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Minimally Invasive Fusion and Fixation Techniques

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Low back pain is one of the most common conditions causing patients to present to seek medical care in the United States [1]. Although most of these patients improve with conservative management, some require fusion of one or more spinal segments to treat their condition adequately. Lumbar fusion plays an important role in the treatment of degenerative disorders of the spine and may also be appropriate for some cases of spine fractures, scoliosis, tumors, spondylolisthesis, facet joint pain, discogenic pain, and lumbar spondylosis [2]. The chances of successful lumbar spinal fusion are increased significantly by the addition of a rigid fixation device. In a prospective randomized study of 124 patients undergoing lumbar or lumbosacral fusion in 1993, Zdeblick [3] showed that rigid fixation with instrumentation in addition to autogenous bone graft resulted in successful fusion in 95% of patients compared with a rate of only 65% for those patients without rigid fixation.

Unfortunately, there are significant complications associated with open instrumentation techniques. These are partially caused by the amount of exposure classically required to perform these procedures and the significant muscle dissection (with its inherent denervation of the erector spinae muscles) sought for sufficient visualization of the bony elements. Direct complications that may be attributed to the approach of these procedures are numerous. First, an average of greater than 500 mL of intraoperative blood loss is common with lumbar fusions, and this amount increases as the number of segments to be fused increases [4]. Transfusion of blood products places patients at risk for administrative errors (ie, ABO incompatibility), transfusion-related acute lung injury, and viral infections [5,6]. Blood loss and the need for transfusions seem to be less common when minimally invasive techniques are used [7]. Second, the degree and duration of muscle retraction are directly correlated with muscle injury. As may seem obvious, muscle damage has been shown to be more common in larger spine procedures, because a greater degree and longer duration of muscle retraction are required for more extensive fusions [8,9].

Nearly all articles examining the morbidity of minimally invasive spine surgery often reveal dramatic improvements when compared with its open counterpart. Because the ultimate goal of the procedure (ie, safely obtaining arthrodesis) remains the same, this benefit can be seen as the effect of limiting the approach-related morbidity. Unfortunately, all the risks of spinal surgery cannot be eliminated. As techniques arise that allow the same operation to be safely and efficaciously performed in more minimally invasive fashions, one would expect a continued reduction of the problems that can arise when performing spinal fusion.

For these reasons, percutaneous instrumentation and minimally invasive spine fusion techniques may offer a better alternative to traditional open fixation techniques by providing the same goals of surgery with less exposure and muscle dissection. This review surveys the history of percutaneous fixation techniques, including percutaneous pedicle screw fixation, percutaneous lumbosacral interbody screw fixation, and percutaneous translaminar facet screw fixation. Minimally invasive lumbar fusion techniques, including laparoscopic anterior (ALIF) and posterior (PLIF) lumbar interbody

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fusion, and the progression of thoracoscopic fusion from anterior release to corpectomy are examined. Further, this review examines the progression of posterior minimally invasive fusion techniques more rostral in the spine. Finally, future targeted therapies using the evolving understanding of the molecular mechanisms of bony fusion are also briefly discussed.

Percutaneous pedicle screw fixation

Early use of percutaneous pedicle screw fixation was in cases of instability from acute trauma or osteomyelitis. Magerl began using pedicle screws fixed to an external spinal fixation system in 1977. This system of external fixation of percutaneous pedicle screws had been developed to improve on the conventional treatment of spinal instability with Harrington rods, which required fusion of at least five vertebrae [10]. In 1984, Magerl [11] published his series of 65 patients who had undergone external spinal fixation. Instability was attributable to acute spinal trauma in 42 patients, most often unstable burst fractures, and attributable to osteomyelitis in 8 patients. Reduction of fracture-dislocations was achieved during surgery after placement of the pedicle screws. External spinal fixation allowed early postoperative mobilization of the patients, and the device was removed after approximately 17 to 18 weeks.

Although Magerl did not recommend the use of external spinal fixation for degenerative disorders, others soon began to investigate broader applications of this treatment. In 1989, Esses and colleagues [12] published the results of a prospective study of temporary external fixation for its value in predicting the outcome of surgical fusion. The authors performed a prospective 2-week trial of external fixation with percutaneous pedicle screws in 35 patients with chronic low back pain. Fifteen patients reported complete relief, and 12 patients reported significant relief of their pain. Of these 27 patients, 21 underwent subsequent open surgical fusion of the segments that had been immobilized by the external fixator. Only 4 of these patients who were subsequently fused reported no improvement or worsening of their pain. Esses and colleagues [12] concluded that the temporary rigid immobilization of the lumbar spine with the external fixator was an excellent test for patients being considered for operative fusion. Subsequently, other groups performed similar percutaneous transpedicular fixation trials before fusion and found a good correlation between the results of the test and the long-term outcome of fusion [13–16].

Recently, others have questioned the utility of a temporary fixation trial to determine the outcome of lumbar fusion [17–19]. Bednar [17] found that only approximately 50% of the patients who underwent subsequent fusion after a good response to temporary fixation continued to have good pain relief at 2 years. Furthermore, Faraj and colleagues [19] questioned the utility of the test after they had significant complications with the external fixation device. Recently, Heini and coworkers [20] proposed that the external fixation test may be more useful as a negative predictor of outcome after fusion. All told, because of the high rate of infection seen in these devices, external spinal fixators are not commonly used at the present time. Further studies are necessary to determine what role, if any, a trial of percutaneous transpedicular fusion has in the management of back pain.

The use of percutaneous transpedicular external fixation as a temporary method to promote bony fusion has been proposed by Leu and his colleagues [21–24] in Switzerland. These investigators initially focused on endoscopic discectomy for contained lumbar disc herniations [25]. Subsequently, they expanded their indications to include patients with segmental instability. Using a biportal approach to the disc space, a discectomy is performed under endoscopic visualization, followed by the placement of bone graft in the prepared disc space [22–24]. To immobilize the affected segment, percutaneous transpedicular fixation is performed in the fashion of Magerl. The external fixator is kept in place for 12 weeks; at that time, imaging studies are performed to assess completeness of bony fusion and the hardware is removed. An obvious advantage of this technique is that patients undergo minimally invasive surgery and can ultimately be free of any internal hardware. The major disadvantage is that patients must live with an external fixator requiring special care to prevent infection and a special mattress on which to sleep. Leu and Hauser [22] have reported that their patients generally tolerate this treatment well but allow that other patient populations may not accept the inconvenience. Nevertheless, they have had generally good outcomes with this technique. Of 50 patients treated with endoscopic discectomy and percutaneous transpedicular fixation, solid bony fusion was achieved in 42 cases [22]. Whether this technique gains wide acceptance remains to be seen.

These experiences with percutaneous pedicle screw placement have led to the development of more sophisticated minimally invasive instrumentation techniques, such as that described by Foley and Gupta [26] in 2002. They described the modification of an existing multiaxial pedicle screw system to allow the percutaneous placement of a connecting rod between two spinal segments. The modification consisted of extension sleeves that fit over the pedicle screws and constrained their orientation so as to allow an attached rod-insertion device to pass a rod between the two screws percutaneously. Foley and Gupta [26] described their results in 12 patients, all of whom underwent some other fusion procedure (ie, anterior interbody fusion) during the same operative session. All patients developed solid fusion, with a mean follow-up of almost 14 months. One of the major advantages of this method over other percutaneous techniques was that the connecting rods were placed under the muscle fascia, allowing shorter pedicle screws (thus, a shorter motion segment) and generating a more rigid arthrodesis than with external fixation.

The percutaneous placement of pedicle screws remains a technical undertaking requiring significant experience for safe placement of the hardware. In a human cadaveric study in 1999, Wiesner and coworkers [27] reported a 10% misplacement rate of 360 pedicle screws. Most misplacements (32 of 37) were medial, and only 7 had pedicle violations greater than 3 mm. One year later, in 2000, Wiesner and colleagues [28] again reported the results of their investigations into misplaced percutaneous pedicle screws. The authors examined the CT scans of 51 patients who had undergone the external fixation test. Of 408 pedicle screws, only 27 (6.6%) were misplaced. Again, most misplacements (19 of 27) were medial. In addition, of all spinal levels, S1 showed the highest misplacement rate (12%). From these reports, it is reasonable to assume that the rate of misplaced pedicle screws historically lies somewhere between 6% and 10%, even in experienced hands. Intraoperative fluoroscopy has been used to improve the rate of correct percutaneous pedicle screw placement and should be considered an essential component of the procedure [29,30]. Familiarity and extensive use of percutaneous instrumentation systems have been shown to decrease the rate of minimally invasive lumbar pedicle screw misplacement, which seems to have decreased to a 1% medial breach rate [31]. With our last nearly 300 pedicle screws implanted, more than half of which have been confirmed by CT, only a single medial breach has been detected (Fig. 1) [32].

Percutaneous translaminar facet fixation

The first description of isolated percutaneous facet joint fusion was published by Stein and colleagues [33] in 1993. Jacobs and coworkers [34] had previously described the use of translaminar facet screws as an adjunct to lumbosacral fusion, and Stein and colleagues [33] investigated the efficacy of isolated percutaneous facet joint screws in a human cadaveric model and a canine model. The authors inserted a guidewire into the facet joint under fluoroscopic guidance. Next, a bone trephine apparatus was introduced coaxially. A core of bone and cartilage was removed from the joint and replaced with a hydroxyapatite bone plug. The animals had no restriction on activity for 4 months. The authors reported successful radiographic fusion in 5 of 12 manipulated facets. In this report, Stein and colleagues [33] demonstrated the feasibility of percutaneous access to the facet joint.

Capitalizing on this concept, Jang and coworkers [35,36] and Shim and colleagues [37] have reported their results with translaminar facet joint fixation with percutaneous screws as an adjunct to ALIF. Jang and coworkers [36] first reported their results in 2003. The authors used a novel guide device to place percutaneous translaminar facet screws in 18 patients who also underwent ALIF for degenerative lumbar disease. The procedure took less than 20 minutes for a single level, and postoperative CT showed 100% proper screw placement. In 2005, Jang and coworkers [35] reported the results of a retrospective study of 84 patients undergoing ALIF with additional posterior fusion. Forty patients underwent ALIF and pedicle screw fixation, whereas 44 patients underwent ALIF and percutaneous facet screw fixation. There was no significant difference in clinical outcome or radiographic fusion at 2 years of follow-up. Nevertheless, there was a significant difference in operative time, with percutaneous instrumentation taking an average of 18 minutes compared with 47 minutes for pedicle screw fixation. Shim and colleagues [37] have reported similarly encouraging results on their experience with percutaneous facet joint fixation under fluoroscopy. The major advantage of this technique is a short operative time and minimal muscle retraction as compared with open

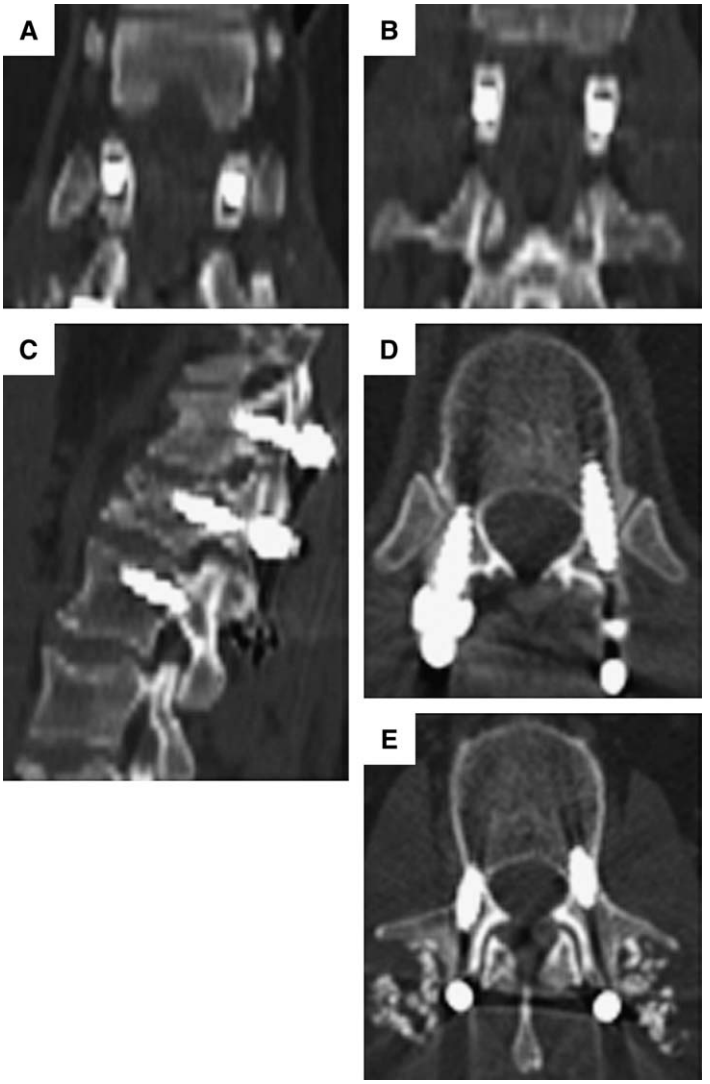

Fig. 1. Postoperative reconstructed CT scan images demonstrate the potential accuracy of percutaneous spinal instrumentation in the thoracic and lumbar spine as revealed in postoperative coronal (*A, B*), sagittal (*C*), and axial (*D, E*) CT scan images.

placement of pedicle screws. No direct comparison with percutaneous pedicle screw instrumentation as an adjunct to ALIF, as described by Foley and Gupta [26], has been performed, however.

Percutaneous lumbosacral interbody fixation

Percutaneous instrumentation has also been used to facilitate fusion at the lumbosacral joint. Unlike other lumbar levels, the L5-to-S1 joint is characterized by greater inaccessibility because of its depth, a thicker layer of covering muscles, and its mechanical characteristics (a transition point between the lumbar and sacral spine). Posterolateral fusion alone for L5-to-S1 spondylolisthesis is associated with a high rate of pseudoarthrosis, likely because of the high degree of mechanical stress at this junction [38]. Kim and coworkers [39] have defined two factors that improve fusion for spondylolisthesis in adults: (1) combined anterior and posterior fusion and (2) rigid postoperative immobilization. Given their overall better health and propensity to fuse, children with spondylolisthesis often do well with uninstrumented

posterolateral fusion alone [40]. Conversely, adults have been shown to have a high rate of failure even with posterior segmental instrumentation. ALIF [41] and PLIF [42] techniques have been described for lumbosacral fusion, but these can be complicated by nerve injury and extensive blood loss.

Minamide and colleagues [43] have studied the biomechanical properties of transdiscal L5-to-S1 screws for lumbosacral fusion. They described a technique for placing S1 pedicle screws through the S1 pedicle, through the superior end plate of S1, through the inferior end plate of L5, and terminating in the L5 body. Using a human cadaveric model, the authors found that transdiscal fixation was 1.6 to 1.8 times stiffer than pedicle screw fixation alone and was equivalent to combined interbody and/or pedicle screw fixation. One of the major advantages of this technique is that exposure and retraction of nerve roots are unnecessary for placement of the instrumentation.

In 1996, MacMillan and coworkers [44,45] presented their experience with percutaneous lumbosacral fixation and fusion using placement of transdiscal interbody L5-to-S1 screws. First, in a cadaveric study, the authors placed 30 percutaneous Steinmann pins through a corridor from the iliac crest through the S1 pedicle to the S1 end plate, continuing through the L5-to-S1 disc space and into the L5 vertebral body. A continuous bony corridor with an average width of 18 mm extends from the S1 pedicle outward to the ilium and is the initial segment of the fixation. Next, in a prospective clinical study, MacMillan and coworkers [44] performed percutaneous lumbosacral fixation in 14 patients with lumbosacral disease. The patients also underwent an L5-to-S1 discectomy and placement of bone graft in the disc space using the intradiscal corridor. To ensure standard of care, the patients also had posterolateral fusions performed using a paraspinal muscle-splitting approach. Thirteen of the 14 patients had good bony fusion at the lumbosacral disc space between 9 and 12 months after surgery, as seen by CT scanning.

Encouraged by these results, MacMillan [46] went on to perform a second prospective study using the placement of a mesh cylinder packed with bone graft through the intradiscal corridor. As with the earlier study, all patients also received posterolateral fusion for additional support. Of the 15 patients who underwent this technique and were available for follow-up, 93% had successful bony fusion at 2 years. Although this technique seems to be appealing for lumbosacral fusion, other groups have yet to report on their experience (Fig. 2).

Minimally invasive posterior lumbar interbody fusion

In 2002, Khoo and colleagues [47] first described a minimally invasive percutaneous technique for lumbar interbody fusion using a posterior approach. The authors first performed a cadaveric study to test feasibility and then applied the technique to three patients. Using fluoroscopic guidance, small bilateral stab incisions were made 1 to 1.5 inch lateral to midline. A guidewire was placed through the stab incisions down to the facet, and serial dilators were then passed, cumulating in a 20-mm working channel, which was fixed in place by a flexible arm mounted to the operating table. Under endoscopic visualization, hemilaminectomy and discectomy were performed with the dura retracted medially. Next, the end plates were prepared, and an interbody distractor was introduced into the disc space. The same series of steps was performed on the contralateral side. Autologous and allograft bone was placed into the disc space, and the tubular retractor system was removed. Instrumentation of the same level was then performed, again under fluoroscopic guidance, placing percutaneous pedicle screws in the manner described by Foley and Gupta [26]. The authors reported an average operating time of 5.4 hours and an inpatient stay of less than 3 days.

Recently, several groups have presented their experience with minimally invasive transforaminal lumbar interbody fusion (TLIF). Schwender and coworkers [48] reported their initial results in 49 patients in February 2005. As with Khoo and colleagues [47], a combination of the tubular retractor and percutaneous pedicle screw-rod placement systems was used. The tubular retractor was docked unilaterally on the facet joint; after facetectomy and discectomy, allograft or interbody cages were placed through the tubular retractor. Next, bilateral percutaneous pedicle screws and rods were placed. At follow-up, all patients had solid radiographic fusions.

Recently, we have presented our experience with microendoscopic transforaminal interbody fusion (METLIF) [7]. Using microendoscopic technology, we performed a unilateral hemilaminectomy, facetectomy, and discectomy, followed by the placement of bone allograft into the disc space (Fig. 3). As with the techniques described

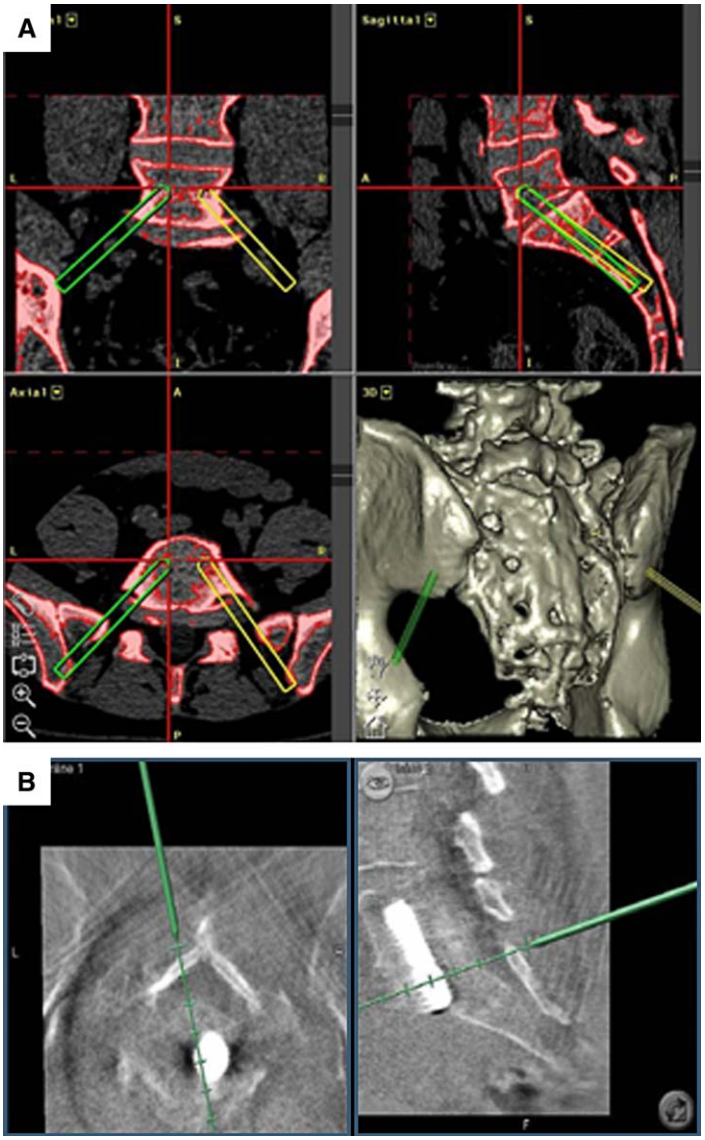

Fig. 2. (*A*) Intraoperative image guidance planning for placement of transalar screws. (Courtesy of M. MacMillan, MD, Gainsville, FL.) (*B*) Various percutaneous approaches to fuse across L5 to S1 have been proposed, including a transsacral screw. (Courtesy of E. Nottmeier, MD, Jacksonville, FL.)

by Khoo and colleagues [47] and Schwender and coworkers [48], the fusion was instrumented with percutaneous pedicle screws. In comparison to the standard open TLIF, we found a substantial difference in blood loss (mean of 226 mL in METLIF group and mean of 1147 mL in TLIF group; $P < .001$). This was also reflected in the need for postoperative transfusion (0% in METLIF and 17% in TLIF; $P < .001$). In addition, as is to be expected with minimizing approach-related morbidity with a minimally invasive technique, the METLIF group had a mean hospital length of stay (LOS) of only 3.4 days compared with 5.1 days for the TLIF group ($P < .02$) and required only half as much pain medication.

Minimally invasive anterior lumbar fusion

The benefits of laparoscopic surgery in the late 1980s led surgeons to find other potential

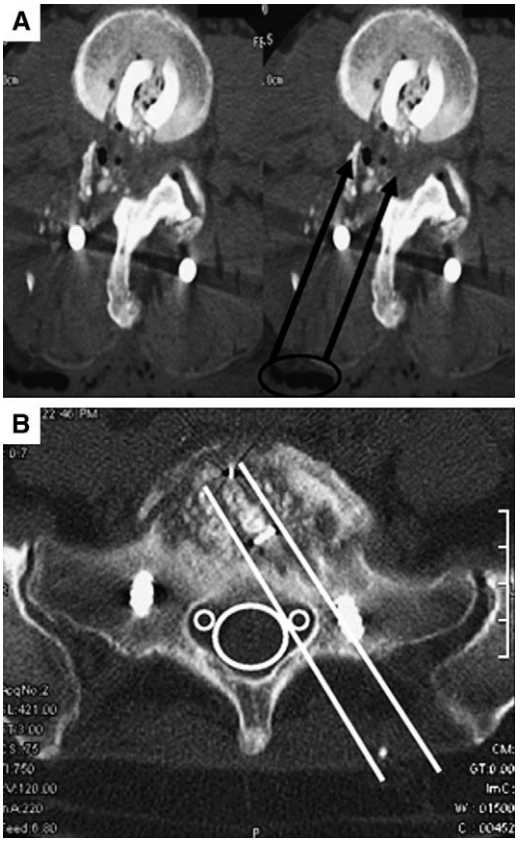

Fig. 3. Early postoperative axial CT scans acquired in a patient who underwent an L4-to-L5 microendoscopic TLIF reconstructed with allograft bone (*A*) and in another patient undergoing a minimally invasive TLIF using an interbody cage (*B*). These reveal the location of fascial entry (*black circle*), approach angle of the procedure (*black arrows*), and various treatment options for obtaining interbody fusion. Note how little thecal sac retraction is required to place a graft in when using a paramedian approach to L5 to S1 (*white circle and lines*).

applications for this technology. In 1991, Obenchain [49] presented the first case report of a laparoscopic lumbar discectomy. The patient was a young man with an acute L5-to-S1 herniated nucleus pulposus who underwent outpatient laparoscopic discectomy. Because of the biomechanical superiority of interbody fusion gained from traditional ALIF, it was not long before others began attempting laparoscopic ALIF. Several case series were reported in the literature in the mid-1990s with the early results of laparoscopic ALIF [50,51]. Reported complications included iliac vein injury [50], bladder injury [51], and retrograde ejaculation [51]. On the whole, however, patients tolerated the procedure well and demonstrated good bony fusion on follow-up imaging studies (Fig. 4). In 1996, Mahvi and Zdeblick [52] presented their prospective experience with 20 patients who underwent laparoscopic ALIF. Although two of the cases were converted to open ALIF because of intraoperative complications, the results were otherwise encouraging, with a short hospital LOS (average of 1.7 days), excellent pain relief in 60% of patients, and radiographic fusion in those patients studied at 6 months.

In spite of these early encouraging results, laparoscopic ALIF failed to gain general acceptance. Heniford and colleagues [53] explained this as a result of the expense of laparoscopic equipment, the technical demands of the procedure, and the fact that intraoperative complications were often severe (eg, vascular injuries). In fact, it is also likely that the laparoscopic ALIF failed to gain wide acceptance because the results were not significantly better than those of open techniques. The potential advantages of laparoscopic ALIF were further undermined by the development of the so-called "mini-ALIF," as first described by Wolf and Meier [54] in 1999. The mini-ALIF minimized the operative approach and took advantage of modern microsurgical technique (Fig. 5). Furthermore, although the laparoscopic ALIF was generally limited to lower lumbar levels (L4–L5 and L5–S1), the mini-ALIF could be used to access from L2 down to L5. Although studies directly comparing laparoscopic and mini-ALIF have variably shown differences with respect to operative time or hospital LOS, they have failed to show any significant difference with respect to postoperative pain or success of fusion. Currently, the high degree of technical skill required for laparoscopic ALIF limits the practice to only a few centers.

Thorascopic fusion

In the early 1990s, as the superiority of video-assisted thoracic surgery (VATS) over traditional thoracotomy was recognized with respect to postoperative pain, shoulder dysfunction, and pulmonary status [55], several groups began applying this technology to treatment of spinal disorders (Fig. 6). Animal studies reported no differences between VATS and open thoracic interbody fusion with respect to the amount of disc resected [56] or mechanical stability [57]. Initially, VATS-guided fusion was used for thoracic spine trauma

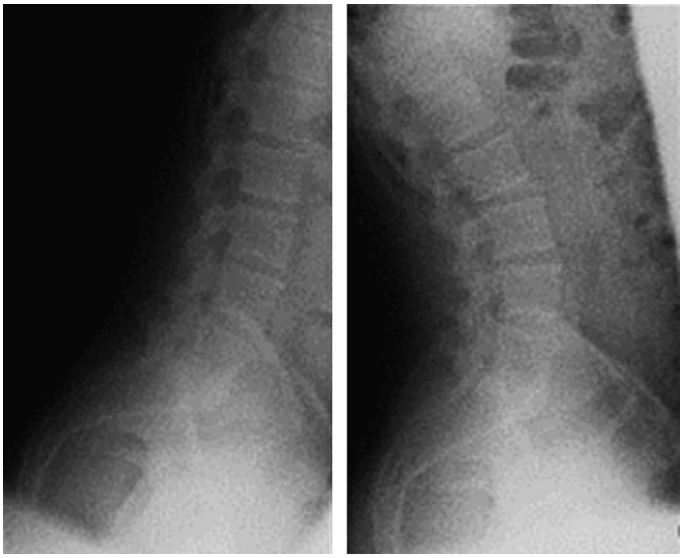

Fig. 4. Postoperative flexion-extension plain films of a patient who has undergone a laparoscopically assisted ALIF using bone morphogenic protein and allograft bone plugs. Despite the relatively less aggressive disc space preparation classically used with the laparoscopic approach, a solid interbody fusion has been achieved.

[58] or for anterior release as part of scoliosis repair [59,60]. In addition, current indications include corpectomy for osteomyelitis or metastatic tumor [6]. The major advantage with VATS fusion is minimization of approach-related morbidity, and the incidence of pneumonia or pneumothorax is less than 2% [6].

In 2002, Anand and Regan [61] presented their series of 100 patients who underwent VATS thoracic disc surgery. The patients were classified by a clinical grading system based on their presenting symptoms: grade 1, pure axial pain; grade 2, pure radicular pain; grade 3A, axial and thoracic radicular pain; grade 3B, axial and lower extremity

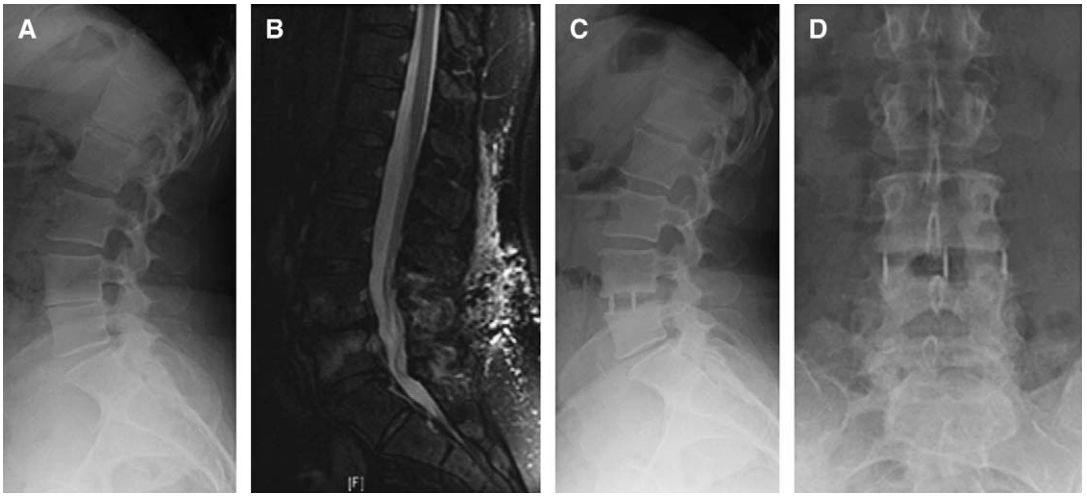

Fig. 5. Preoperative (*A, B*) and postoperative (*C, D*) images of a lateral percutaneous interbody fusion. As opposed to laparoscopic ALIF, by accessing the interbody space without having to mobilize the anterior vascular structures or their associated branches and without having to dissect through the superior hypogastric plexus, the lateral percutaneous approach is gaining favor as a minimally invasive alternative to the ALIF procedure.

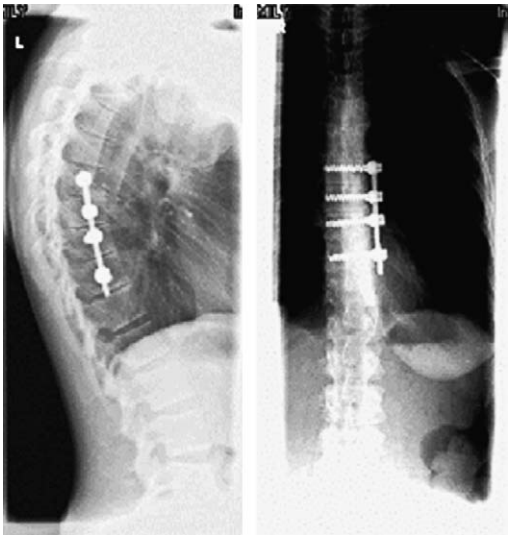

Fig. 6. Thoracoscopic fusion techniques allow for multilevel spinal arthrodesis.

pain; grade 4, myelopathy; and grade 5, paralysis. Two thirds (n = 66) of the patients received a grade of 1 or 3A. A total of 117 discs were excised in these 100 patients, and 50 patients required fusion of one or more adjacent segments. Minor complications occurred in 21 patients, and no patient had a worsening of neurologic status. Overall clinical success, defined as a greater than 20% improvement in the Oswestry score, was achieved in 70% of patients, and there was an 84% overall subjective patient satisfaction rate.

Beisse and his colleagues [62] have published their vast experience with VATS fusion for thoracic and lumbar fractures. Between May 1996 and May 2001, 371 patients with fractures between T3 and L3 were treated with a thoracoscopically assisted procedure. Seventy-three percent of the fractures were located at the thoracolumbar junction, and in almost 50% of patients, mobilization of the diaphragm was performed (Fig. 7). One third of the patients underwent only anterior reconstruction with instrumentation, whereas the remaining two thirds required supplemental posterior pedicle screw instrumentation. The authors reported a low serious complication rate (aortic injury, splenic contusion, neurologic deterioration, cerebrospinal fluid [CSF] leak, or wound infection) of only 1.3%. Furthermore, compared with a group of 30 patients who underwent an open thoracotomy, the thoracoscopically treated patients required 42% less narcotics for postoperative pain control.

Combined minimally invasive fusion techniques

The marriage of various endoscopic and minimally invasive techniques has allowed our group to perform a variety of complex surgical fusions in a less invasive fashion using a combination of the techniques mentioned previously. After proving

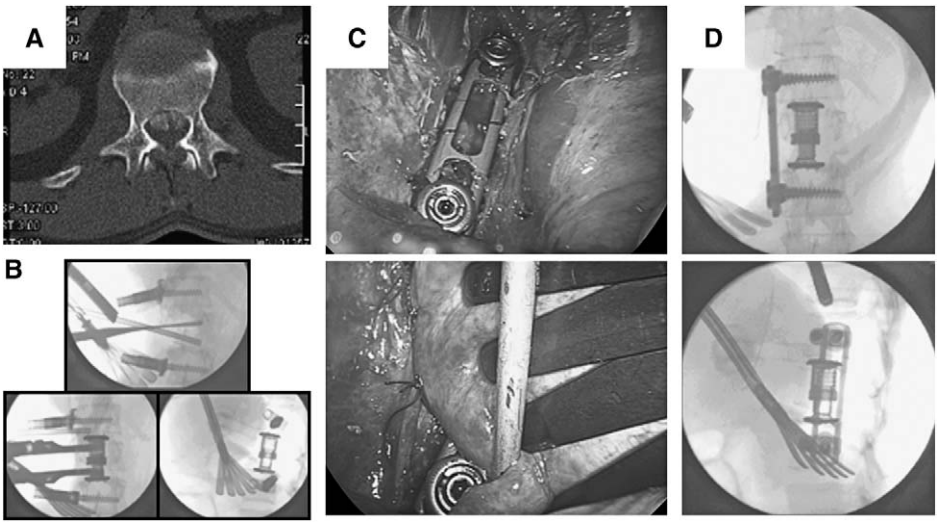

Fig. 7. Preoperative (*A*) and intraoperative (*B–D*) images of a patient undergoing a thoracoscopic vertebrectomy and reconstruction for an L1 burst fracture. Given the location of the fracture, a 3-cm diaphragmatic incision was required to access the retroperitoneal space, remove the vertebra, and reconstruct the spine.

the relative safety of percutaneous pedicle screw instrumentation in the thoracic spine [32], percutaneous pedicle screw instrumentation has been used to treat most burst fractures, fracture-dislocations, and flexion-distraction injuries seen at our institution over the past 3 years [32]. These techniques have further been adapted to the posterior endoscopic treatment of pathologic burst fractures from cancer. When required, minimally invasive circumferential reconstruction and hardware application can be performed as well (Fig. 8).

Minimally invasive cervical fusion

There has been little application of minimally invasive percutaneous techniques for instrumentation of the cervical spine. Currently, there are only two reports in the literature of minimally invasive instrumentation of the cervical spine, both with lateral mass screws. In 2003, Wang and coworkers [63] described their experience treating three patients with traumatic single-level facet dislocations. Two patients were successfully reduced with traction, underwent anterior decompression and fusion, and were then turned prone for posterior percutaneous lateral mass screw placement. A third patient underwent open posterior decompression, followed by percutaneous lateral mass screw placement (Fig. 9). The authors reported no follow-up data for these three patients, because their goal was only to report the feasibility of the technique. In 2005, Fong and Duplessis [64] also described minimally invasive percutaneous lateral mass screw fusion in two patients with traumatic facet dislocation. As with the first two patients of Wang and coworkers [63], these patients had anterior decompression and fusion of the affected level, followed by minimally invasive posterior fusion with lateral mass screws. Again, no follow-up data were reported. On the

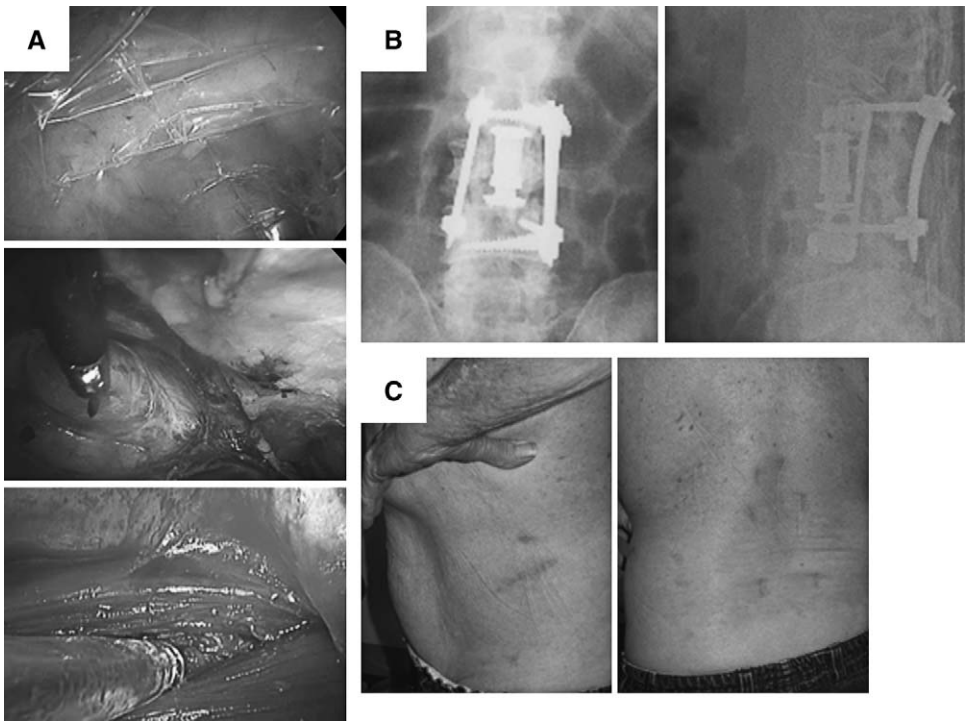

Fig. 8. Because unstable osteoporotic burst fractures have been shown to fail at an unusually high rate when a standalone anterior approach is used, a short-segment anteroposterior construct, with both stages being performed in a minimally invasive fashion, may be a preferential form of treatment. Shown are the intraoperative images (*A*), postoperative radiographs (*B*), and clinical images (*C*) of a 75-year-old man with a chronic osteoporotic burst fracture requiring a laparoscopic-assisted L3 vertebrectomy augmented with percutaneous pedicle screw instrumentation. Operated on for progressive paraparesis because of incessant collapse, he required a walker for ambulation before surgery as the result of a bilateral foot drop. Three years out from surgery, although originally on chronic narcotics, he is off pain medication, neurologically improved to normal, and walking independently, without a significant loss of correction.

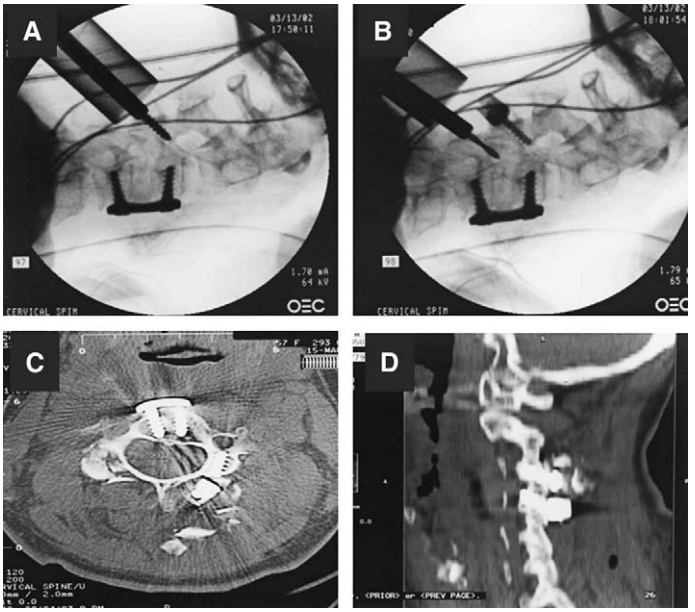

Fig. 9. Intraoperative fluoroscopic images (*A, B*) and postoperative CT scan images (*C, D*) of lateral mass screws placed in a minimally invasive fashion highlight the potential of the minimally invasive surgery techniques in the cervical spine. (Courtesy of M. Wang, MD, Los Angeles, CA.)

whole, percutaneous posterior fusion is appealing insofar as it preserves the posterior tension band provided by posterior ligaments and muscles. Nevertheless, much more work needs to be done in this area to determine if the biomechanical benefits have practical significance.

Future directions

The goal of stable bony fusion of a spinal segment requires stabilization of the joint and the necessary local milieu so as to promote bone ingrowth. Instrumentation is performed to provide stabilization long enough for bony fusion to occur. An osteogenic environment is generated by the placement of material (ie, bone graft) providing a structure into which new bone may grow. It is relatively straightforward to place bone graft into the appropriate location when a fusion procedure is performed in an open fashion, because the location is directly visualized. For true isolated percutaneous fusion to be realized, it is necessary not only to provide adequate stabilization but to generate the milieu necessary for bony fusion.

The evolving understanding of the molecular mechanisms of osteogenesis is already generating novel directed therapies. Ideally, a drug would be delivered to the fusion site at the same time as instrumentation and would consistently result in bony fusion. Bone morphogenic proteins (BMPs) comprise a family of polypeptides within the transforming growth factor-β (TGFβ) superfamily that induce ectopic bone formation by a well-characterized pathway [65]. Alden and coworkers [66] have demonstrated lumbosacral fusion in rats injected at the lumbosacral junction with a replication-deficient adenovirus expressing BMP-2. Studies such as this provide encouragement for progress of percutaneous techniques for spinal fusion.

Summary

An increasing awareness of health care costs and a more medically informed population drive surgeons to find more efficient ways of appropriately caring for patients. Percutaneous techniques for spinal fusion offer patients a better chance for a shorter hospital stay and a more rapid return to full physical activity, both through a smaller incision compared with open techniques. Since the first description of percutaneous instrumentation by Magerl [11] in 1984, there has been a rapid development of novel percutaneous and minimally invasive techniques for spinal arthrodesis. Much work remains to be done, especially regarding cervical fusion and the incorporation of our better understanding of the molecular and cellular mechanisms of bony fusion.

References

[1] Manek NJ, MacGregor AJ. Epidemiology of back disorders: prevalence, risk factors, and prognosis. Curr Opin Rheumatol 2005;17:134–40.

[2] Zdeblick TA. The treatment of degenerative lumbar disorders. A critical review of the literature. Spine 1995;20(Suppl):126S–37S.

[3] Zdeblick TA. A prospective, randomized study of lumbar fusion. Preliminary results. Spine 1993;18: 983–91.

[4] Johnson RG, Murphy M, Miller M. Fusions and transfusions. An analysis of blood loss and autologous replacement during lumbar fusions. Spine 1989;14:358–62.

[5] Goodnough LT. Risks of blood transfusion. Crit Care Med 2003;31(Suppl):S678–86.

[6] Han PP, Kenny K, Dickman CA. Thoracoscopic approaches to the thoracic spine: experience with 241 surgical procedures. Neurosurgery 2002;51(Suppl): S88.

[7] Isaacs RE, Podichetty VK, Santiago P, et al. Minimally invasive microendoscopy-assisted transforaminal lumbar interbody fusion with instrumentation. J Neurosurg Spine 2005;3:98–105.

[8] Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. A histologic and enzymatic analysis. Spine 1996;21:941–4.

[9] Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. Part 2: histologic and histochemical analyses in humans. Spine 1994;19:2598–602.

[10] Dickson JH, Harrington PR, Erwin WD. Results of reduction and stabilization of the severely fractured thoracic and lumbar spine. J Bone Joint Surg Am 1978;60:799–805.

[11] Magerl FP. Stabilization of the lower thoracic and lumbar spine with external skeletal fixation. Clin Orthop 1984;125–41.

[12] Esses SI, Botsford DJ, Kostuik JP. The role of external spinal skeletal fixation in the assessment of low-back disorders. Spine 1989;14:594–601.

[13] Bednar DA, Raducan V. External spinal skeletal fixation in the management of back pain. Clin Orthop 1996;131–9.

[14] Jeanneret B, Jovanovic M, Magerl F. Percutaneous diagnostic stabilization for low back pain. Correlation with results after fusion operations. Clin Orthop 1994;130–8.

[15] Soini J, Slatis P, Kannisto M, et al. External transpedicular fixation test of the lumbar spine correlates with the outcome of subsequent lumbar fusion. Clin Orthop 1993;89–96.

[16] van der Schaaf DB, van Limbeek J, Pavlov PW. Temporary external transpedicular fixation of the lumbosacral spine. Spine 1999;24:481–4.

[17] Bednar DA. Failure of external spinal skeletal fixation to improve predictability of lumbar arthrodesis. J Bone Joint Surg Am 2001;83:1656–9.

[18] Faraj AA. External fixation in lumbar segmental instability. Acta Orthop Belg 2003;69:9–12.

[19] Faraj AA, Akasha K, Mulholland RC. Temporary external fixation for low back pain: is it worth doing? Eur Spine J 1997;6:187–90.

[20] Heini PF, Gahrich U, Orler R. The external fixator: a tool for evaluation of complex low back pain problems. J Spinal Disord Tech 2004;17:8–14.

[21] Leu H, Hauser R, Schreiber A. Percutaneous lumbar spine fusion. Acta Orthop Scand Suppl 1993;251: 116–9.

[22] Leu HF, Hauser RK. Percutaneous endoscopic lumbar spine fusion. Neurosurg Clin N Am 1996;7: 107–17.

[23] Leu HF, Hauser RK, Schreiber A. Lumbar percutaneous endoscopic interbody fusion. Clin Orthop 1997;58–63.

[24] Leu HF, Schreiber A, Elsig JP, et al. Percutaneous disc surgery at Balgrist since 1979—from discotomy to interbody fusion. Bull Hosp Joint Dis 1996;54:190–7.

[25] Schreiber A, Suezawa Y, Leu H. Does percutaneous nucleotomy with discoscopy replace conventional discectomy? Eight years of experience and results in treatment of herniated lumbar disc. Clin Orthop 1989;35–42.

[26] Foley KT, Gupta SK. Percutaneous pedicle screw fixation of the lumbar spine: preliminary clinical results. J Neurosurg 2002;97:7–12.

[27] Wiesner L, Kothe R, Ruther W. Anatomic evaluation of two different techniques for the percutaneous insertion of pedicle screws in the lumbar spine. Spine 1999;24:1599–603.

[28] Wiesner L, Kothe R, Schulitz KP, et al. Clinical evaluation and computed tomography scan analysis of screw tracts after percutaneous insertion of pedicle screws in the lumbar spine. Spine 2000;25:615–21.

[29] Acosta FL Jr, Thompson TL, Campbell S, et al. Use of intraoperative isocentric C-arm 3D fluoroscopy for sextant percutaneous pedicle screw placement: case report and review of the literature. Spine J 2005;5:339–43.

[30] Holly LT, Foley KT. Three-dimensional fluoroscopy-guided percutaneous thoracolumbar pedicle screw placement. Technical note. J Neurosurg 2003; 99:324–9.

[31] Roedel AL, Zak SM, Fessler RG, et al. Pedicle screw stimulation in minimally invasive spinal instrumentation. Presented at the Thirteenth Annual Meeting of the American Society of Neurophysiological Monitoring. Lake Buena Vista, FL; May 2–8, 2002.

[32] Powers CJ, Podichetty VK, Isaacs RE. Placement of percutaneous pedicle screws without imaging guidance. Neurosurg Focus 2006;20(3):E3.

[33] Stein M, Elliott D, Glen J, et al. Young Investigator Award. Percutaneous facet joint fusion: preliminary experience. J Vasc Interv Radiol 1993;4:69–74.

[34] Jacobs RR, Montesano PX, Jackson RP. Enhancement of lumbar spine fusion by use of translaminar facet joint screws. Spine 1989;14:12–5.

[35] Jang JS, Lee SH. Clinical analysis of percutaneous facet screw fixation after anterior lumbar interbody fusion. J Neurosurg Spine 2005;3:40–6.
[36] Jang JS, Lee SH, Lim SR. Guide device for percutaneous placement of translaminar facet screws after anterior lumbar interbody fusion. Technical note. J Neurosurg 2003;98:100–3.
[37] Shim CS, Lee SH, Jung B, et al. Fluoroscopically assisted percutaneous translaminar facet screw fixation following anterior lumbar interbody fusion: technical report. Spine 2005;30:838–43.
[38] Suk SI, Lee CK, Kim WJ, et al. Adding posterior lumbar interbody fusion to pedicle screw fixation and posterolateral fusion after decompression in spondylolytic spondylolisthesis. Spine 1997;22: 210–9.
[39] Kim SS, Denis F, Lonstein JE, et al. Factors affecting fusion rate in adult spondylolisthesis. Spine 1990;15:979–84.
[40] Wiltse LL, Jackson DW. Treatment of spondylolisthesis and spondylolysis in children. Clin Orthop 1976;92–100.
[41] Flynn JC, Hoque MA. Anterior fusion of the lumbar spine. End-result study with long-term follow-up. J Bone Joint Surg Am 1979;61:1143–50.
[42] Lin PM, Cautilli RA, Joyce MF. Posterior lumbar interbody fusion. Clin Orthop 1983;154–68.
[43] Minamide A, Akamaru T, Yoon ST, et al. Transdiscal L5-S1 screws for the fixation of isthmic spondylolisthesis: a biomechanical evaluation. J Spinal Disord Tech 2003;16:144–9.
[44] MacMillan M, Fessler RG, Gillespy M, et al. Percutaneous lumbosacral fixation and fusion: anatomical study and two-year experience with a new method. Clin Neurosurg 1996;43:423–36.
[45] MacMillan M, Fessler RG, Gillespy M, et al. Percutaneous lumbosacral fixation and fusion: anatomic study and two-year experience with a new method. Neurosurg Clin N Am 1996;7:99–106.
[46] MacMillan M. Computer-guided percutaneous interbody fixation and fusion of the L5–S1 disc: a 2-year prospective study. J Spinal Disord Tech 2005; 18(Suppl):S90–5.
[47] Khoo LT, Palmer S, Laich DT, et al. Minimally invasive percutaneous posterior lumbar interbody fusion. Neurosurgery 2002;51(Suppl):S166–81.
[48] Schwender JD, Holly LT, Rouben DP, et al. Minimally invasive transforaminal lumbar interbody fusion (TLIF): technical feasibility and initial results. J Spinal Disord Tech 2005;18(Suppl):S1–6.
[49] Obenchain TG. Laparoscopic lumbar discectomy: case report. J Laparoendosc Surg 1991;1:145–9.
[50] Mathews HH, Evans MT, Molligan HJ, et al. Laparoscopic discectomy with anterior lumbar interbody fusion. A preliminary review. Spine 1995;20: 1797–802.
[51] Olsen D, McCord D, Law M. Laparoscopic discectomy with anterior interbody fusion of L5-S1. Surg Endosc 1996;10:1158–63.
[52] Mahvi DM, Zdeblick TA. A prospective study of laparoscopic spinal fusion. Technique and operative complications. Ann Surg 1996;224:85–90.
[53] Heniford BT, Matthews BD, Lieberman IH. Laparoscopic lumbar interbody spinal fusion. Surg Clin North Am 2000;80:1487–500.
[54] Wolf O, Meier U. [First experiences using microsurgical techniques for minimally invasive ventral interbody fusion of the lumbar spine (MINI-ALIF).] Z Arztl Fortbild Qualitatssich 1999;93:267–71 [in German].
[55] Landreneau RJ, Hazelrigg SR, Mack MJ, et al. Postoperative pain-related morbidity: video-assisted thoracic surgery versus thoracotomy. Ann Thorac Surg 1993;56:1285–9.
[56] Huntington CF, Murrell WD, Betz RR, et al. Comparison of thoracoscopic and open thoracic discectomy in a live ovine model for anterior spinal fusion. Spine 1998;23:1699–702.
[57] Cunningham BW, Kotani Y, McNulty PS, et al. Video-assisted thoracoscopic surgery versus open thoracotomy for anterior thoracic spinal fusion. A comparative radiographic, biomechanical, and histologic analysis in a sheep model. Spine 1998;23: 1333–40.
[58] Hertlein H, Hartl WH, Dienemann H, et al. Thoracoscopic repair of thoracic spine trauma. Eur Spine J 1995;4:302–7.
[59] Newton PO, Wenger DR, Mubarak SJ, et al. Anterior release and fusion in pediatric spinal deformity. A comparison of early outcome and cost of thoracoscopic and open thoracotomy approaches. Spine 1997;22:1398–406.
[60] Nymberg SM, Crawford AH. Video-assisted thoracoscopic releases of scoliotic anterior spines. AORN J 1996;63:561–2.
[61] Anand N, Regan JJ. Video-assisted thoracoscopic surgery for thoracic disc disease: classification and outcome study of 100 consecutive cases with a 2-year minimum follow-up period. Spine 2002;27: 871–9.
[62] Khoo LT, Beisse R, Potulski M. Thoracoscopic-assisted treatment of thoracic and lumbar fractures: a series of 371 consecutive cases. Neurosurgery 2002; 51(Suppl):S104–17.
[63] Wang MY, Prusmack CJ, Green BA, et al. Minimally invasive lateral mass screws in the treatment of cervical facet dislocations: technical note. Neurosurgery 2003;52:444–7.
[64] Fong S, Duplessis S. Minimally invasive lateral mass plating in the treatment of posterior cervical trauma: surgical technique. J Spinal Disord Tech 2005;18: 224–8.
[65] Riley EH, Lane JM, Urist MR, et al. Bone morphogenetic protein-2: biology and applications. Clin Orthop 1996;39–46.
[66] Alden TD, Pittman DD, Beres EJ, et al. Percutaneous spinal fusion using bone morphogenetic protein-2 gene therapy. J Neurosurg 1999;90:109–14.