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Interbody Fusion and Instrumentation

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Fusion indications in adult degenerative disk disease of the lumbosacral spine include isolated disk resorption, primary and secondary instability, recurrent disk herniation, and pseudarthrosis. Common to these indications are variable proportions of biomechanical insufficiency of the motion segment, instability, deformity, and spinal stenosis. Apart from favorable psychosocial and work related variables, satisfactory outcome is dependent on treatment by a combination of diskectomy, decompression, and deformity correction, in addition to fusion. Isolated intertransverse or interbody fusions show variable fusion rates that are increased by concurrent instrumentation. Persistent pseudarthrosis rates and instrumentation failures have prompted circumferential fusion techniques. Posterior lumbar interbody fusion (PLIF) and segmental pedicle-based plate fixation overcome earlier problems with PLIF by allowing for wide decompression and increased exposure for disk space preparation, minimizing neural injury. Pedicle fixation restores segmental stability and minimizes graft retropulsion. Restoration of anterior column support prolongs instrumentation life, and increases fusion rates irrespective of the number of levels fused. Disk space distraction, with the use of instrumentation as a working tool, permits safer decompression of the intraforaminal zone, a common area of stenosis, and single or multilevel deformity correction to restore coronal, axial, and sagittal alignment and spinal balance. Even though the surgical technique is demanding, fusion rates up to 96% and clinical success up to 86% are achieved.

BIOMECHANICS

Clinical and laboratory studies have defined the load-carrying capacities of the spinal motion segment in compression, shear, and torsion, demonstrating the predominant role of the anterior and middle columns.[18,74]

The biomechanical environment of the degenerated functional spinal unit (FSU) has a direct impact on the success rates of different fusion techniques. The principle consideration is the interplay of compression, shear, and torsional forces.

Posterolateral fusion rates are reported to vary from 44% to 100%.[37,69] While Lee and Langrana[45] and Yang *et al.*[78] have demonstrated satisfactory *in vitro* motion segment resistance to compression and torsional loading, clinical series report increased pseudarthrosis rates with increasing fusion levels, in revision of pseudarthrosis, and in extensive decompressive procedures.[63] In high-grade spondylolisthesis, the posterolateral fusion mass can elongate, with a resultant increase in deformity.[29] In low-grade translational deformities, increased postoperative olisthesis can occur during fusion consolidation.[46]

Concurrent use of instrumentation has been shown to increase fusion rates by increasing rigidity at the fusion site.[35,39,43] Goel *et al.*[24] have demonstrated a 70% decrease in flexion–extension, a 65% decrease in lateral bend, and a 65% decrease in axial motion with bilateral segmental pedicle plate fixation in a cadaver model. Lorenz and co-workers[47] reported 100% fusion for posterolateral fusion with segmental pedicle plate fixation, compared with 58.6% without instrumentation. Laminar-based systems have also been employed to enhance fusion rates with posterolateral grafting.[58,75] Kaneda *et al.*[36] reported a 96.3% fusion rate in degenerative

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spondylolisthesis using combined compression and distraction instrumentation.

Notwithstanding the concern of stress shielding-induced vertebral osteopenia from rigid instrumentation constructs, McAfee *et al.*,[48] in an animal model, have demonstrated a correlation between instrumentation rigidity and the likelihood of successful fusion. In comparing laminar- and pedicle-based instrumentation systems, Gurr *et al.*[26] demonstrated superior axial, torsional, and flexural rigidity with pedicle-based segmental instrumentation systems.

Early clinical series with pedicle-based segmental fixation reported screw fracture rates up to 15% and pseudarthrosis rates of 22%.[32,49,73,76] Improved screw materials and design have decreased this rate; however the morbid biomechanical milieu merits more detailed analysis.

Carson,[11] using a corpectomy model stabilized by pedicle screw instrumentation, demonstrated a sevenfold increase in the bending moment on the upper screws, compared with a model with an intact anterior column. The clinical equivalent of this model is an unstable fracture with acute insufficiency of anterior and middle column load-carrying capacity. Although of a different order of magnitude, decreased anterior and middle column load-carrying capacity of the degenerated motion segment places increased bending moments on pedicle screws. This can result in screw fracture, frequently associated with pseudarthrosis. Although it is not possible to determine the threshold of diminished load-carrying capacity of the degenerated motion segment beyond which screw failure with or without pseudarthrosis would occur, restoration of anterior column support by interbody fusion would decrease the bending moment on the instrumentation and fusion site.

Despite the early reports by Cloward,[14] of 93% fusion rates and 95% clinical success, posterior lumbar interbody fusion (PLIF) has not gained wide acceptance. Attempts to reproduce these results led to reports of graft dislodgement, and neural injury,[82] diminishing the enthusiasm for this procedure.

Anterior lumbar interbody fusion (ALIF),[3,13,21,25,31,33,59,62] appealing because of avoidance of canal exploration and the attendant risks of epidural fibrosis and neural injury, has reported fusion rates that vary from 56% to 91%. Pseudarthrosis rates are related to increasing levels of fusion and prior posterior decompressive surgery.

To address the pseudarthrosis rates of isolated interbody or intertransverse fusions, circumferential or 360 fusion procedures have been described.

O'Brien *et al.*[52] reported a series of 150 patients who had single-stage ALIF and instrumented posterolateral fusion using a laminar-based system. Kozak and O'Brien,[42] in reviewing this clinical series, reported a fusion rate of greater than 90% in one- and two-level procedures, and satisfactory clinical status in approximately 80%. Of particular interest was the rate of clinical success without canal exploration or concurrent decompressive procedures. Selby *et al.*[60] reported a 100% fusion rate with 90% patient satisfaction.

Posterior lumbar interbody fusion and segmental pedicle based plate fixation, with concurrent posterolateral fusion, accomplishes circumferential fusion of the degenerated motion segment through a single approach. Its advantages include: (1) minimizing the morbidity of two surgical approaches; (2) maximizing decompression without the concern of insufficient bone stock to support laminar-based instrumentation; (3) restoring of segmental stability by addressing all three spinal columns; (4) enhancing capabilities for neural decompression, especially in the intraforaminal and extraforaminal zone; and (5) providing the ability to correct single or multiplanar deformity through control of the pedicle "force nucleus."[79] Iatrogenic instability induced by decompressive laminectomy and facetectomy can be addressed by pedicle fixation.

Graft migration with isolated PLIF[82] is eliminated in part, by virtue of the enhanced rigidity afforded by the segmental fixation. Neural injury reported in earlier series was in

part related to limitation of working space while trying to preserve the facet joints.[82] This complication is minimized by preliminary wide decompressive laminectomy and variable facetectomy, to accommodate protective retractors and disk space instrumentation, without undue traction or compression of neural structures.

Brantigan *et al.*[9] have developed a carbon fiber-reinforced cage that surpasses the mechanical resistance of tricortical autograft and ETO allograft bone for interbody grafting. Its hollow structure is filled with morcellized cancellous bone harvested from a small keyhole window in the posterior iliac crest, thereby minimizing long-term morbidity from iliac crest harvesting,[44] and maximizing the fusion rate (Fig. 1). Preliminary results have demonstrated a 100% fusion rate.[7]

INSTABILITY AND DEFORMITY

There is an emerging consensus that fusion be performed along with any concurrent decompressive procedure for instability.[17,28] Degenerative spondylolisthesis serves as a useful model for primary instability of the degenerated motion segment. Feffer *et al.*[20] and Herkowitz and Kurz[30] have reported superior clinical outcomes with fusion compared with decompression alone. Other indications include postlaminectomy instability, and pseudarthrosis.

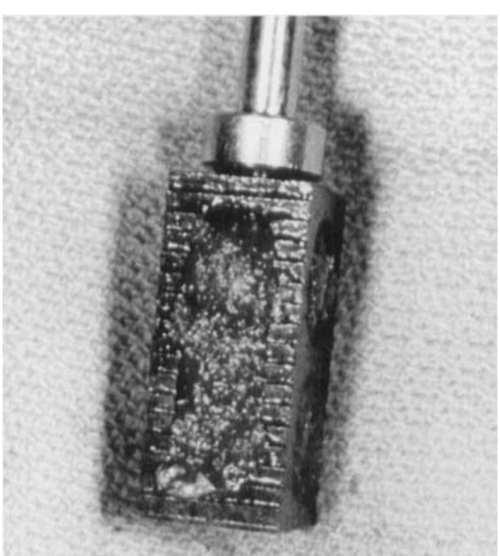


FIG. 1. Carbon cage filled with autologous bone and attached to its inserter. Note superior surface ridges that prevent graft retropulsion.

Controversy exists, however, regarding the advisability of concurrent deformity correction versus fusion *in situ.*[27,53] Fusion *in situ,* in the face of translation, angular, or combination deformities, frequently results in compensatory deformities that develop to reorient the gravity line. Harris and Weinstein[29] described one patient with a high-grade L5–S1 spondylolisthesis who had retrodisplacement at L4–5. Long-term eccentric loading on these adjacent motion segment may lead to degeneration over and above what would have been the case for fusion in a balanced spine. This frequently results in secondary surgery at the compensatory levels, and a relentless surgical ascent up the spine.

Clinically, iatrogenic flat back syndrome is an example of the adverse effects of an unbalanced spine in the sagittal plane secondary to iatrogenic loss of lumbar lordosis.[40,41]

In the short term, deformity correction can optimize the biomechanical environment for instrumentation and fusion. In the case of anterior translational deformities, decreasing the bending moment through restoration of the anteriorly displaced gravity line should minimize instrumentation failure and enhance fusion rates.[34] Correction of rotational instability or deformity can relieve pedicular encroachment on the thecal sac or nerve roots described by Farfan.[19]

Laminar-based distraction systems can "unwind" rotational deformities,[27] but concurrently may accentuate anterior translational deformities or only give partial corrections.[6,57] Intraoperatively, in the absence of deformity, iatrogenic segmental kyphosis can result, especially when multiple-level fusions are undertaken, resulting in a flat back.[40]

Pedicle-based segmental fixation provides control over the vertebrae in the sagittal, coro-

nal, and axial planes.[1,61,64,65,80] However, distraction and posterior reduction of translational deformities through screw manipulation alone, even with appropriate contouring of longitudinal members, is associated with screw pullout, loosening, or pedicle fracture.

Distractive forces applied through the disk space are over a broader surface, and do not have these risks.[14,64,67,68] The unwinding effect on rotational deformities has been described, as has correction of translation deformities. Incremental disk space distraction anterior to the center of rotation of the motion segment, using tapered devices, can restore segmental lordosis,[4] while correcting translational deformities through tensioning or ligamentotaxis of the collapsed annulus fibrosus.

With temporary working plates secured to the pedicle screws, maintaining the disk space distracted, PLIF can be undertaken. This restores anterior column support and maintains deformity correction. Multilevel deformities are treated by repeating the basic single-level technique, one motion segment at a time, by stacking successive sets of working plates.

STENOSIS

Lateral recess stenosis can result from entrapment of the descending nerve roots in the subarticular zone from hypertrophic facet joints. Intraforaminal stenosis has been attributed to impingement of the superior tip of the subluxed superior facet against the exiting nerve root.[38] Both forms of stenosis have been treated by direct (*i.e.*, laminectomy and facetectomy) and indirect (*i.e.*, interlaminar or interbody distraction) methods of decompression.

Ray[56] has reported that the most common form of intraforaminal stenosis is related to bulging posterolateral annulus fibrosus with or without an osteophytic bar. This causes "up–down" stenosis with compression of the exiting nerve root against the undersurface of the pedicle. He states that this type of stenosis is far more common than "front–back" and lateral recess stenosis from enlarged facet joints, and when untreated, is a common cause of failed decompressive procedures.[10] Computed tomography scanning and magnetic resonance imaging detail the intraforaminal zone particularly well, allowing for the distinction between these forms of stenosis.

Facetectomy is indicated for front–back stenosis, or when front–back combines with up–down stenosis, causing "pin hole" stenosis. Facetectomy will not decompress up–down stenosis, yet can compromise segmental stability.

Steffee and co-workers[64,65,68] have described a technique that uses segmental pedicle-based screws and plates as a working tool to aid decompression. By distracting the disk space, foraminal height is increased and variable decompression secondary to subluxed facet joints and bulging posterolateral annulus is accomplished. By securing temporary "working plates" to pedicle screws, the increased available space can be used to more safely decompress persistent bulging annulus fibrosus and vertebral osteophytes anterior and inferior to the exiting nerve root, with less risk of neural injury. Extension of these lesions into the extraforaminal zone can be decompressed concurrently. Posterior lumbar interbody fusion then can be carried out, maintaining the restored disk space and foraminal heights. Segmental pedicle-based plate fixation completes the requirement for segmental rigidity.

PATIENT SELECTION

The increasing appreciation of the influence of psychosocial and work variables on the outcome of surgical intervention obligates the practitioner to assess these variables,[51] if necessary, in a multidisciplinarian environment.[59] Attention should be given to possible extraspinal causes of radicular symptoms such as piriformis syndrome, neuropathy, and contributing variables such as limb length inequality and hip arthritis.

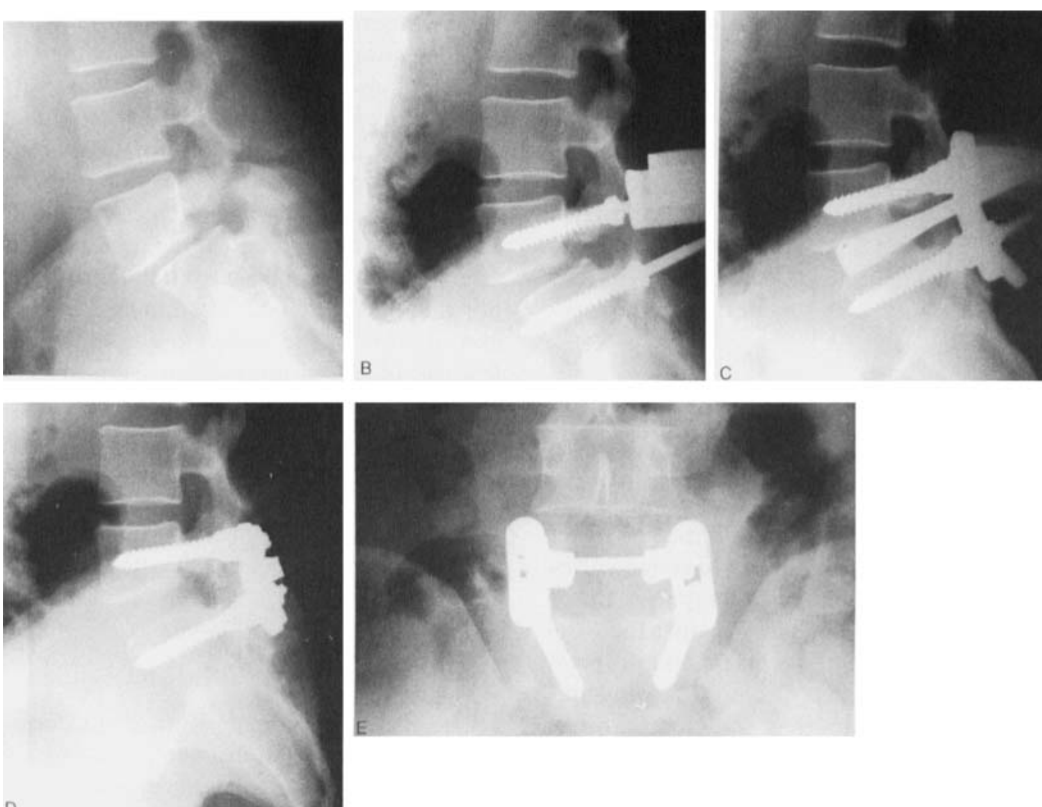
INVESTIGATION

Given the significant incidence of asymptomatic radiographic signs of degenerative disk disease,[22,77] correlative testing (*e.g.*, selective nerve root block) is frequently required to define the relationship of the patient's symptoms and signs to a particular radiographic finding. Notwithstanding the controversy regarding diskography,[50,70] the authors find it to be of value, particularly in assessing levels adjacent to a proposed fusion, to rule out subclinical degenerative disk disease.

Somatosensory-evoked potentials are performed preoperatively.

PREOPERATIVE PLANNING

Pedicle diameters are assessed to assure that they are large enough to accommodate the range of screw diameters. Developmentally narrow or sclerotic pedicles may preclude pedicle-based instrumentation.



FIGS. 2A–2E. (A) Lateral radiograph of 45-year-old man with L5–S1 Grade 2 spondylolytic spondylolisthesis. (B) Pedicle screws have been inserted with the S1 screws penetrating the anterior S1 cortex. (C) Disk height restored by distraction with tapered intradiskal shapers. Translational deformity has been corrected and segmental lordosis maintained. (D) Lateral radiograph at the two-year follow-up examination shows maintenance of reduction and consolidated PLIF graft. (E) Anteroposterior radiograph at the two-year follow-up examination shows consolidated PLIF graft and transverse cross connector.

SURGICAL TECHNIQUE

SINGLE-LEVEL PLIF AND VSP (VARIABLE SCREW PLACEMENT; ACROMED, CLEVELAND, OHIO)[8,64] (FIG. 2)

Appropriate decompressive laminectomy and facetectomy are performed. Care is taken to preserve the superior portion of the superior lamina and spinous process and the attached spinous ligaments, as well as the facet joint capsule of the next motion segment, to minimize adjacent level instability.

Bony decompression is generally to the medial walls of the superior and inferior pedicles. In revision cases, scar tissue can be removed by establishing a normal dural plane beyond the superior limit of the prior decompression. The scar tissue is dissected inferiorly, laterally, and anteriorly, to expose the nerve roots and posterior disk.

Screw insertion is begun on one side, starting proximally and progressing distally.[71] In the presence of segmental deformity, the screws may not initially line up to accommodate a straight VSP plate, which can only be contoured in the sagittal plane (Fig. 3). Disk space distraction generally corrects these deformities and aligns the pedicle screws. Inability to correct these rotation, angular, and lateral displacement deformities precludes use of the VSP plates. A rod system should then be used.

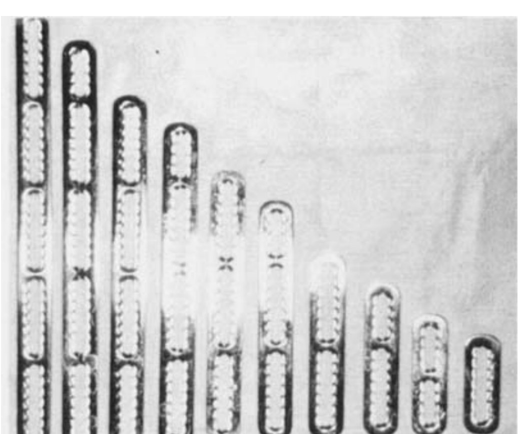


FIG. 3. Variable-length VSP plates in full- and half-slot combinations. Plate nests accommodate the tapered nut on the machine thread portion of the VSP screws.

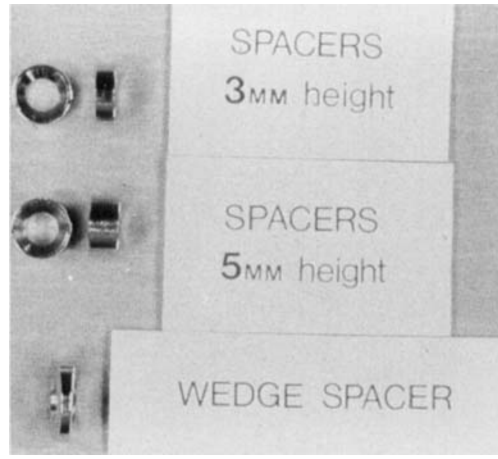


FIG. 4. Cylindrical and oblique spacers.

The S1 screw is the last to be inserted and should be in line with the L5 screw. Anterior sacral cortical purchase in the midline is recommended.

Spacers are applied to the superior portion of the integral nut of all screws (Fig. 4). This provides a better interface for force transmission to the plate, increases available space for intertransverse bone graft, and prevents impingement of the upper portion of the plate against the intact superior facet joint.

Ensuing preparation of the disk space for PLIF requires sufficient release of scar tissue and adhesions to allow mobilization of the thecal sac to the midline from either side. If this is not possible, pedicle fixation and posterolateral fusion should be performed. Staged anterior interbody fusion should be considered.

Starting on one side, an 8-mm intradiskal shaper is inserted parallel to the end plates and rotated a number of times. These devices have side cutting flutes and blunt ends so that disk material and endplate are removed with-

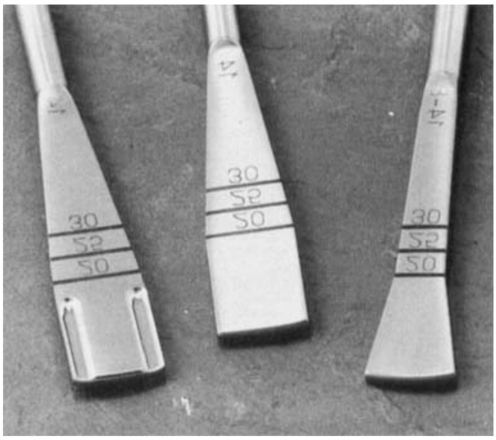


FIG. 5. Intradiskal distractors. Left, side cutting shaper with flutes for removal of disk material and end plates as well as simultaneous distraction. Middle, spreader with smooth sides, used for distraction exclusively. Right, tapered spreader provides for greater anterior disk space distraction and restoration of segmental angulation.

out the risk of penetrating the annulus fibrosus anteriorly (Fig. 5). Alternating sides by 1-mm increments, the shapers result in distraction of the disk space. The end point of distraction is achieved when rotation of the shapers perpendicular to the end plates is accompanied by a palpable sense of tightness between the superior and inferior subchondral bone plates. This indicates a tight annulus fibrosus circumferentially. Through ligamentotaxis, virtually all segmental deformities can be corrected (Fig. 2C).

Use of tapered shapers and spreaders permits greater distraction of the anterior portion of the disk space, and restoration of segmental lordosis (Fig. 2C).

With disk space distraction maintained by the shapers or spreaders on either side of the disk space, temporary contoured working plates are applied to the pedicle screws and tapered nuts are tightened. Radiographs are taken to assess deformity correction and segmental lordosis. Sole reliance on screw manipulation to correct deformities, without preliminary disk space distraction, often results in screw loosening, pullout, or pedicle fracture.

The intradiskal shapers and spreaders are removed. With disk space distraction maintained by the working plates, decompression anterior and inferior to the nerve root is facilitated. This decompression should be extended extraforaminally, based on palpation with a blunt dissector. Ultimately it should be possible to pass a 5- or 6-mm foraminal probe through the foramen, indicating adequate decompression of the nerve roots bilaterally.

The disk space is prepared to receive precut rectangular-shaped allograft bone plugs bilaterally, by use of a broach system available in 11-, 13-, and 15-mm diameters (Fig. 6). Precise fitting of the bone plugs is achieved by cutting them to the same diameters as the broach system. Protective retractors are used. The broach instruments are used in sequence, paying particular attention to the distance marks on the instruments, so as not

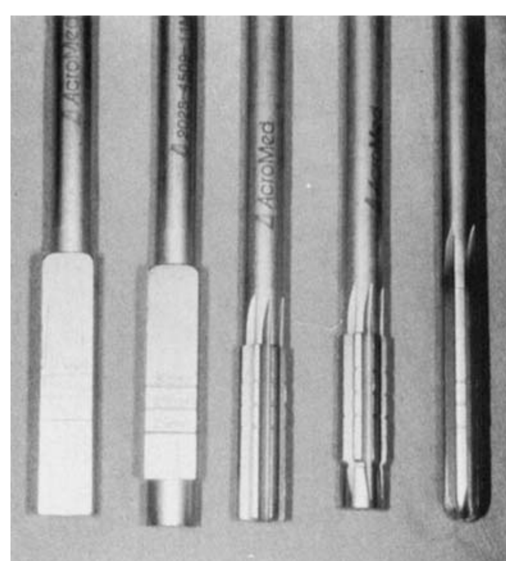


FIG. 6. Posterior lumbar interbody fusion broach instruments used in sequence from right to left. Note depth marks at 20 mm, 25 mm, and 35 mm.

to penetrate the annulus anteriorly with the attendant risk of hemorrhage from the major vessels. Generally 25–30 mm is the average safe depth of disk space preparation. Depth gauge measurement should be used if any doubt exists. Disk material and cartilaginous end plates are removed and the site inspected to assure that bleeding subchondral bone is exposed for optimum graft fusion.

Bilateral grafts are then measured for length, to allow them to be countersunk 3–5 mm below the level of the posterior wall of the vertebrae, minimizing possible neural impingement.

At completion of PLIF graft insertion, the superior tapered nuts are loosened, often accompanied by a visible recoil from the tensioned annulus fibrosus. This recoil enhances graft compression. The tapered nuts are then retightened.

Starting on one side, the working plate is removed, while the contralateral plate maintains the achieved correction. The intertransverse bed is prepared with a burr or gouge and bone graft placed. A final plate of appropriate length is then selected and contoured appropriately into lordosis. The plate is contoured to be perpendicular to the screws and spacers. If this is not possible, oblique spacers are used. Failure to do this can result in a bending moment applied to the screw, causing premature failure. The final contoured plate is applied and tapered nuts are tightened. These steps are repeated for the opposite side (Fig. 2D).

Carson[11] has demonstrated that the bolt-type connection of the VSP system transfers forces and movements directly within the metallic components. Screw-type connections require laminar bone to plate contact to achieve stability. This can lead to a claw hammer effect, resulting in bone crushing and screw pullout.[55]

The open slot design of the VSP plates allows adaptation of the plate to the screw position, independent of its vertical position and sagittal angulation (Fig. 3). Plates of appropriate length are important. Selection of plates that are too short can result in approximation of the screws and iatrogenic foraminal stenosis, screw loosening, or pedicle fracture.

A transverse connector is applied for single-level instrumentation to prevent a parallelogram effect with lateral translation of the construct (Fig. 2E).[2,12,23]

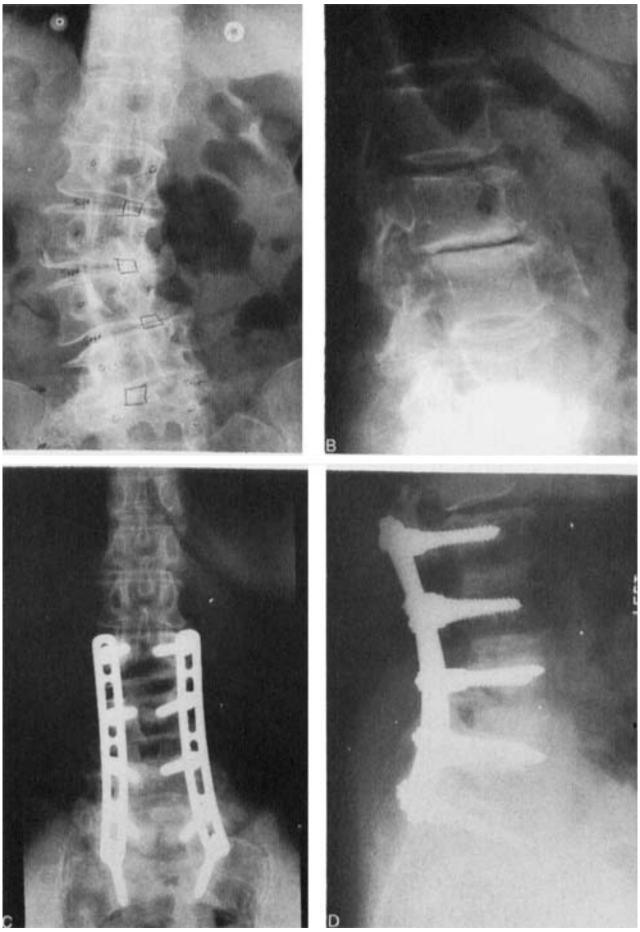
MULTILEVEL TECHNIQUE (FIGS. 7A–7D)

Multilevel deformities[16,64] such as degenerative scoliosis, or multilevel instability after decompressive laminectomies, are treated by repeating the basic single-level technique one motion segment at a time, beginning inferiorly and progressing superiorly. This is accomplished by stacking successive sets of working plates on top of each other by the use of spacers overlapping on the machine thread of the screws. After PLIF is accomplished at each level, the tapered nuts are loosened to permit recoil of the annulus, then are retightened before disk space distraction at the next proximal level is undertaken. This maneuver prevents inadvertent crushing of a PLIF graft from distraction at the disk space above it.

When all levels are completed, working plate removal and intertransverse bed preparation are done as in the single-level technique, followed by application of single-contoured plates bilaterally. (Figs. 7C and 7D). Posterior lumbar interbody fusion is not performed superior to the L2–3 disk to avoid injury to the conus medullaris.

RESULTS

Steffee and Brantigan[66] reviewed 169 patients with three or fewer levels of fusion using the VSP system. For postsurgical failed back syndrome, there was 80.2% satisfactory clinical results and a 91.6% fusion rate. For spondylolisthesis, clinical success was achieved in 86.3% and fusion in 91.5%. For spinal stenosis, there was 78.1% satisfactory results and a fusion rate of 96.8%. The overall fusion rate was 93%, with no signifi-



FIGS. 7A–7D. (A) Anteroposterior radiograph of a 73-year-old woman with degenerative lumbar scoliosis with multilevel rotational and lateral translational deformities. (B) Lateral radiograph shows multilevel degenerative disk disease, rotational deformities, and decrease of lumbar lordosis. (C) Anteroposterior radiograph at the two-year follow-up examination shows L2–S1 PLIF and plate. The deformity has been completely corrected in the coronal plane. (D) Lateral radiograph at the two-year follow-up examination shows restoration of lumbar lordosis, wide foraminal patency, and consolidation of all interbody grafts.

cant difference when comparing the number of levels fused.

Reports of early series of fusion with VSP instrumentation have detailed significant local complication rates including nerve root injury from screw penetration, nerve root injury from manipulation, deep wound infection, and screw fracture.[5,49,54,72,73,76,81] Larger clinical series reflecting increased experience with this demanding surgical technique have reported decreased complication rates. Davne and Myers[15] reported on the complications of VSP segmental plate fixation in 486 patients. The deep wound infection rate was 0.6%, and the overall neural injury rate was 1.1%. In their last 333 procedures, there were no device-related neural injuries.

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