Biomechanical evaluation of a new AxiaLIF technique for two-level lumbar fusion

Serkan Erkan · Chunhui Wu · Amir A. Mehbod ·
Brian Hsu · Douglas W. Pahl · Ensor E. Transfeldt

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Abstract Single level axial lumbar interbody fusion (AxiaLIF) using a transsacral rod through a paracoccygeal approach has been developed with promising early clinical results and biomechanical stability. Recently, the transsacral rod has been extended to perform a two-level fusion at both L4–L5 and L5–S1 levels (AxiaLIF II). No biomechanical studies have been conducted on multilevel fusion using the AxiaLIF technique. In this study, the biomechanics of L4–S1 motion segments instrumented with the AxiaLIF II transsacral rod was evaluated. Six human cadaveric lumbosacral spine segments from L4 to S1 were used (age ranges 46–74 years). Unconstrained and non-destructive pure moments in axial torsion, lateral bending, and flexion extension were applied to each specimen following intact, standalone AxiaLIF II, and AxiaLIF II with two posterior fixation options: facet screws and pedicle screws with rods. Range of motion was calculated from the raw data collected with an optical motion tracking system. The two-level transsacral rod was successfully inserted in all the specimens. At L4–L5 level in axial torsion (AT) and flexion extension (FE), none of the surgical treatments showed statistically significant difference between the procedures (all $P > 0.05$) although facet screws and pedicle screws had higher stability on average. In lateral bending (LB), the two posterior fixation techniques had significantly higher construct stability ($P < 0.05$) than the

standalone rod. No significant difference was found between facet screws and pedicle screws ($P = 0.821$). At L5–S1 level in AT and LB, none of the surgical treatments were found to be statistically significant (all $P > 0.05$). In FE, standalone two-level transsacral rod had significantly higher range of motion (ROM) compared with the posterior fixation techniques ($P < 0.05$). In conclusion, the standalone rod reduced intact ROM significantly. Supplementary fixations including facet screws and pedicle screws are required to achieve higher construct stability for successful fusion. Further clinical studies are essential to evaluate the practical success of this technique.

Keywords Transsacral fixation · Facet screw · Pedicle screw · Interbody fusion

Introduction

Instability due to degenerative disc disease and spondylolisthesis is frequently seen at L4–L5 and L5–S1 levels which may require fusion to achieve stability and relieve symptoms. Posterolateral intertransverse process or interbody fusion can be achieved through open or minimally invasive approaches. Open techniques involve dissection, retraction, and mobilization of soft tissues and vital structures such as nerve roots, major vessels, ligaments, annuli, and abdominal viscera [8, 12, 13, 20, 24]. The traditional open approach is often associated with significant postoperative pain, disability, and dysfunction. Minimally invasive techniques are more technically challenging for inexperienced surgeons but they provide symptomatic relief equivalent to that of open approaches based on short-term clinical data [19]. Moreover, clinical benefits of minimally invasive techniques include significantly

S. Erkan · A. A. Mehbod · B. Hsu · D. W. Pahl ·
E. E. Transfeldt
Twin Cities Spine Center, 913 East 26th Street,
Suite 600, Minneapolis, MN 55404, USA

C. Wu (✉)
Foundation for the Advancement of Spinal Knowledge,
913 East 26th Street, Suite 600, Minneapolis, MN 55404, USA
e-mail: cwu@spineknowledge.org

reduced blood loss, postoperative pain, hospital stays, and narcotic usage [3, 10, 15, 18, 19, 23].

Interbody implants may be biomechanically beneficial compared to other types of fixation owing to their proximity to the instantaneous axis of rotation where they are loaded mainly in axial compression [14]. The paracoccygeal transsacral fixation referred to as AxiaLIF (TranS1, Inc., Wilmington, NC) is one of the recent minimally invasive techniques developed to achieve fusion at L5–S1 level with minimal morbidity and injury to the retroperitoneal viscera and dorsal neural elements [8, 17, 26, 27]. Transsacral interbody fixation can be performed using a transsacral cage, fibular strut grafts, transdiscal S1 pedicle screws, or a transsacral rod with or without additional posterior fixation techniques [5, 6, 8, 16, 17, 26]. It has been shown that the transsacral rod performed with the paracoccygeal approach has advantages over other techniques because of its preservation of muscles, ligaments, and annulus [8, 17].

Single level AxiaLIF using a transsacral rod through the paracoccygeal approach has promising early clinical results and biomechanical stability. These studies had short-term average follow-up (5–24 months, range), minimal blood loss (30–88 cc, range), and high average fusion rates (85–93%, range). Oswestry Disability Index questionnaire and Visual Analog Scale assessing back and leg pain showed significant improvement with a low complication rate (0–3%) and short length of hospital stay (1–2.6 days) [2, 4, 8, 14, 17, 21, 22, 25].

Recently, the transsacral rod has been extended to perform two-level fusion at both L4–L5 and L5–S1 levels (AxiaLIF 2LTM, TranS1, Inc) using the same paracoccygeal approach. The AxiaLIF 2L rod has two separate portions: distal rod and proximal rod (Fig. 1). The distal rod engages L5 and the partial L4 whereas the proximal rod engages sacrum.

No biomechanical studies have been conducted on multilevel fusion using the AxiaLIF technique. The objective of this study is to characterize the biomechanics of L4–S1 lumbar motion segments instrumented with the AxiaLIF 2L transsacral rod using multidirectional flexibility test. Additional posterior fixation with facet screws and pedicle screws were compared.

Materials and methods

Specimen preparation

Six fresh human cadaveric L4–S1 motion segments (mean age 65.1; 46–74 years) were harvested. There were three female and three male specimens. The facet joints and all ligamentous structures were kept intact. All the specimens

Fig. 1 The AxiaLIF 2L rod has two separate portions: distal rod and proximal rod. The distal rod engages L5 and partial L4 whereas the proximal rod engages sacrum

were screened via fluoroscopy in order to rule out any major anatomical abnormality (e.g., fracture, deformity, dysplasia, pars defects, or congenital anomaly). Dual energy X-ray absorptiometry (Lunar Prodigy, GE, Louisville, KY) was performed at L4, L5, and S1 in the anterior–posterior position to determine the average bone mineral density (BMD) of each specimen. The BMD was evaluated to ensure that the bone quality was adequate and consistent. All the specimens were frozen at -20°C and stored until the day of testing. The specimens were allowed to thaw slowly at room temperature. Each motion segment was anchored by wood screws in various directions and embedded into two 7.5-cm diameter potting cups filled with polyurethane resin (Fastcast 891, Goldenwest Manufacturing, Cedar Ridge, CA) to provide solid fixation in a multidirectional testing machine. Specimens were wrapped in saline-soaked gauze in order to prevent dehydration during testing.

Biomechanical testing

Unconstrained and non-destructive pure moments in axial torsion (AT), lateral bending (LT), and flexion–extension (FE) were applied to each specimen using a $\pm 7.5\text{-Nm}$ sinusoidal waveform, at 0.05 Hz, with an MTS Bionix 858II spine simulator (MTS, Eden Prairie, MN, USA). Three load cycles were applied for each loading condition with the last cycle used for data analysis. The spine simulator consisted of an AT actuator and two rotational actuators for LB and FE. These actuators were mounted on the upper side of the test machine. A low-friction slide

table mounted on the lower side allowed pure bending moments to be applied.

Segmental motions were recorded at 10 Hz with an OptoTrak Certus video tracking system (NDI, Ontario, Canada). The video tracking system had 0.1 mm of spatial accuracy for each optical diode. Three rigid bodies consisting of four optical diodes each were attached to L4, L5, and S1, respectively, through anchoring wood screws. Our pilot experiments with controlled rotation demonstrated that this configuration was able to achieve accuracy of 0.1 degree in rotation angle.

The specimens were tested in the following sequence: intact, standalone AxiaLIF 2L rod, AxiaLIF 2L rod with facet screws, and AxiaLIF 2L rod with pedicle screws. The length of the AxiaLIF 2L rods were selected according to the lateral X-ray of the specimens using a template. The pitch difference of the distal rod was selected based on the height of the L4–L5 disc space and the desired amount of distraction. If minimal distraction was required (2–2.5 mm), a smaller thread pitch differential (e.g., 10×11) was selected. For L4–L5 disc spaces requiring more distraction (4–5 mm), a larger thread pitch differential (e.g., 10×12) was selected. Thus, the mechanism of disc space distraction at L4–L5 with the distal rod is the same as the distraction achieved in single level AxiaLIF. However, the L5–S1 disc space in AxiaLIF 2L is distracted by rotating the proximal rod after these two rods engaged axially. Referring to Fig. 1, the proximal rod can be further rotated in the engaged position. Thus, the amount of distraction can be easily controlled and verified by radiographs intra-operatively. The facet screws (TranS1, Inc, Wilmington, NC) were 5 mm in diameter and 30 mm or 35 mm in length. Pedicle screws (Legacy, Medtronic Sofamor Danek, Memphis, TN) of 45 mm long were placed in L4 and the sacrum and 50-mm screws were placed at L5; all were 6.5 mm in diameter.

Surgical technique

A sharp guide pin (3 mm in diameter) was initially positioned at the S1–S2 junction. The guide pin was tapped via a cannulated hammer through the sacrum along a trajectory verified by lateral and AP X-rays. Tubular dilators of 6, 8, and 10 mm were introduced consecutively to create a working channel in the sacrum. A 9-mm cannulated drill was then inserted to extend the working channel into the L5–S1 disc space. Following the insertion of a 12-mm tubular dilator/sheath assembly, a 10.5-mm cannulated drill was introduced, to enlarge the working channel to the L5–S1 disc space. The 12-mm sheath was temporarily left docked in to the sacrum to preserve the working channel. The combination of dilation and drilling procedures were performed to reduce the risk of bony fracture at the sacrum.

After removing the 10.5-mm cannulated drill, a series of disc reamers were inserted into the L5–S1 disc space. The reamer has a loop-shaped blade and was rotated to fragment the nucleus and endplate cartilage. A number of stainless steel wire brushes were inserted through the working channel to extract the fragmented nucleus and cartilage.

Once the discectomy of L5–S1 disc space was completed, the 12-mm tubular sheath was advanced to the inferior endplate of the L5 vertebral body. A 9-mm drill was introduced to create a channel to the L4–L5 disc space. Following the removal of the 9-mm drill, a series of disc reamers were inserted into the L4–L5 disc space and rotated to fragment the nucleus and endplate cartilage (Fig. 2). Again, a number of stainless steel wire brushes were inserted through the working channel to extract the fragmented nucleus and cartilage.

A 7.5-mm drill was advanced through the L4–L5 disc space into the L4 vertebral body after discectomy. An appropriately sized distal rod was then threaded into the osseous channel from the sacrum to L4 along the guide pin until its proximal end reached inferior end plate of L5. The proximal rod was then inserted into the same osseous channel and engaged to the distal rod at L5–S1 disc space (Fig. 3a). Disc space distraction was then performed by rotating the proximal rod against the distal rod.

Additional fixation methods included posterior facet screws, using the transfacet-pedicular technique, or pedicle screw and rod system. Facet screws and pedicle screws have been widely used with satisfactory clinical outcomes, and their surgical technique has been described elsewhere [7, 11]. Figure 3b, c show facet screws and pedicle screws, respectively.

Fig. 2 Loop-shaped disc reamers were inserted into the L4–L5 disc space and rotated to fragment the nucleus and endplate cartilage

Fig. 3 **a** The proximal rod engaged to the distal rod at L5–S1 disc space. **b** AxiaLIF 2L rod with facet screws. **c** After removal of facet screws pedicle screws were inserted

Statistical analysis

One-way repeated measure ANOVA was used to analyze the range of motion data of various treatments including intact, standalone AxiaLIF 2L rod, standalone AxiaLIF 2L rod with facet screws, and standalone AxiaLIF 2L rod with pedicle screws and rod system. Post-hoc pairwise comparisons of the range of motion data in degrees between the treatment methods were performed using Student Newman Keuls test. The significance was adjusted for multiple comparisons.

Results

The mean BMD was $1.12 \pm 0.19 \text{ g/cm}^2$, which suggested moderate-to-low bone quality compared with the BMD

scores of young American adults (20–40 years). However, these results are common for patients more than 50 years old. The average range of motion (ROM) in AT, LB, and FE of the intact specimens and subsequent treatments at L4–L5 and L5–S1 levels are presented in Figs. 4 and 5.

At L4–L5 level, the mean ROM of the intact specimens was 4.3 ± 3.2 , 7.5 ± 4.0 , and 7 ± 3.7 degrees in AT, LB, and FE, respectively. The ROM decreased by 63% in AT ($P < 0.05$, ranks), 42% in LB ($P = 0.03$), and 51% in FE ($P = 0.013$) with standalone two-level transsacral rod. The combination of transsacral rod and facet screws decreased the intact ROM by 75% ($P < 0.05$, ranks), 84% ($P < 0.001$), and 84% ($P < 0.001$) in AT, LB, and FE, respectively. The intact ROM decreased by 71% in AT ($P < 0.05$, ranks), 88% in LB ($P < 0.001$), and 91% in FE ($P < 0.001$) with pedicle screw and rod fixation.

Fig. 4 Range of motion at L4–L5 level. Significant difference was observed between standalone and posterior fixation in lateral bending

Fig. 5 Significant difference was observed between standalone and posterior fixation in flexion extension at L5–S1 level

At L4–L5 level in AT, none of the three surgical treatments showed statistically significant difference in range of motion (degrees) between the procedures (all $P > 0.05$) although facet screws and pedicle screws had higher stability on average. In LB, the two posterior-fixation techniques had significantly higher construct stability ($P < 0.05$) than the standalone rod. No significant difference was found between facet screws and pedicle screws ($P = 0.821$). In FE, none of the surgical treatments were statistically significant (all $P > 0.05$) although both facet screws and pedicle screws had higher stability on average.

At the L5–S1 level, the mean ROM of the intact specimens was 2.5 ± 1.2 , 4.8 ± 2.7 , and 8 ± 2.8 degrees in AT, LB, and FE, respectively. The intact ROM decreased by 74% in AT ($P < 0.001$), 66% in LB ($P < 0.001$), and 75% in FE ($P < 0.05$) with standalone two-level transsacral rod. The combination of transsacral rod and facet screws reduced the intact ROM by 83% ($P < 0.001$), 82% ($P < 0.001$), and 93% ($P < 0.05$) in AT, LB, and FE, respectively. The intact ROM decreased by 76% in AT

($P < 0.001$), 83% in LB ($P < 0.001$), and 93% in FE ($P < 0.05$) with the addition of pedicle screw and rod system.

At the L5–S1 level in AT and LB, none of the surgical treatments showed statistically significant difference (all $P > 0.05$) although facet screws and pedicle screws had smaller mean ROM. In FE, standalone two-level transsacral rod had significantly higher ROM compared with the other two posterior-fixation techniques ($P < 0.05$ with facet screws and with pedicle screws).

Discussion

Through the paracoccygeal approach, it is possible to perform discectomy and fusion without violation of the annulus and ligaments and without retracting the vascular and neural structures. Moreover, two-level transsacral rod fixation through a paracoccygeal approach offers the biomechanical advantage of maintaining strong ligamentotaxis forces as a result of an intact annulus and ligaments in selected pathologies [1, 14, 17]. However, it must be recognized that if the patient has damaged annulus at the operative level(s), the strong ligamentotaxis cannot be provided using this AxiaLIF technique. In this case, other fixation options, such as pedicle screw rod system, must be used. The technique and experience learned with the single-level AxiaLIF technique at L5/S1 can be applied to L4–L5 level.

Compared with the single level procedure at L5–S1, the AxiaLIF 2L has two mating rods. The alignment of the proximal and distal rods is important because any misalignment before these two rods engage at L5–S1 disc level will lead to postoperative iatrogenic deformity. Furthermore, the risk of advancing the proximal rod through L5 is also higher in misaligned proximal and distal rods. These have been confirmed in the pilot specimens. Radiographic confirmation is necessary when the proximal rod is threaded into the osseous channel of the sacrum. With careful alignment and radiographic verification, it is possible to assemble the proximal and distal rods with optimal position. It is also advisable to monitor the rotation of the proximal rod as not to over distract the disc space. Over distracting could possibly strip the bone threads in the vertebral bodies. This potential surgical risk would be greater for patients with lower bone density.

The disc preparation technique is very important for successful fusion. Because of the rotational action of the disc reamers, the area of discectomy is determined by the length of the blade of the larger disc reamer. Inspection of the dissected specimens, after experiments were completed, showed that discectomy area was circular with a diameter of approximately 25 mm. This area should be

Fig. 6 The circular footprint on both inferior and superior endplates after discectomy (L4–L5)

subtracted by the area covered by the 10-mm hole occupied by the threaded rod. Thus, the decorticated surface area on the endplate became 412 mm^2 or 4.1 cm^2 . Occasionally, if the osseous channel is not located near the center of the vertebral body, the area of discectomy will be reduced because the reamer cannot sweep in full 360-degree turn. In many cases, a well-defined circular patch (25 mm in diameter) of endplate was decorticated (see Fig. 6). Sometimes the osseous channel was closer to one side of the annulus, and a full turn of the disc reamer was not possible without damaging the annulus. In this case, the discectomy area was approximately 60–70% of a full-turn circular area.

The biomechanics of the lumbosacral segments is well described in the literature. The typical load of an intact lumbar spine accounts for 80% of the axial load over the anterior column. This factor makes the anterior spine a common objective for stabilization [8]. When two level fusion from L4 to S1 is planned through an anterior approach, the procedure involves high surgical risks due to the proximity of anatomic structures (e.g., aorta, etc.). This two-level transsacral fusion technique may be helpful when fusion of these two levels is necessary. In performing this procedure, the trajectory of the transsacral rod is important. A more anterior position may lead to cortical breach at the anterior wall of L4 whereas a more posterior approach may cause spinal canal intrusion. The potential risks at L4–L5 due to improper trajectory of the rod can often be avoided with fluoroscopic monitoring. The surgeon has chances to adjust the rod trajectory during drilling, dilation, and rod insertion. Hence, it is not difficult to avoid these risks in a clinical setting. In preoperative planning of this technique, it is important to check the patient's anatomy using lateral X-rays and a transparency template to make sure a feasible and safe trajectory exists. The template has printed images of the rod shown in various sizes. For patients with abnormal lumbar lordosis or having spondylolisthesis, there may not exist a safe rod trajectory. In this case, this procedure should not be performed on these patients. For

all the donors in this study, we were able to find a good trajectory. It took more time to adjust the rod trajectory for the first few specimens. However, with increased surgical experience, the authors were able to quickly create the osseous channel with good trajectory.

Data from this study indicate that the standalone two-level transsacral rod fixation reduced ROM more than 42% at L4–L5 level and 66% at L5–S1 level compared with the intact condition. These results were consistent with another study by Akesen et al. [2] which found that standalone transsacral rod reduced ROM more than 40% at L5–S1 level. Detailed examination of the L5–S1 motion data for the single level AxiaLIF [2] and the two level AxiaLIF suggested that standalone AxiaLIF 2L reduced motion more effectively at the L5–S1 level in all the three loading directions despite the fact that the AxiaLIF 2L implant had mobile clearance fit between its distal rod and proximal rod. These results can be partially attributed to the bicortical engagement of the distal rod at L5 in AxiaLIF 2L compared to the partial engagement at L5 in the single level AxiaLIF. The bicortical bone purchase provides better fixation between the implant and the L5 vertebra. Another potential factor is the greater rod diameters in AxiaLIF 2L for both L5 and S1. For similar reasons, the motion at the L4–L5 level appears to be greater than that at the L5–S1 level in the standalone AxiaLIF 2L. The L4–L5 level in standalone AxiaLIF 2L and the L5–S1 level in standalone single level AxiaLIF share some biomechanical similarities. In both cases, the intact motion was reduced approximately by a half in all the three loading directions. Both implants partially engaged the upper vertebral body. The rod size was also similar. Despite the success of the limited number of standalone single-level AxiaLIF at the L5–S1 level and the biomechanical similarity, the clinical efficacy of a standalone AxiaLIF 2L at the L4–L5 level has yet to be confirmed.

Although no statistical difference was found between the standalone transsacral rod and additional posterior fixation except in FE at L5–S1 and in LB at L4–L5 level, this amount of reduction in ROM may not be adequate when high construct stability is required to obtain successful fusion. Therefore, facet screws and pedicle screws in conjunction with rod system should be used to enhance construct stability and reduce the stresses at the bone–implant interface.

Facet screws can be inserted with a minimally invasive approach under fluoroscopic guidance and cause less morbidity to the patient. The mean ROM of the transsacral rod used with facet screws was measured as 1° or less at both levels. Our experimental data showed no statistical difference between the facet screws and pedicle screw system under all loading directions at both levels. These results are consistent with another biomechanical study

comparing translaminar facet screws with pedicle screws in a two-level interbody fusion model [9]. Although facet and pedicle screws have similar biomechanics at both the L4–L5 and L5–S1 levels, further clinical studies should also be performed to evaluate the fusion rate of these two fixation methods. Best et al. showed that facet screws had a lower rate of reoperation compared to pedicle screws [7]. Furthermore, facet screws are less invasive and lower in cost. However, facet screws may not be appropriate for some patients with severe facet pathology or anatomic abnormality. Therefore, the choice of facet screws or pedicle screws should be carefully considered prior to surgery.

One limitation of this study is its small sample size. In order to identify large differences greater than 30%, this size is sufficient. To detect smaller difference, a larger sample size is needed. However, a larger sample size would significantly increase the experimental cost. In this study, the additional posterior fixation and standalone rod had no statistical difference in some load directions at both L4–L5 and L5–S1. However, the conclusion of this study will not be affected even if the sample size is increased and statistical difference is detected in these load directions. Posterior fixation appears to be necessary to reduce the risk of pseudarthrosis. Another limitation is the order of test sequence. It was not randomized because the pedicle screw hole may have permanent damage to the facet capsules along the facet screw trajectory.

In conclusion, the standalone rod reduced intact ROM significantly. Supplementary fixations including facet screws and pedicle screws were required to achieve higher construct stability for successful fusion. Facet screws and pedicle screws showed similar construct stability at both L4–L5 and L5–S1 levels. Further clinical studies are essential to evaluate the practical success of this technique.

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References

- Ahlgren BD, Vasavada A, Brower RS et al (1994) Anular incision technique on the strength and multidirectional flexibility of the healing intervertebral disc. *Spine* 19:948–954. doi:10.1097/00007632-199404150-00014
- Akesen B, Wu C, Mehdod AA et al (2008) Biomechanical evaluation of paracoccygeal transsacral fixation. *J Spinal Disord Tech* 21:39–44. doi:10.1097/BSD.0b013e3180577242
- Asgarzadie F, Khoo LT (2007) Minimally invasive operative management for lumbar spinal stenosis: overview of early and long-term outcomes. *Orthop Clin North Am* 38:387–399. doi:10.1016/j.ocl.2007.02.006 abstract vi-vii
- Asgarzadie F, Khoo LT, Cosar M (2007) One year outcomes of minimally-invasive presacral approach and instrumentation technique for anterior lumbosacral intervertebral discectomy and fusion congress of neurological surgeons. San Diego, California
- Bartolozzi P, Sandri A, Cassini M et al (2003) One-stage posterior decompression-stabilization and trans-sacral interbody fusion after partial reduction for severe L5–S1 spondylolisthesis. *Spine* 28:1135–1141. doi:10.1097/00007632-200306010-00010
- Beringer WF, Mobasser JP, Karahalios D et al (2006) Anterior transvertebral interbody cage with posterior transdiscal pedicle screw instrumentation for high-grade spondylolisthesis. Technical note. *Neurosurg Focus* 20:E7. doi:10.3171/foc.2006.20.4.4
- Best NM, Sasso RC (2006) Efficacy of translaminar facet screw fixation in circumferential interbody fusions as compared to pedicle screw fixation. *J Spinal Disord Tech* 19:98–103. doi:10.1097/01.bsd.0000179244.76244.5e
- Cragg A, Carl A, Casteneda F et al (2004) New percutaneous access method for minimally invasive anterior lumbosacral surgery. *J Spinal Disord Tech* 17:21–28. doi:10.1097/00024720-200402000-00006
- Eskander M, Brooks D, Ordway N et al (2007) Analysis of pedicle and translaminar facet fixation in a multisegment interbody fusion model. *Spine* 32:E230–E235. doi:10.1097/01.brs.0000259232.30302.bf
- Farooq N, Grevitt MP (2004) “Does size matter?” A comparison of balloon-assisted less-invasive vs conventional retroperitoneal approach for anterior lumbar interbody fusion. *Eur Spine J* 13:639–644. doi:10.1007/s00586-004-0680-x
- Grob D, Humke T (1998) Translaminar screw fixation in the lumbar spine: technique, indications, results. *Eur Spine J* 7:178–186. doi:10.1007/s005860050053
- Guiot BH, Khoo LT, Fessler RG (2002) A minimally invasive technique for decompression of the lumbar spine. *Spine* 27:432–438. doi:10.1097/00007632-200202150-00021
- Heary RF (2001) Intradiscal electrothermal annuloplasty: the IDET procedure. *J Spinal Disord* 14:353–360. doi:10.1097/00002517-200108000-00013
- Ledet EH, Tymeson MP, Salerno S et al (2005) Biomechanical evaluation of a novel lumbosacral axial fixation device. *J Biomech Eng* 127:929–933. doi:10.1115/1.2049334
- Lehman RA Jr, Vaccaro AR, Bertagnoli R et al (2005) Standard and minimally invasive approaches to the spine. *Orthop Clin North Am* 36:281–292. doi:10.1016/j.ocl.2005.02.012
- Mac Millan M (2005) Computer-guided percutaneous interbody fixation and fusion of the L5–S1 disc: a 2-year prospective study. *J Spinal Disord Tech* 18(Suppl):S90–S95. doi:10.1097/01.bsd.0000112044.70321.d4
- Marotta N, Cosar M, Pimenta L et al (2006) A novel minimally invasive presacral approach and instrumentation technique for anterior L5–S1 intervertebral discectomy and fusion: technical description and case presentations. *Neurosurg Focus* 20:E9. doi:10.3171/foc.2006.20.1.10
- Ozgur BM, Yoo K, Rodriguez G et al (2005) Minimally-invasive technique for transforaminal lumbar interbody fusion (TLIF). *Eur Spine J* 14:887–894. doi:10.1007/s00586-005-0941-3
- Park Y, Ha JW (2007) Comparison of one-level posterior lumbar interbody fusion performed with a minimally invasive approach or a traditional open approach. *Spine* 32:537–543. doi:10.1097/01.brs.0000256473.49791.f4
- Perez-Cruet MJ, Fessler RG, Perin NI (2002) Review: complications of minimally invasive spinal surgery. *Neurosurgery* 51:S26–S36
- Pimenta L (2006) Minimal invasive percutaneous presacral axial lumbar fusion. disorders of the spine and peripheal nerves. Chicago, IL
- Roush T, Bradley W, Hisey M (2007) Interbody fusion using a unique trans-sacral approach. 14th international meeting of advanced spinal techniques. Bahamas, Paradise Island

23. Stevens KJ, Spenciner DB, Griffiths KL et al (2006) Comparison of minimally invasive and conventional open posterolateral lumbar fusion using magnetic resonance imaging and retraction pressure studies. *J Spinal Disord Tech* 19:77–86. doi:[10.1097/01.bsd.0000193820.42522.d9](https://doi.org/10.1097/01.bsd.0000193820.42522.d9)
24. Thalgott JS, Chin AK, Ameriks JA et al (2000) Minimally invasive 360 degrees instrumented lumbar fusion. *Eur Spine J* 9(Suppl 1):S51–S56. doi:[10.1007/PL00010022](https://doi.org/10.1007/PL00010022)
25. Tobbler W (2007) AxiaLIF registry. Annual Meeting of the American Association of Neurological Surgeons. Washington, DC
26. Trambert JJ (1999) Percutaneous interventions in the presacral space: CT-guided precoccygeal approach—early experience. *Radiology* 213:901–904
27. Yuan PS, Day TF, Albert TJ et al (2006) Anatomy of the percutaneous presacral space for a novel fusion technique. *J Spinal Disord Tech* 19:237–241. doi:[10.1097/01.bsd.0000187979.22668.c7](https://doi.org/10.1097/01.bsd.0000187979.22668.c7)