Boco, and J. Lobel, "Minimally invasive transpedicular vertebrectomy for metastatic disease to the thoracic spine," *Journal of Spinal Disorders and Techniques*, vol. 21, no. 2, pp. 101–105, 2008.

[15] D. Chou and D. C. Lu, "Mini-open transpedicular corpectomies with expandable cage reconstruction. Technical note," *Journal of Neurosurgery*, vol. 14, no. 1, pp. 71–77, 2011.

[16] C. Crafoord, T. Hiertonn, K. Lindblom, and S. E. Olsson, "Spinal cord compression caused by a protruded thoracic disc: report of a case treated with antero-lateral fenestration of the disc," *Acta Orthopaedica*, vol. 28, no. 1-2, pp. 103–107, 1958.

[17] L. N. Sekhar and P. J. Jannetta, "Thoracic disc herniation: operative approaches and results," *Neurosurgery*, vol. 12, no. 3, pp. 303–305, 1983.

[18] N. Sundaresan, J. Shah, K. M. Foley, and G. Rosen, "An anterior surgical approach to the upper thoracic vertebrae," *Journal of Neurosurgery*, vol. 61, no. 4, pp. 686–690, 1984.

[19] P. L. Turner and J. K. Webb, "A surgical approach to the upper thoracic spine," *The Journal of Bone & Joint Surgery B*, vol. 69, no. 4, pp. 542–544, 1987.

[20] D. Rosenthal, R. Rosenthal, and A. de Simone, "Removal of a protruded thoracic disc using microsurgical endoscopy. A new technique," *Spine*, vol. 19, no. 9, pp. 1087–1091, 1994.

[21] M. Visocchi, R. Masferrer, V. K. H. Sonntag, and C. A. Dickman, "Thoracoscopic approaches to the thoracic spine," *Acta Neurochirurgica*, vol. 140, no. 8, pp. 737–744, 1998.

[22] B. T. Ragel, A. Amini, and M. H. Schmidt, "Thoracoscopic vertebral body replacement with an expandable cage after ventral spinal canal decompression," *Neurosurgery*, vol. 61, no. 5, supplement 2, pp. 317–323, 2007.

[23] D. Rosenthal, G. Marquardt, R. Lorenz, and M. Nichtweib, "Anterior decompression and stabilization using a microsurgical endoscopic technique for metastatic tumors of the thoracic spine," *Journal of Neurosurgery*, vol. 84, no. 4, pp. 565–572, 1996.

[24] M. J. Mack, J. J. Regan, P. C. McAfee, G. Picetti, A. Ben-Yishay, and T. E. Acuff, "Video-assisted thoracic surgery for the anterior approach to the thoracic spine," *Annals of Thoracic Surgery*, vol. 59, no. 5, pp. 1100–1106, 1995.

[25] P. Kan and M. H. Schmidt, "Minimally invasive thoracoscopic approach for anterior decompression and stabilization of metastatic spine disease," *Neurosurgical Focus*, vol. 25, no. 2, article E8, 2008.

[26] D. S. Yanni, C. Connery, and N. I. Perin, "Video-assisted thoracoscopic surgery combined with a tubular retractor system for minimally invasive thoracic discectomy," *Neurosurgery*, vol. 68, no. 1, supplement, pp. ons138–ons143, 2011.

[27] M. J. Mack, J. J. Regan, W. P. Bobechko, and T. E. Acuff, "Application of thoracoscopy for diseases of the spine," *Annals of Thoracic Surgery*, vol. 56, no. 3, pp. 736–738, 1993.

[28] P. F. Ferson, R. J. Landreneau, R. D. Dowling et al., "Comparison of open versus thoracoscopic lung biopsy for diffuse infiltrative pulmonary disease," *Journal of Thoracic and Cardiovascular Surgery*, vol. 106, no. 2, pp. 194–199, 1993.

[29] P. C. McAfee, "Complications of anterior approaches to the thoracolumbar spine: emphasis on Kaneda instrumentation," *Clinical Orthopaedics and Related Research*, no. 306, pp. 110–119, 1994.

[30] P. C. McAfee, J. R. Regan, T. Zdeblick et al., "The incidence of complications in endoscopic anterior thoracolumbar spinal reconstructive surgery: a prospective multicenter study comprising the first 100 consecutive cases," *Spine*, vol. 20, no. 14, pp. 1624–1632, 1995.

[31] P. C. McCormick, "Retropleural approach to the thoracic and thoracolumbar spine," *Neurosurgery*, vol. 37, no. 5, pp. 908–914, 1995.

[32] R. Moskovich, D. Benson, Z. H. Zhang, and M. Kabins, "Extracoelomic approach to the spine," *The Journal of Bone & Joint Surgery B*, vol. 75, no. 6, pp. 886–893, 1993.

[33] K. M. Scheufler, "Technique and clinical results of minimally invasive reconstruction and stabilization of the thoracic and thoracolumbar spine with expandable cages and ventrolateral plate fixation," *Neurosurgery*, vol. 61, no. 4, pp. 798–809, 2007.

[34] M. K. Kasliwal and H. Deutsch, "Minimally invasive retropleural approach for central thoracic disc herniation," *Minimally Invasive Neurosurgery*, vol. 54, no. 4, pp. 167–171, 2011.

[35] S. Keshavarzi, M. S. Park, H. E. Aryan et al., "Minimally invasive thoracic corpectomy and anterior fusion in a patient with metastatic disease: case report and review of the literature," *Minimally Invasive Neurosurgery*, vol. 52, no. 3, pp. 141–143, 2009.

[36] E. Dakwar, A. Ahmadian, and J. S. Uribe, "The anatomical relationship of the diaphragm to the thoracolumbar junction during the minimally invasive lateral extracoelomic (retropleural/retroperitoneal) approach," *Journal of Neurosurgery*, vol. 16, no. 4, pp. 359–364, 2012.

[37] N. Capener, "The evolution of lateral rhachotomy," *The Journal of Bone & Joint Surgery B*, vol. 36, no. 2, pp. 173–179, 1954.

[38] S. J. Larson, R. A. Holst, D. C. Hemmy, and A. Sances Jr., "Lateral extracavitary approach to traumatic lesions of the thoracic and lumbar spine," *Journal of Neurosurgery*, vol. 45, no. 6, pp. 628–637, 1976.

[39] D. K. Resnick and E. C. Benzel, "Lateral extracavitary approach for thoracic and thoracolumbar spine trauma: operative complications," *Neurosurgery*, vol. 43, no. 4, pp. 796–802, 1998.

[40] E. C. Benzel, "The lateral extracavitary approach to the spine using the three-quarter prone position," *Journal of Neurosurgery*, vol. 71, no. 6, pp. 837–841, 1989.

[41] A. W. Graham III, M. Mac Millan, and R. G. Fessler, "Lateral extracavitary approach to the thoracic and thoracolumbar spine," *Orthopedics*, vol. 20, no. 7, pp. 605–610, 1997.

[42] M. H. Schmidt, S. J. Larson, and D. J. Maiman, "The lateral extracavitary approach to the thoracic and lumbar spine," *Neurosurgery Clinics of North America*, vol. 15, no. 4, pp. 437–441, 2004.

[43] R. Delfini, N. Di Lorenzo, P. Ciappetta, R. Bristot, and G. Cantore, "Surgical treatment of thoracic disc herniation: a reappraisal of Larson's lateral extracavitary approach," *Surgical Neurology*, vol. 45, no. 6, pp. 517–522, 1996.

[44] D. J. Maiman, S. J. Larson, E. Luck, and A. El-Ghatit, "Lateral extracavitary approach to the spine for thoracic disc herniation: report of 23 cases," *Neurosurgery*, vol. 14, no. 2, pp. 178–182, 1984.

[45] L. T. Khoo, Z. A. Smith, F. Asgarzadie et al., "Minimally invasive extracavitary approach for thoracic discectomy and interbody fusion: 1-year clinical and radiographic outcomes in 13 patients compared with a cohort of traditional anterior transthoracic approaches," *Journal of Neurosurgery*, vol. 14, no. 2, pp. 250–260, 2011.

[46] Z. A. Smith, Z. Li, N. F. Chen, D. Raphael, and L. T. Khoo, "Minimally invasive lateral extracavitary corpectomy: cadaveric evaluation model and report of 3 clinical cases," *Journal of Neurosurgery*, vol. 16, no. 5, pp. 463–470, 2012.

[47] B. E. Snell, F. F. Nasr, and C. E. Wolfla, "Single-stage thoracolumbar vertebrectomy with circumferential reconstruction and arthrodesis: surgical technique and results in 15 patients," *Neurosurgery*, vol. 58, no. 4, supplement 2, pp. 263–269, 2006.

[48] B. Shaw, F. L. Mansfield, and L. Borges, "One-stage posterolateral decompression and stabilization for primary and metastatic vertebral tumors in the thoracic and lumbar spine," *Journal of Neurosurgery*, vol. 70, no. 3, pp. 405–410, 1989.

[49] D. Chou and V. Y. Wang, "Trap-door rib-head osteotomies for posterior placement of expandable cages after transpedicular

corpectomy: an alternative to lateral extracavitary and costotransversectomy approaches," *Journal of Neurosurgery*, vol. 10, no. 1, pp. 40–45, 2009.

[50] D. C. Lu, D. Lau, J. G. Lee, and D. Chou, "The transpedicular approach compared with the anterior approach: an analysis of 80 thoracolumbar corpectomies," *Journal of Neurosurgery*, vol. 12, no. 6, pp. 583–591, 2010.

[51] P. Klimo Jr., A. T. Dailey, and R. G. Fessler, "Posterior surgical approaches and outcomes in metastatic spine-disease," *Neurosurgery Clinics of North America*, vol. 15, no. 4, pp. 425–435, 2004.

[52] M. H. Bilsky, P. Boland, E. Lis, J. J. Raizer, and J. H. Healey, "Single-stage posterolateral transpedicle approach for spondylectomy, epidural decompression, and circumferential fusion of spinal metastases," *Spine*, vol. 25, no. 17, pp. 2240–2250, 2000.

[53] D. C. Lu, V. Wang, and D. Chou, "The use of allograft or autograft and expandable titanium cages for the treatment of vertebral osteomyelitis," *Neurosurgery*, vol. 64, no. 1, pp. 122–130, 2009.

[54] K. H. Bridwell, A. B. Jenny, T. Saul, K. M. Rich, and R. L. Grubb, "Posterior segmental spinal instrumentation (PSSI) with posterolateral decompression and debulking for metastatic thoracic and lumbar spine disease. Limitations of the technique," *Spine*, vol. 13, no. 12, pp. 1383–1394, 1988.

[55] T. J. Huang, R. W. W. Hsu, C. W. Sum, and H. P. Liu, "Complications in thoracoscopic spinal surgery: a study of 90 consecutive patients," *Surgical Endoscopy*, vol. 13, no. 4, pp. 346–350, 1999.

[56] R. C. Sasso, N. M. Best, T. M. Reilly, and R. A. McGuire Jr., "Anterior-only stabilization of three-column thoracolumbar injuries," *Journal of Spinal Disorders & Techniques*, vol. 18, supplement, pp. S7–S14, 2005.

[57] R. C. Sasso, K. Renkens, D. Hanson, T. Reilly, R. A. McGuire Jr., and N. M. Best, "Unstable thoracolumbar burst fractures: anterior-only versus short-segment posterior fixation," *Journal of Spinal Disorders & Techniques*, vol. 19, no. 4, pp. 242–248, 2006.

[58] C. A. Dickman, "Thoracoscopic correction and placement of anterior instrumentation for scoliotic deformity. Case report," *Neurosurgical Focus*, vol. 7, no. 5, article e2, 1999.

Hindawi Publishing Corporation
Minimally Invasive Surgery
Volume 2012, Article ID 141032, 6 pages
doi:10.1155/2012/141032

Clinical Study

Minimal Invasive Percutaneous Fixation of Thoracic and Lumbar Spine Fractures

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Received 2 March 2012; Accepted 1 June 2012

Academic Editor: Zachary A. Smith

We studied 122 patients with 163 fractures of the thoracic and lumbar spine undergoing the surgical treatment by percutaneous transpedicular fixation and stabilization with minimally invasive technique. Patient followup ranged from 6 to 72 months (mean 38 months), and the patients were assessed by clinical and radiographic evaluation. The results show that percutaneous transpedicular fixation and stabilization with minimally invasive technique is an adequate and satisfactory procedure to be used in specific type of the thoracolumbar and lumbar spine fractures.

1. Introduction

Surgical treatment of thoracic and lumbar spine fractures is based on different factors. Type of fracture, neurological deficit, general conditions, and associated injuries affect both treatment and final result. Although type B and C fractures following AO-Magerl classification [1] require surgical treatment, most type A fractures without neurological involvement can be safely treated in a conservative way [2, 3]. Conservative treatment is a demanding procedure for the patient, and the risk of a final deformity has to be considered as a residual kyphosis can consistently worsen the quality of life of the patient. Moreover, some situations rule out the chance for a conservative treatment. In case of polytrauma, claustrophobia, psychological disease, venous disease or previous deep venous thrombosis, obesity, and bronchopulmonary diseases, conservative treatment is not advisable. Attention must also be paid to the fact that younger and active workers refuse the conservative treatment in order to avoid bed rest and an inactive period.

A traditional open surgery may be an overtreatment in all these cases, considering blood loss, possible complications, hospital stay, and delayed functional recovery. In this setting, a good option can be a percutaneous minimally invasive surgery (MIS) [4, 5]. This technique is suggested by the authors every time a conservative treatment is not indicated or advisable, and posterior open arthrodesis may represent an overtreatment.

2. Materials and Methods

From May 2005 to December 2011, 163 vertebral fractures of the thoracic and lumbar spine in 122 patients were stabilized. Eighty-tree patients were males and 39 females, the mean age was 48 years (from 15 to 85). Eighteen patients were polytrauma with an average Injury Severity Score of 25.2 (from 17 to 34). In those patient, percutaneous fixation was also intended to be a damage control procedure.

The most frequent location was the thoracolumbar junction (T12-L1). All fractures were classified according to the AO-Magerl classification: the vast majority were type A fractures (A1 and A3), while type B or type C were recorded in a few cases (Table 1).

The most frequent construct was the monosegmental one (one level above and one below the fractured vertebra) in 96 cases. A multilevel construction was performed in 26 cases of multiple injuries. Overall, 553 pedicle screws were implanted with a percutaneous technique.

In 18 cases, a bone substitute (cement and hydroxyapatite) was introduced in the fractured vertebra to fill the

Table 1: Fractures distribution according to the type and level.

	A1	A2	A3	B1	B2	B3	C1	C2	TOT
T4								1	1
T5	3				1				4
T6	2	1							3
T7	2	1							3
T8	3			1	2			1	7
T9	3								3
T10	4				1				5
T11	6	3				1			10
T12	14	2	17		1				34
L1	15	4	27	1	1		1		49
L2	6	4	8	1					19
L3	3	1	5		1			1	11
L4	4	2	3		1				10
L5	2		2						4
TOT	67	18	62	3	8	1	1	3	163

anterior gap left after reduction, to better support the anterior column.

In one of patients with poor bone stock due to osteoporosis, we used a fenestrated cemented screw, associated with kyphoplasty, to stabilize a T12 type A3 fracture (Figure 1).

In one case, the fracture stabilization was associated with a minimally invasive endoscopic-assisted discectomy and interbody fusion for a preexisting symptomatic degenerative disc-disease at the same level.

In another case where T11, T12, and L3 type A fractures were associated with L1 and L2 type B fractures, we performed a percutaneous stabilization from T10 to L4 and an L1-L2 arthrodesis with a miniopen approach (Figure 2).

In no other case fusion was associated to the MIS.

To monotrauma patients with type A1, A2, and A3.1 fractures without significant stenosis of the spinal canal, a conservative option consisting of cast and bed rest was also offered but was rejected in 85% of cases. In all cases, the impairment of the spinal canal was less than 30%, and local kyphosis was less than 20° except in one case.

All patients underwent plain radiographs and CT scan preoperatively and immediately postoperatively and were followed over time with systematic clinical and radiographic controls at 1, 3, 6, 12, and 24 months after surgery.

3. Results

The average surgical time was 113 minutes (range 35 to 240 minutes), and it was directly related to the number of screws implanted: the average time, reduced to 106 minutes using 4 pedicle screws, becomes 144 minutes with 6 screws and 171 minutes with 8 screws. Blood losses were not assessable intraoperatively. Postoperative analgesia was performed in all cases with a 36-hour lasting elastomeric pump containing an opioid and an NSAID. All monotrauma patients recovered the standing position in the second postoperative day on the average and were discharged on the fifth day. In polytrauma patients has been granted an immediate mobilization in the bed.

The mean followup was 38 months, with a minimum of 6 months and a maximum of 72 months.

All the cases, except one, have been considered healed after a 6-month control. Radiological examinations confirmed good spontaneous reconstruction of the anterior and posterior columns. Radiographic evaluation was performed through the measurement of the segmental kyphosis and the wedging deformity of the involved vertebral body [6]. Back pain, evaluated by VAS scale was 1.9 points at FU. Clinical evaluation was performed by subjective evaluation of the final results by patients themselves, and every patient was satisfied of surgical procedure.

Radiographic evaluation showed a real improvement in the postoperative period (segmental kyphosis: 4.1 preop, −2.2 postop, and 2.7 FU kyphosis of the fractured vertebral segment: 12.2 preop, 5.9 postop, and 8.7 FU), but also a worsening of the segmentary kyphosis in the cases treated with CD Horizon Longitude (6.4 preop, 3.5 postop, and 7.8 FU) if implanted with multiaxial screws. (5.7 preop, 4.8 postop, 9.9 FU) (Table 2).

In two patients, one screw was found medial into the spine canal on the postoperative TC, without any clinical consequence.

At the beginning of our experience, we planned to remove all implants including L2 or a lower vertebra, no implant above T10 and all the implants in the thoracolumbar junction showing clinical (local pain) or mechanical problems (hardware failure or screws mobilization). We planned hardware removal in the lumbar spine as we were afraid that posterior fixation without fusion in such a mobile part of the spine could lead to hardware failure and consequently to clinical problems. Overall, the instrumentation has been removed in 23 patients (19%), in 5 cases due to a local complication and in 17 cases, as scheduled, because of implantation in the lumbar spine (Figure 3). The average delay from first surgery to implant removal was 9,5 months (range: 6–36). In the 17 patients in which implant removal had been planned, only 3 showed screws mobilization, and only 2 had pain. None of them showed pain or loss of sagittal alignment at six-month followup.

4. Complications

The complications were divided according to a temporal order of appearance in intraoperative and postoperative. The latter were divided into early if they appear within one month from the date of surgery and late when they occurred after that period [7].

Depending on the severity, we divided complications into major and minor [8]. Major complications were those involving an increased hospitalization, or a second operation not scheduled.

We recorded 12 complications (9.8%) divided into 4 intraoperative (3.3%), 6 early postoperative (4.9%), 2 late postoperative (1.6%). Four complications were minor (3.3%) and 8 major (6.5%).

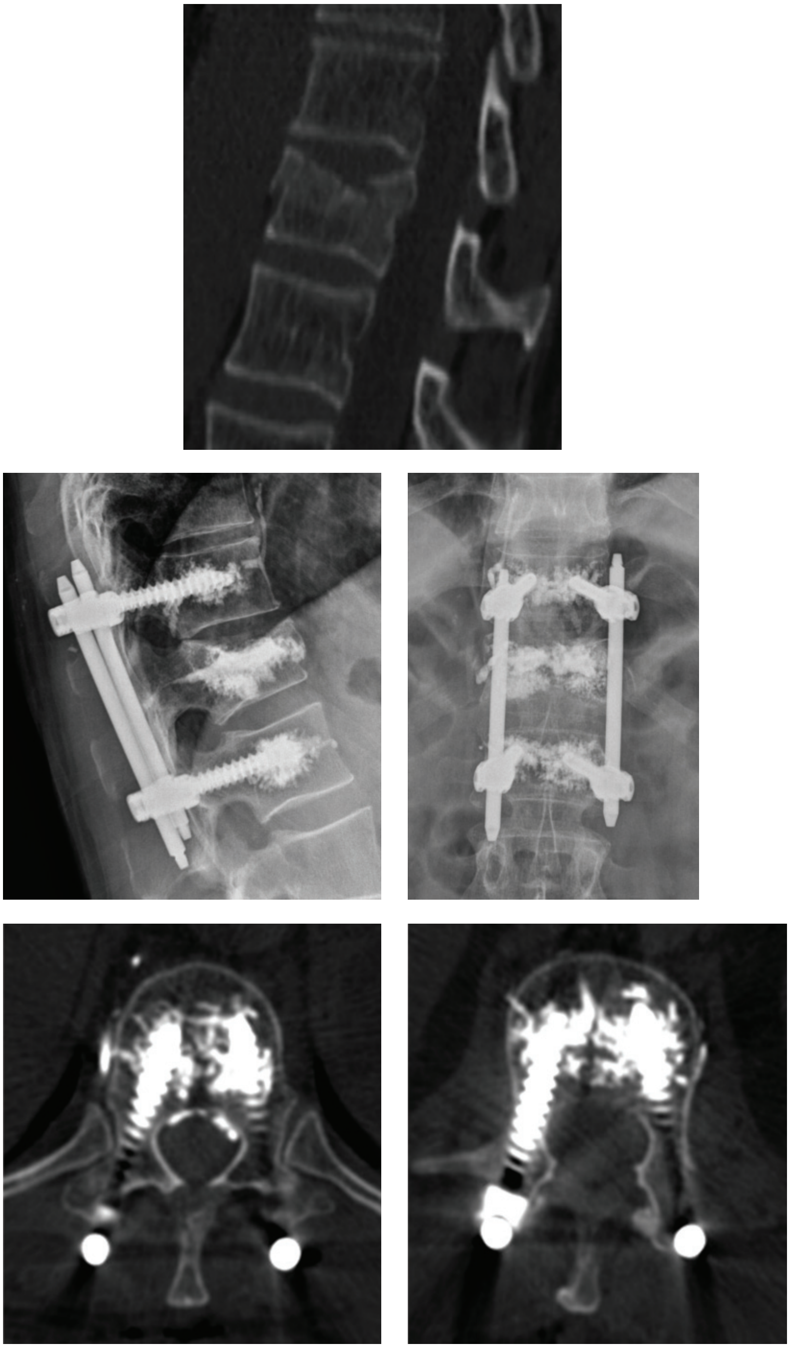

Figure 1: T12 type A3.1 fracture treated with cemented fenestrated screw and kyphoplasty.

Table 2: Radiographic evaluation.

	Segmental kyphosis			Vertebral wedging		
	Preop	Postop	FU	Preop	Postop	FU
Sextant + longitude	4.1	−2.2	2.7	12.2	5.9	8.7
Sextant	3.2	−4.8	0.3	11.8	4.5	8.2
Longitude	**6.4**	**3.5**	**7.8**	13.3	8.8	10
Long. polyaxial screws	**5.7**	**4.8**	**9.9**	14.3	9.3	10.3
Long. monoaxial screws	7.5	1	3.8	11.5	8	9.5

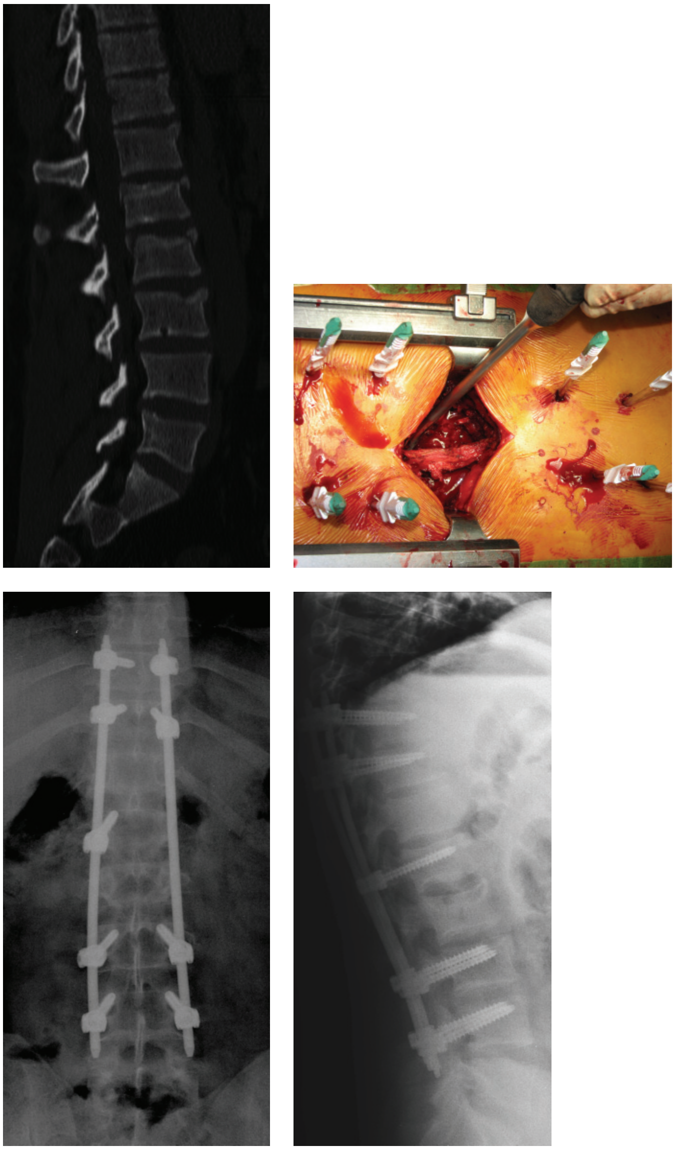

Figure 2: T11, T12, and L3 type A fractures associated with L1 and L2 type B fractures. Percutaneous stabilization from T10 to L4 and L1-L2 arthrodesis with a miniopen approach.

Intraoperative complications were all minor, related to mechanical instruments, which lengthened the surgical time but without any consequence for the patients. Early postoperative complications were all major: 4 mechanical, 1 neurological and 1 infectious complication. In 2 patients the screw head disconnected from the stem in the first postoperative day.

In one case, the patient was reoperated, while the other had to wear a brace for 3 months postoperatively.

In 2 patients we recorded a pullout of the pedicle screws, 15 days and 20 days after surgery respectively.

The first case was a 63-year old patient with 2 noncontiguous type A1 fractures (T11 and L1) undergoing MIS from T10 – L3 with bilateral pedicle screws in L1. The second case was a patient of 67 years fixed from T12 to L2 for a type A3 L1 fracture. In both cases, we performed the implant removal and a percutaneous augmentation of the vertebral bodies with cement.

The neurologic complication was a cauda equina syndrome which appeared in the second postoperative day in a patient treated for a type A L1 fracture by T12–L2 MIS. The patient underwent urgent surgical revision. In that occasion, we found an organized intradural hematoma sleeve enveloping the conus medullaris. We performed a complete removal of the hematoma with a microsurgical technique without finding the source of bleeding. Surprisingly no screw was found in the spinal canal during the revision surgery. The patient was subsequently sent to a rehabilitation center, and he completely regained the neurological functions in 2 months.

A 35-year old patient had a *Staphylococcus epidermidis* infection with surgical wound dehiscence. The patient had

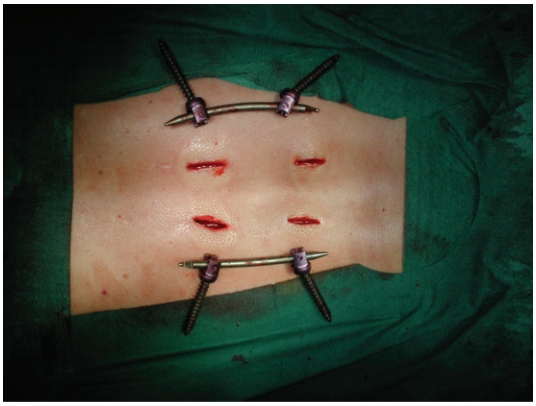

Figure 3: Percutaneous minimal invasive removal of the instrumentation.

been submitted to MIS for a type A2 T11 fracture. Two and a half after surgery underwent surgical debridement and removal of the instrumentation resulting in healing of the infection. The patient wore a 3-point bodice for further 45 days, and the fracture healed with a residual kyphosis of 18 degrees.

Both late postoperative complications were major. In one case there was a nonunion in a patient with an A3 type T12 fracture, with initial kyphosis of 25°. Three months after surgery the patient still complained pain during weight bearing, and there was no evidence of healing on the CT scan. The patient underwent anterior fusion by thoracoscopic approach with incomplete pain relief.

In the other case, there was an aseptic loosening of the screws in L5 in a young patient of 28 years, treated 3 years earlier by L3–L5 MIS for a B2 type L4 fracture. The patient had been scheduled for instrumentation removal 6 months after surgery, but he refused the operation. The patient underwent minimally invasive removal of fixation, with immediate disappearance of pain.

5. Discussion

The choice of treatment of the thoracic and lumbar spine injuries is related to many factors such as the type of fracture, the presence of neurological damage, associated injuries, patient's age, and others more.

Conservative treatment of stable vertebral fractures is proposed with success by many authors [2, 3, 9–11], with different techniques: bed rest followed by external orthoses, extension gymnastics, plaster jacket in bed, or stand reduction [12]. Regardless of the methodology adopted, the treatment should be continued for a period of at least 3-4 months during which the patient care and cooperation is mandatory. The problems related to bed rest, particularly in the elderly, are countless, although difficult to calculate. Deep vein thrombosis may affect up to 30% of patients. Obesity, chronic obstructive pulmonary disease, venous incompetence, and psychiatric disorders are almost absolute contraindications to conservative treatment.

In addition, today more and more patients need to return to their social and working life in a short time; therefore, surgery becomes the simplest way to shortcut recovery. In our experience, only 15% of the patients eligible for MIS opted for a conservative treatment.

The rationale for applying MIS in the management of the spine fractures is to reduce the approach-related morbidity associated with the conventional technique: iatrogenic muscle denervation, increased intramuscular pressures, ischemia, pain, and functional impairment.

Because of the impossibility to perform a fusion, the minimally invasive percutaneous stabilization has been limited to relatively stable vertebral fractures, involving mainly bone component with a consistent possibility of spontaneous healing after immobilization; the screws and rods implanted acted as an internal fixator, leading to the biological healing of all fractures. Wang et al. comparing two groups of patients with thoracolumbar burst fractures, one treated by instrumented fusion, while the other just fixed without fusion, showed that there were no statistically significant differences in the long term between the two groups with a slight advantage, both for clinical than for radiographic parameters, for the group treated only with fixation without fusion [13]. This study further justifies the minimally invasive approach we have taken.

PMMA injection through fenestrated cannulated screws provided additional stability in fixation procedures carried out on osteoporotic vertebral columns without affecting fracture healing.

Implant removal remains a controversial key point against this technique as it requires a second surgery and a general anesthesia, adding risks for the patient and costs for the hospital. Nevertheless, the real need for implant removal is probably much lower than that showed in our study as most of the patients who had the implant removed showed no clinical or radiological complications at the time of second surgery. Further studies are required to determinate the real need for hardware removal. The loss of correction, we observed during the followup for the cases treated with multiaxial screws could be explained by the possibility of this type of screws to have slight movement, also after implantation, between the head and the arm of the screw. For this reason, monoaxial screws should be considered for this kind of surgery, when it is possible.

There are yet no studies that analyze the complications of MIS in thoracic and lumbar spine fractures. A retrospective study compares two groups of patients treated by MIS (10 patients) and arthrodesis with conventional technique (11 patients), with a minimum followup of 5 years. There is evidence of reduced blood loss for the group treated with MIS, but the study did not consider the complications occurred [14].

The complications in our series are comparable to those reported in the literature for conservative treatment, and much less than with open fusion.

6. Conclusion

MIS in the treatment of thoracolumbar and lumbar spine fractures represents a good alternative option to conservative treatment.

Clinical and functional results are better or comparable, time of recovery is much quicker and the rate of complications is low. Implants need to be removed in case of complications or symptoms referred by the patient. Otherwise system hardware removal is mandatory only when fixation involves L2 or lower segments.

An adequate learning curve is important in order to minimize complications. The surgeon should also be confident about the instrumentation to reduce the duration of surgery and radiation exposure. The major complications primarily occur in the immediate postoperative period and can be related both to the implant and to the surgical procedure.

The correct surgical indication remains mandatory. Patients should be informed about the potential complications and the possible need for instrumentation removal.

References

[1] F. Magerl, M. Aebi, S. D. Gertzbein et al., "A comprehensive classification of thoracic and lumbar injuries," *European Spine Journal*, vol. 3, no. 4, pp. 184–201, 1984.

[2] J. Mumford, J. N. Weinstein, K. F. Spratt, and V. K. Goel, "Thoracolumbar burst fractures: the clinical efficacy and outcome of nonoperative management," *Spine*, vol. 18, no. 8, pp. 955–970, 1993.

[3] W. J. Shen and Y. S. Shen, "Nonsurgical treatment of three-column thoracolumbar junction burst fractures without neurologic deficit," *Spine*, vol. 24, no. 4, pp. 412–415, 1999.

[4] Y. R. Rampersaud, N. Annand, and M. B. Dekutoski, "Use of minimally invasive surgical techniques in the management of thoracolumbar trauma: current concepts," *Spine*, vol. 31, no. 11, supplement, pp. S96–S102, 2006.

[5] G. Barbanti Brodano, F. De Iure, M. Cappuccio et al., "Osteosintesi con tecnica percutanea mininvasiva nel trattamento delle fratture vertebrali toraciche e lombari. Esperienza preliminare," *Giot*, vol. 33, pp. 78–85, 2007.

[6] T. R. Kuklo, D. W. Polly Jr., B. D. Owens, S. M. Zeidman, A. S. Chang, and W. R. Klemme, "Measurement of thoracic and lumbar fracture kyphosis: evaluation of intraobserver, interobserver, and technique variability," *Spine*, vol. 26, no. 1, pp. 61–66, 2001.

[7] J. J. Wise, J. S. Fischgrund, H. N. Herkowitz, D. Montgomery, and L. T. Kurz, "Complication, survival rates, and risk factors of surgery for metastatic disease of the spine," *Spine*, vol. 24, no. 18, pp. 1943–1951, 1999.

[8] M. F. McDonnell, S. D. Classman, J. R. Dimar II, R. M. Puno, and J. R. Johnson, "Perioperative complications of anterior procedures on the spine," *Journal of Bone and Joint Surgery—Series A*, vol. 78, no. 6, pp. 839–847, 1996.

[9] H. D. Been, R. W. Poolman, and L. H. Ubags, "Clinical outcome and radiographic results after surgical treatment of post-traumatic thoracolumbar kyphosis following simple type A fractures," *European Spine Journal*, vol. 13, no. 2, pp. 101–107, 2004.

[10] E. A. Seybold, C. A. Sweeney, B. E. Fredrickson, L. G. Warhold, and P. M. Bernini, "Functional outcome of low lumbar burst fractures: a multicenter review of operative and nonoperative treatment of L3–L5," *Spine*, vol. 24, no. 20, pp. 2154–2161, 1999.

[11] W. J. Shen, T. J. Liu, and Y. S. Shen, "Nonoperative treatment versus posterior fixation for thoracolumbar junction burst fractures without neurologic deficit," *Spine*, vol. 26, no. 9, pp. 1038–1045, 2001.

[12] G. H. Chow, B. J. Nelson, J. S. Gebhard, J. L. Brugman, C. W. Brown, and D. H. Donaldson, "Functional outcome of thoracolumbar burst fractures managed with hyperextension casting or bracing and early mobilization," *Spine*, vol. 21, no. 18, pp. 2170–2175, 1996.

[13] S. T. Wang, H. L. Ma, C. L. Liu, W. K. Yu, M. C. Chang, and T. H. Chen, "Is fusion necessary for surgically treated burst fractures of the thoracolumbar and lumbar spine? A prospective, randomized study," *Spine*, vol. 31, no. 23, pp. 2646–2652, 2006.

[14] M. H. Wild, M. Glees, C. Plieschnegger, and K. Wenda, "Five-year follow-up examination after purely minimally invasive posterior stabilization of thoracolumbar fractures: a comparison of minimally invasive percutaneously and conventionally open treated patients," *Archives of Orthopaedic and Trauma Surgery*, vol. 127, no. 5, pp. 335–343, 2007.