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Introduction: Adult spinal deformity

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Since Galen first coined the terms "scoliosis," "lordosis," and "kyphosis" in the 2nd century A.D., the evaluation and management of spinal deformity has remained a controversial and challenging endeavor. It is no secret that neurosurgeons today are playing an ever larger role in the care of patients with scoliosis and other spinal deformities. The field of adult spinal deformity is experiencing an explosion of interest, and the need for better evidence-based strategies to care for these conditions is intensifying as the incidence and prevalence increase in our society.

This issue of *Neurosurgical Focus* presents several timely reviews of adult spinal deformity as well as original articles with contributions to the field, 17 articles in total. Highlights include the first article, a review from Silva and Lenke on the evaluation and management of adult degenerative scoliosis. Yadla and colleagues present an informative meta-analysis of radiographic and clinical outcomes in over 3000 patients who underwent surgery for adult scoliosis, a discussion of which occurs in a podcast accompanying this issue.

Kuntz and colleagues report on their software for presurgical planning of sagittal imbalance that also allows virtual surgical manipulation of the spine to test putative constructs. The authors are making this "freeware" available to colleagues in the field. Several articles appear regarding the extreme-lateral, transpsoas approach in the treatment of scoliosis, one from the University of Pittsburgh group, one from the University of South Florida group, one from the Cedars-Sinai group, and one from the University of Miami/University of California, San Francisco. The extreme-lateral approach is one of the newest strategies in the management of adult spinal deformity; a frank discussion of the major complications in applying the approach to scoliosis is a welcome addition to the literature.

The minimally invasive theme is furthered in a follow-up study by Anand and colleagues reporting their mid- and long-term outcomes following minimally invasive scoliosis correction, and in Wang and Mummaneni's report of their initial minimally invasive experience. In both instances, the results lend further support to the use of these techniques in selected patients.

The issue also includes a treatment algorithm for Parkinson disease; a description of a novel S2-alar-iliac pelvic screw construct; intraoperative CT-based neuronavigation for placing instrumentation in deformity; a review of posterior spinal osteotomy techniques; unilateral interbody cage placement for coronal plane deformity correction; and 2 articles on cervical deformity.

We hope that you enjoy this issue of *Neurosurgical Focus* devoted to the latest clinical issues in spinal deformity surgery.

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Adult degenerative scoliosis: evaluation and management

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Degenerative scoliosis is a prevalent issue among the aging population. Controversy remains over the role of surgical intervention in patients with this disease. The authors discuss a suitable approach to help guide surgical treatment, including decompression, instrumented posterior spinal fusion, anterior spinal fusion, and osteotomy. These treatment options are based on clinical analysis, radiographic analysis of the mechanical stability of the deformity, given pain generators, and necessary sagittal balance. The high potential complication rates appear to be outweighed by the eventual successful clinical outcomes in patients suitable for operative intervention. This approach has had favorable outcomes and could help resolve the controversy. *(DOI: 10.3171/2010.1.FOCUS09271)*

Key Words • **degenerative scoliosis** • **decompression** • **fusion**

Generally, scoliosis can be divided into 2 types: nonstructural and structural. The nonstructural type includes postural, hysterical, sciatic, inflammatory, and compensatory scoliosis, and some of these can become structural. The key is that the curve has no rotatory component. On the other hand, structural scoliosis includes congenital, neuromuscular, idiopathic, de novo, traumatic, and iatrogenic types among others. Our focus is on structural scoliosis in the adult population—more specifically, de novo ADS.

Adult scoliosis is a spinal deformity in a skeletally mature individual, with a curve measuring > 10° according to the Cobb method.[12] Scoliosis in adults can be further divided into idiopathic and de novo types. Adult idiopathic scoliosis refers to a patient with a history of AIS with increasing symptoms or progression of the deformity into adulthood. In ADS, the curve develops during adulthood due to the degeneration of spinal motion segments.[4,14] Generally, the deformity begins as the intervertebral disc starts to deteriorate, with ensuing degeneration and eventual lack of competency of the posterior elements, especially the facet joints.[25] Thereafter, axial rotation of the involved spinal segments leads to lateral olisthesis, and ligamentous laxity occurs.

Demographics

Adult scoliosis prevalence ranges from 1 to 10%.[17,24,28] This new-onset deformity is observed in more than 30% of elderly patients with no history of spinal abnormalities.[4,27] Degenerative scoliosis is typically diagnosed in patients older than 40 years and without a history of AIS.[27] These are lumbar curves measuring > 10° with associated distal fractional curves. Although these lumbar curves are not associated with structural thoracic curves, compensatory thoracic curves can occur. As in AIS, curve prevalence in ADS is inversely proportional to curve magnitude. The prevalence of 10°, 10–20°, and > 20° curves is 64, 44, and 24%, respectively. These curves have roughly a 1:1 female/male ratio and are rarely present before the age of 40 years, with a mean age of 70.5 years at the time of presentation.[14]

Natural History

Patients with ADS typically present in the 6th decade with symptoms of spinal stenosis. They can also present with a history of back pain that is worsening, radiculopathy, or a combination. Symptoms from spinal stenosis in this group of patients are not relieved by forward posture, as has been noted in those with neurogenic claudication not associated with scoliosis, unless a patient sits with his or her trunk supported by the arms. This distinction is important because the prognosis and treatment of ADS are different from those in patients with degenerative spinal stenosis. Similar to AIS curves, which can progress into adulthood, ADS curves tend to progress 1–6° per year (average 3° per year).[25] Osteopenia seems to play a role in this progression, but this hypothesis has been refuted.[26,27,31] Nonetheless, certain parameters do appear to factor into curve progression.[25] Patient age and sex do not affect curve progression in this category of defomity.[18] Curves with Cobb angles > 30°, an apical rotation greater than Grade II, a lateral olisthesis > 6 mm, and an intercrest line through L-5 appear to have a higher degree of progression.[25]

Abbreviations used in this paper: ADS = adult degenerative scoliosis; AIS = adolescent idiopathic scoliosis; ASF = anterior spinal fusion; TLIF = transforaminal lumbar interbody fusion.

TABLE 1: Lenke-Silva levels of treatment for operative ADS: clinically and radiographically based decision making matrix*

Symptom	Nonop Management	Level I	Level II	Level III	Level IV	Level V	Level VI
neurogenic claudication/ radiculopathy	minimal	+	+	+	+	+	+
back pain	minimal	minimal	+/−	+	+	+	+
ant osteophytes	+	+	−	−	−	−	−
olisthesis	−	−	−	+	+	+	+
coronal Cobb (<30°)	−	−	−	+	+	+	+
lumbar kyphosis	−	−	−	−	+	+	+
global imbalance	−	−	−	−	−	+ (flexible)	+ (stiff/ fused)

* See text *(Six Levels of Operative Treatment: Lenke-Silva Treatment Levels I–VI)* for specific descriptions of levels of treatment.
Abbreviations: ant = anterior; + = present; − = absent.

Evaluation

A thorough history and general physical examination are completed. More specifically, a history of idiopathic scoliosis is elicited to discount the possibility of a degenerative idiopathic deformity. In addition, patients are asked if they have experienced any changes in body habitus, gait, or how their clothes fit. Pain is investigated in terms of its initial onset, location, duration, characteristics, aggravating/relieving factors, and any previous modalities of treatment. A crucial question is whether the pain is purely axial or is also radicular in nature. Axial pain is more likely associated with the degree of radiographic lateral subluxation and sagittal imbalance, and therefore may require inclusion of the lumbar deformity (lateral subluxation) as well as extensive sagittal realignment. With radicular pain, it is important to note whether the location of the pain is the same as that of the concavity. Moreover, it helps to determine if leg pain stems from central or lateral recess (entrance zone, midzone, or exit zone) stenosis or both, as the latter may require greater bone decompression and probably instrumented fusion at the area of decompression. Finally, pain can include both the lower back and the extremities, and the operative approach should be tailored accordingly.

Patients are examined in their underwear and, for females, bra. As patients stand with hips and knees fully extended, they are observed at an appropriate distance and any trunk shift is noted. The relationship of the patient's head to the pelvis is also noted when evaluating overall coronal and sagittal balance. Any shoulder or pelvic asymmetry is documented. Forward and lateral bending maneuvers help assess the curve's rigidity, which is an important factor in terms of prognosis. Leg-length discrepancy and pelvic obliquity are evaluated. When leg-length discrepancy is the likely cause of the deformity, a shoe lift is used to reevaluate the patient to see if the curve can be corrected, although such correction is unlikely in stiffer curves. A neurological examination, including all cranial nerves, motor strength, reflexes, sensory modalities, and gait, is performed. A vascular examination, using Doppler ultrasonography if needed, is performed. Sacroiliac joints and trochanters are palpated and evaluated for any hip or knee contractures, and the degree of flexibility is noted. Finally, cardiopulmonary, bone quality, nutritional, and general health statuses are evaluated to determine if the patient is a suitable operative candidate.

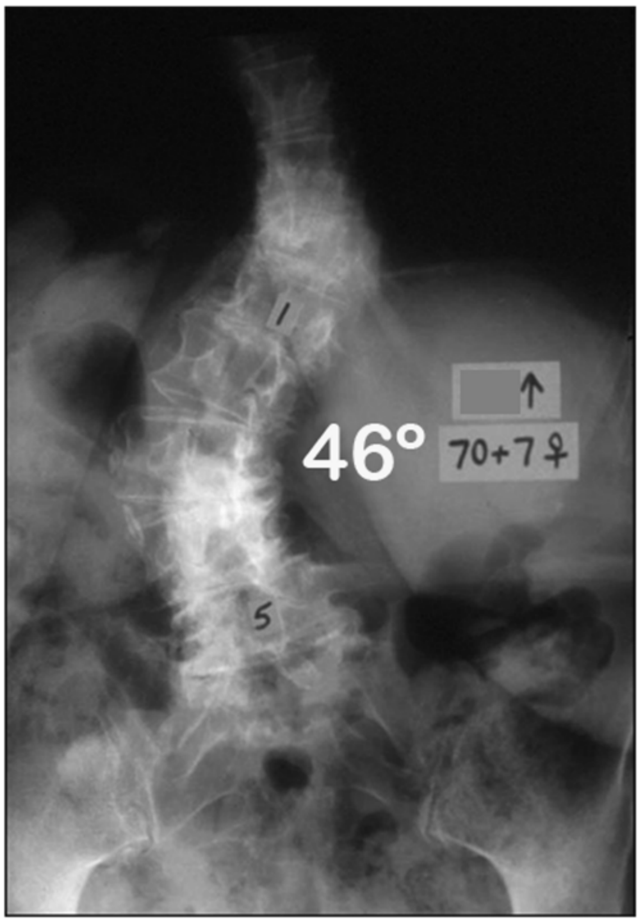

Fig. 1. Radiograph demonstrating features of fractional degenerative lumbar scoliosis.

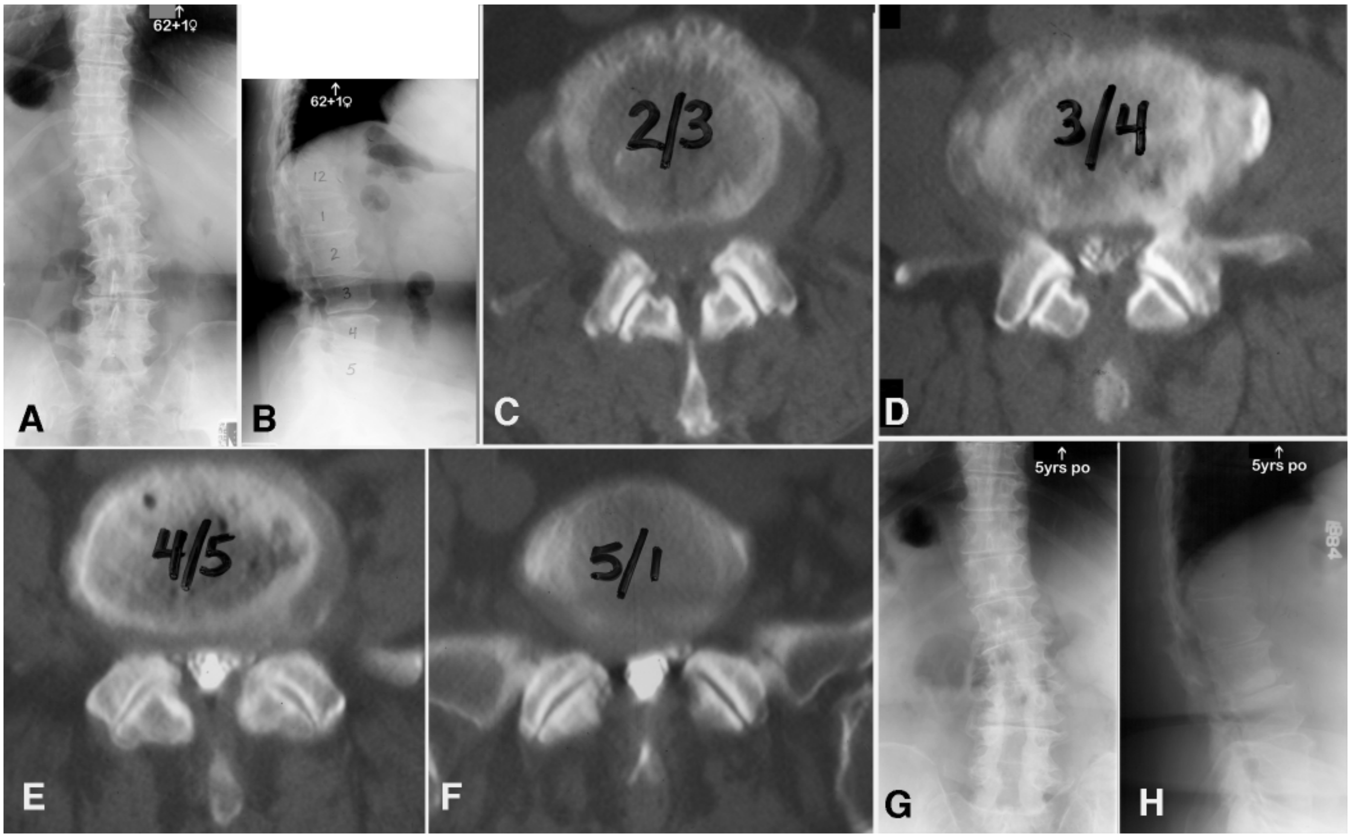

Fig. 2. Lenke-Silva Treatment Level I. **A and B:** Images obtained in a 62-year-old male with neurogenic claudication. **C–F:** Computed tomography myelograms of L2–3, L3–4, L4–5, and L5–S1 showing spinal stenosis. **G and H:** Five-year postoperative radiographs demonstrating maintained alignment from L-2 to the sacrum.

Radiographic Evaluation

Full-length standing anteroposterior and lateral radiographs are obtained.[22] Supine long cassette radiographs—removing gravity from the trunk—are obtained if operative intervention is planned, as these images quickly show the degree of correction spontaneously occurring. These curves typically have an L2–3 apex and are associated with lateral olisthesis, rotatory subluxation, and minimal structural vertebral deformity. They tend to have lumbar hypolordosis and short reciprocating curves without significant scoliosis above the lumbar levels. A fractional curve, L-4 to the sacrum, is also typically evident (Fig. 1). Computed tomography myelograms and MR images are also obtained. The former are particularly useful in this older age group, as some patients cannot undergo MR imaging studies because of cardiac pacemaker placement. Provocative testing helps to elucidate the pain generators, which can include facet/nerve root blocks and discograms. Such testing helps to further determine whether the structural deformity and/or the other pathologies are the primary pain generators, which in turn helps to determine the necessary portions of pathology that should be addressed, would best relieve the patient's symptoms, and produce a successful clinical outcome.[15] Appropriate Cobb angle measurements as well as the parameters of spinopelvic balance are calculated for surgical planning. In this group of patients, sagittal balance is of the utmost importance as it has been correlated with successful clinical outcomes.[16] Additionally, the degree of rotatory subluxation and olisthesis is quantified, and osteophytes are noted.[22] The latter is crucial in terms of radiographic mechanical stability and helps in planning the type of operative intervention required for a given patient.

Treatment

Nonoperative Treatment Options

Nonoperative management is started provided that there are no significant stenotic, radicular, and/or back pain symptoms, including curves < 30° with < 2 mm of subluxation with anterior osteophytes.[13] Patients undergoing such procedures usually have reasonable sagittal and coronal balance. Patients are asked to get involved in a low-impact muscle-strengthening endurance program. The use of nonsteroidal antiinflammatory drugs is instituted as needed, and based on DEXA scan findings, appropriate referral for osteopenia/porosis treatment is requested. Epidural and/or selective nerve root injections are carefully considered based on clinical findings and neuroradiographic studies. Bracing really has no role in this population. It is not likely to halt curve progression, as the mode of progression is usually not spinal growth but transverse instability, and its method of temporary pain relief will be outweighed by deconditioning.[30] Operative intervention is offered to those who do not meet the above criteria, who fail conservative pain management, and/or those whose disease progresses.

Indications for Operative Intervention

Patients whose nonoperative pain management has failed are considered for surgical treatment. Specific treatment options are offered when correlation occurs between clinical and specific radiographic findings, particularly, L-3 and L-4 endplate angulations, lumbar lordosis, thoracolumbar kyphosis, and lateral olisthesis.[28] Lumbar curves with > 30–40° and/or 6 mm of olisthesis on presentation are also considered for operative intervention. Moreover, curve progression as well as progressive neurological deficits are indicators for surgical intervention.[25] Patients whose curves progress more than 10° and/or have an increase in subluxation > 3 mm with increasing clinical symptomatology are offered surgical options.

Six Levels of Operative Treatment: Lenke-Silva Treatment Levels I–VI

Six distinct levels of operative treatment are available for ASD and include the following: I, decompression alone; II, decompression and limited instrumented posterior spinal fusion; III, decompression and lumbar curve instrumented fusion; IV, decompression with anterior and posterior spinal instrumented fusion; V, thoracic instrumentation and fusion extension; and VI, inclusion of osteotomies for specific deformities. A matrix is presented to help sort the patient's symptoms and radiographs into these 6 levels of treatment (Table 1).

Level I treatment consists of decompression alone, which is usually suitable for patients with neurogenic claudication due to central stenosis and requiring a limited decompression. Radiographically, anterior osteophytes should be present with no more than 2 mm of subluxation and reasonable sagittal/coronal balance. Additionally, there should be minimal or no back pain and/or deformity complaints, and the curve should be < 30° without thoracic hyperkyphosis and/or imbalance (Fig. 2). However, decompression alone for stenosis with associated scoliosis can lead to deformity progression and worsening of symptoms.

TABLE 2: Patient demographics comparing Lenke-Silva Treatment Level I with Level II*

Characteristic	Treatment Level I	Treatment Level II	p Value
age at surgery (yrs)	75.0 ± 6	66.3 ± 7.6	0.01
average follow-up (yrs)	4.6 ± 2.7	4.6 ± 2.4	0.39
preop curve magnitude (°)	16.0 ± 6	22.0 ± 8	0.23
postop curve change (°)	3.0 ± 4	1.0 ± 8	0.5

* Values are presented as mean ± SD unless otherwise indicated.

Level II treatment involves adding instrumentation limited to the area of the decompression in patients with the above symptoms (requiring extensive decompression) and curves < 30°, more than 2 mm of subluxation, and no anterior osteophytes in the area of decompression. Again, there should be no back pain/deformity symptoms or thoracic hyperkyphosis in a relatively well-balanced patient (Fig. 3). In a series of 55 consecutive patients with ADS treated using decompression alone (Level I, 16 patients) versus decompression with limited instrumented fusion (Level II, 39 patients), the Level I patients were older and had smaller curves (Table 2). At a minimum 2-year follow-up, 62% of Level I versus 82% of Level II patients

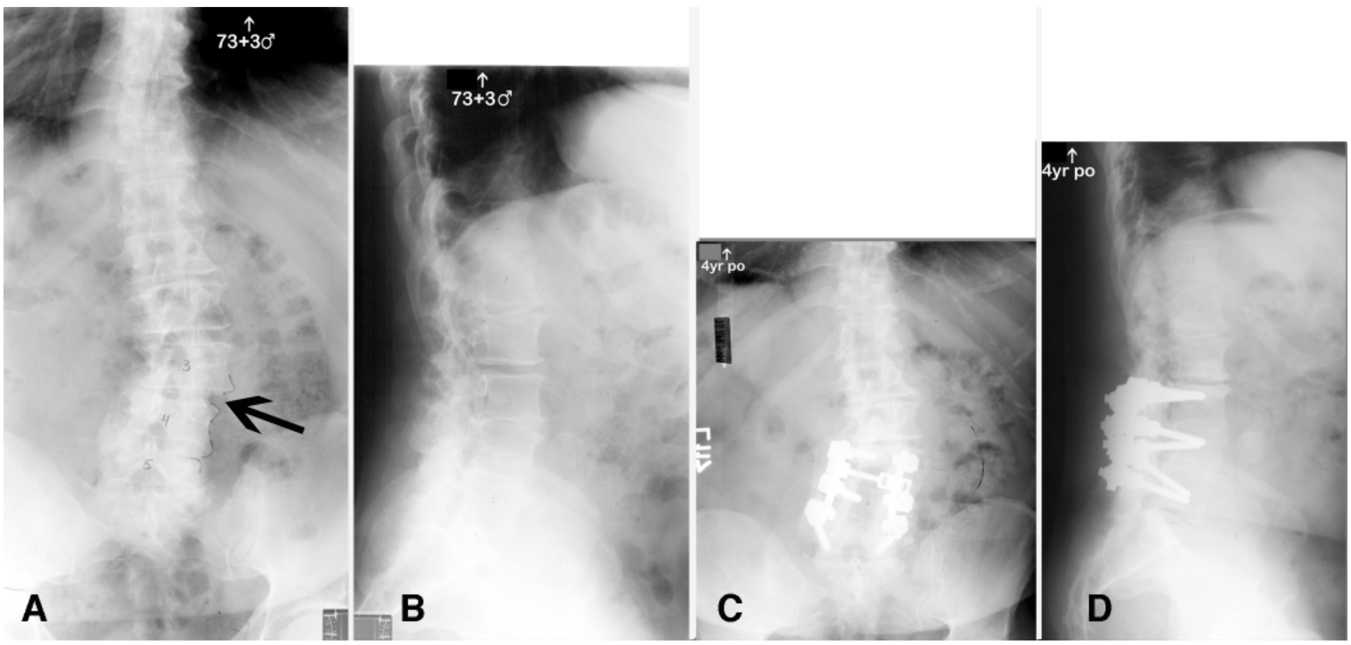

Fig. 3. Lenke-Silva Treatment Level II. **A and B:** Radiographs obtained in a 73-year-old male, showing spinal stenosis from L-3 to L-5 and a rotary subluxation at L3–4. He was treated with decompression and a posterior spinal fusion from L-3 to L-5. **C and D:** At 4 years postoperatively, he had a solid fusion from L-3 to L-5 with slight disc degeneration at L2–3.

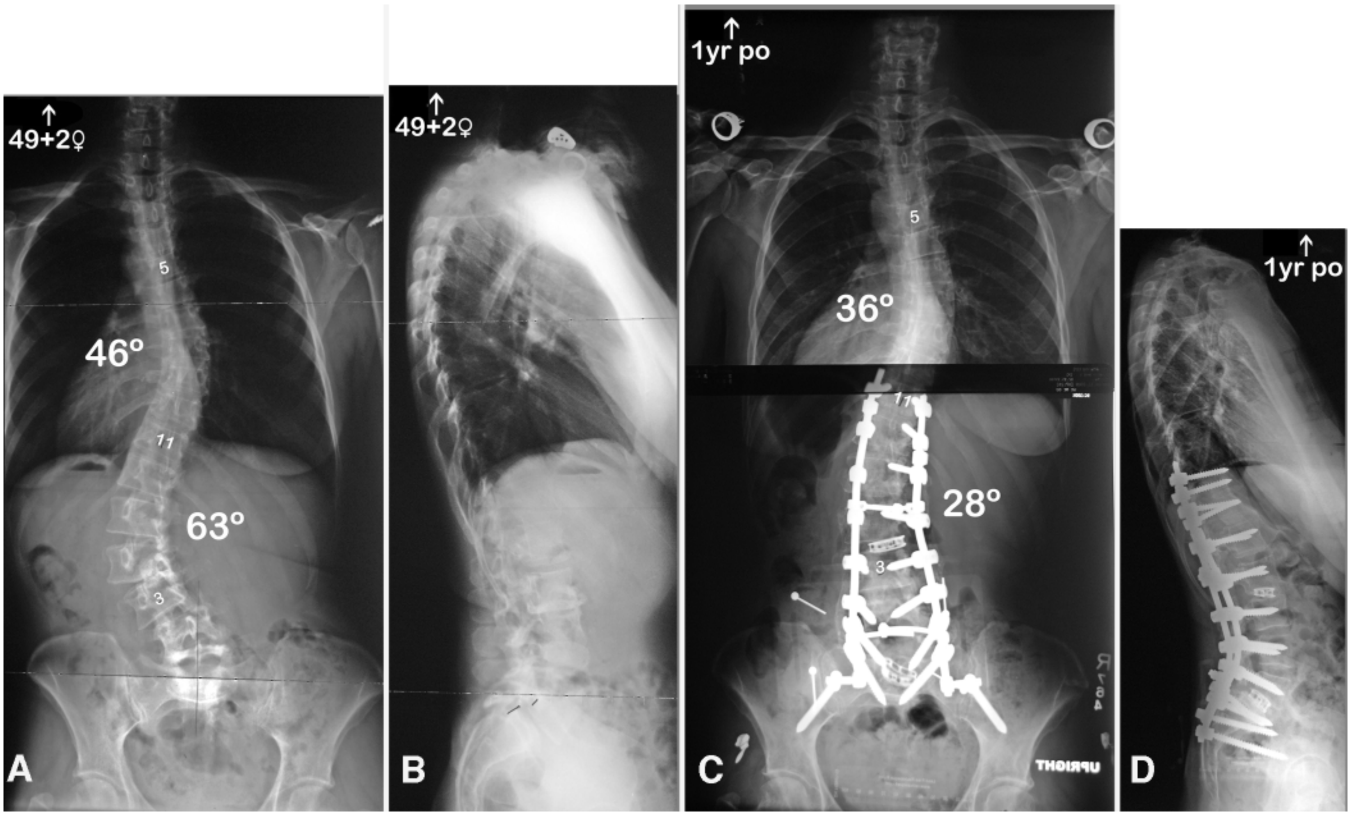

Fig. 4. Lenke-Silva Treatment Level III. **A–D:** Images obtained in a 49-year-old female with degenerative lumbar scoliosis and associated back and leg pain. She underwent a T-11 to the sacrum posterior spinal fusion with TLIFs at L2–3 and L5–S1.

reported a good–excellent result ($p < 0.05$). By 5 years of follow-up, 12 of the 16 Level I patients had recurrent stenosis, whereas 14 of the 39 Level II patients had adjacent level stenosis; the stenosis rate was greater in the Level I than in the Level II patients ($p = 0.008$) (Cheh G, Lenke LG, Bridwell KH, et al., presented at the Scoliosis Research Society Annual Meeting, 2006).

For Level III treatment, the entire lumbar curve in addition to the necessary decompressions is included in the instrumented fusion when symptoms of primary back pain are associated with the spinal deformity. Here, the clinical correlation of pain with the location of the curve becomes very important in terms of further selecting the appropriate operative treatment. Typically, these curves are > 45°, have > 2 mm of subluxation, and lack anterior osteophytes in the operative region, although there is reasonable coronal and sagittal balance (Fig. 4). Anterior spinal fusion via a TLIF approach can be an important adjunct at the lower ends of the construct when fusing to the lumbosacral junction.

Level IV treatment consists of anterior and posterior fusion of the lumbar spine. Anterior spinal fusion has played a significant role in correcting lumbar hypokyphosis and imbalance. In addition, it adds indirect decompression via foraminal distraction. It helps decrease pseudarthrosis, especially in smokers, patients with diabetes, and osteopenic patients. In the latter group, it also helps prevent posterior instrumentation failure by load sharing, especially in obese patients. Note, however, that there is increased mobility from a formal anterior approach in older patients. Hence, an ASF is selectively recommended for patients with severe stenosis, back pain, and deformity symptoms with mild sagittal imbalance. There should be no anterior osteophytes or thoracic hyperkyphosis and > 2 mm of subluxation (Fig. 5).

Level V treatment involves extending the fusion and instrumentation into the thoracic region in patients satisfying the aforementioned criteria and having thoracic hyperkyphosis and/or thoracic decompensation. In addition, those with global and/or coronal imbalance become candidates for thoracic extension of their fusion/instrumentation (Fig. 6). Very often, osteotomies can be particularly useful in this subgroup of patients.

Osteotomy Choices: Treatment Level VI

Patients whose deformity demonstrates > 30% correction on bending radiographs do not require osteotomies, as they are considered flexible. Curves that are corrected < 30% are considered stiff deformities and might require osteotomies. However, many deformities are rigid, and patients are not clinically balanced or they have already undergone fusion. It is this group of patients that may also require osteotomies, because the deformities are stuck. Osteotomies can aid not only in clinically rebalancing the patient, but also in decreasing the load placed on the instrumentation at the metal-bone interface. Rebalancing the spine is of the utmost clinical importance as a significant link has been found between it and outcomes.[1] The

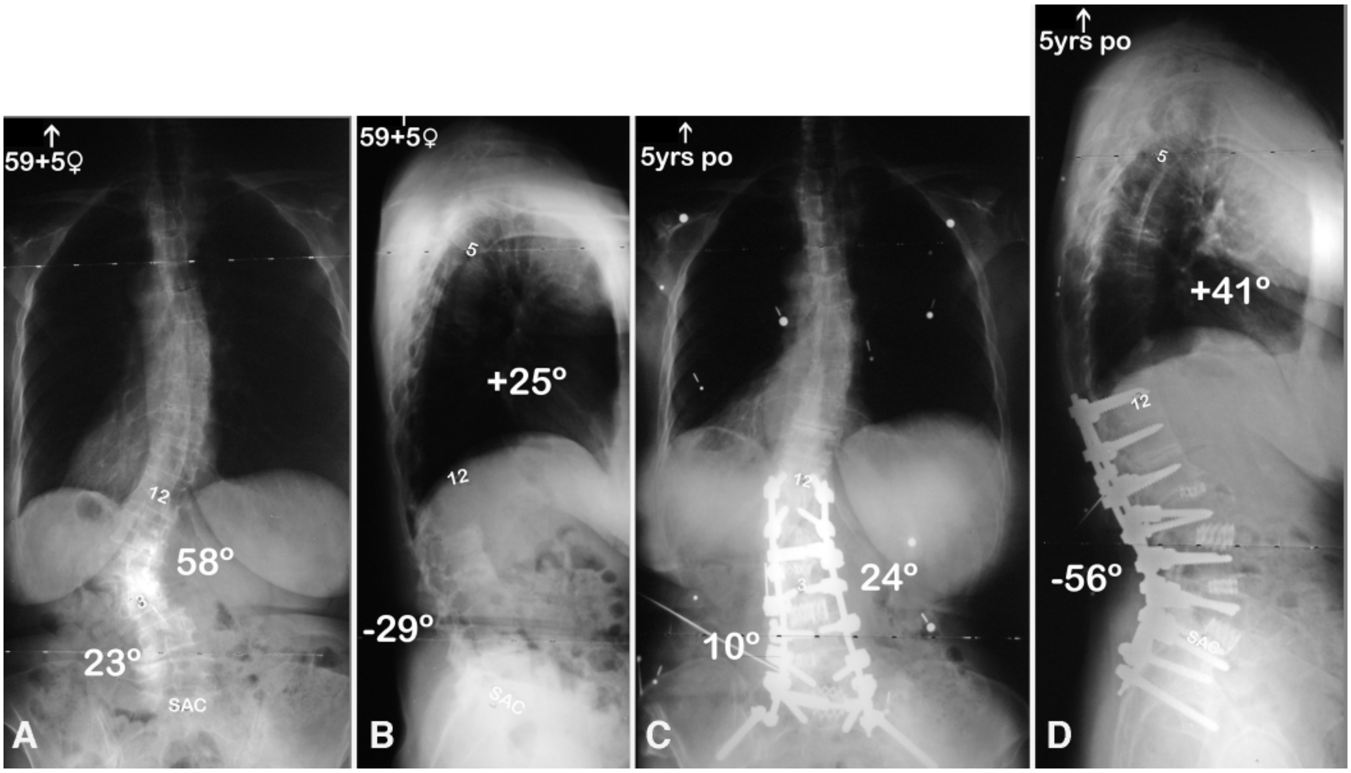

Fig. 5. Lenke-Silva Treatment Level IV. **A–D:** Images obtained 59-year-old female with a 58° ADS lumbar curve who underwent a same-day L-2 to the sacrum ASF and a T-12 to the sacrum posterior spinal fusion for correction of her deformity.

intelligent use of osteotomies begins with the judicious evaluation of both clinical and radiographic coronal and sagittal balance and is the main component of Level VI treatment. Cases of sagittal imbalance can be classified into Type I or II.[7]

Type I sagittal imbalance refers to patients who are globally balanced but in whom a segmental portion of the spine is flat or kyphotic. In contrast, Type II sagittal imbalance refers to global and segmental imbalance. When sagittal and coronal imbalance coexist, they can also be classified into Type A or B.[7] With Type A imbalance, the patient's shoulders and pelvis are tilted in opposite directions. Conversely, with Type B imbalance, both the shoulders and the pelvis tilt in the same direction. Once

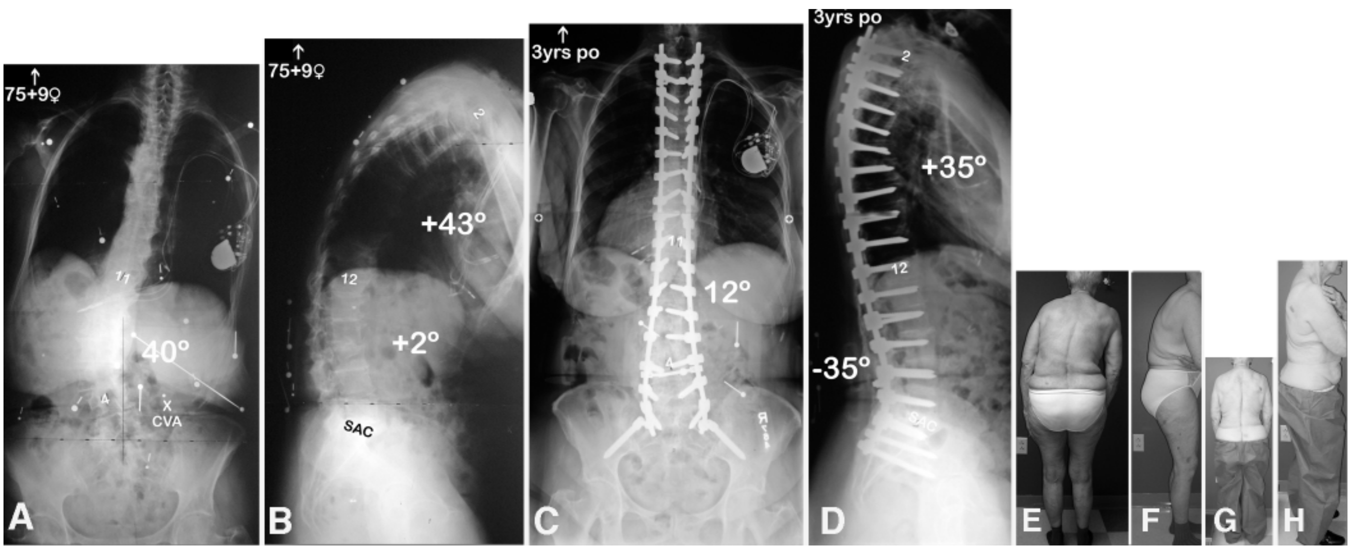

Fig. 6. Lenke-Silva Treatment Level V. **A and B:** Images obtained in a 75-year-old female with degenerative lumbar scoliosis and associated coronal and sagittal imbalance. She underwent a posterior spinal fusion from T-2 to the sacrum and TLIFs at L4–5 and L5–S1. **C and D:** At 3 years postoperatively, her alignment was nicely restored and maintained. **E–H:** Preoperative and postoperative clinical photos demonstrating restored coronal and sagittal alignment/balance.

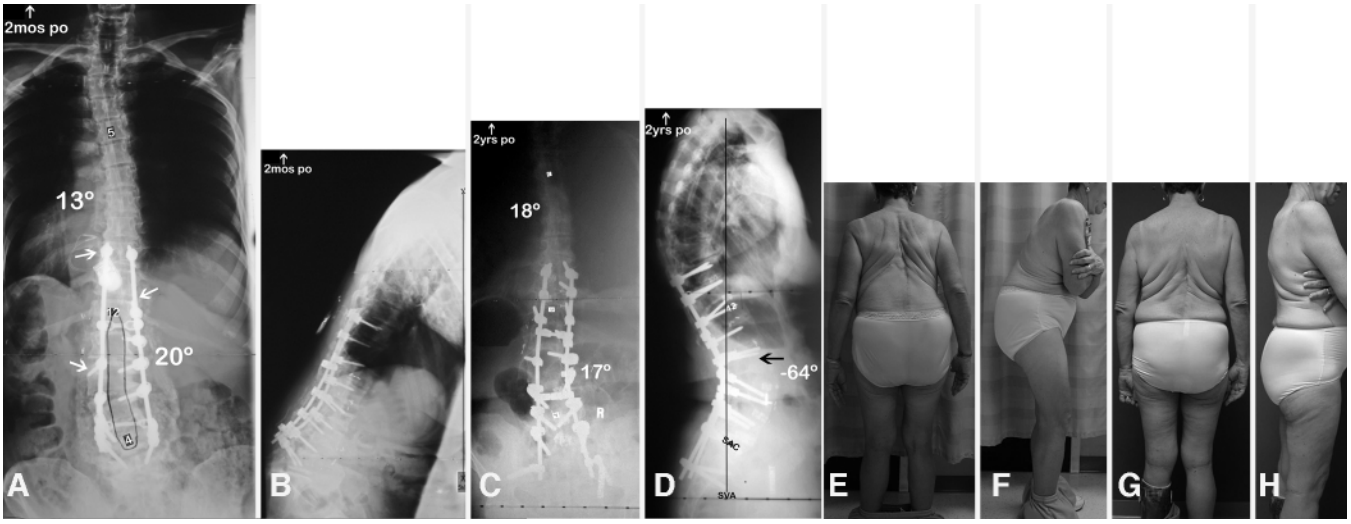

Fig. 7. Lenke-Silva Treatment Level VI. **A and B:** Images obtained in a 63-year-old female with lumbar degenerative scoliosis. Two months after surgery, which was performed elsewhere, early L-5 screw pullout developed as did subsequent severe sagittal imbalance. The patient then underwent a revision posterior spinal fusion, an L-3 pedicle subtraction osteotomy, and an ASF. **C and D:** At 3 years postoperatively, images revealed corrected sagittal balance. **E–H:** Preoperative and postoperative clinical photos demonstrating excellent coronal and sagittal balance.

the latter situation is recognized in the rigid spine, then alternative options of bone resection techniques can be determined.

With Type I sagittal imbalance, Smith-Petersen osteotomies are typically indicated, provided that mobility at the disc space is adequate to permit extension.[29] If the disc space is not sufficiently mobile but bone stock is adequate, then anterior releases with a concomitant morselized graft can be used. If bone stock is inadequate, then anterior structural grafts are used. The latter can also be used for Type II imbalances when Smith-Petersen osteotomies will permit the weight-bearing line to fall within 3 cm of the sacrum (Fig. 7). Another alternative for Type II imbalance is a pedicle subtraction osteotomy, which is useful when bone stock is poor as well as in smokers and diabetic patients because bone-on-bone contact occurs at the time of osteotomy closure, with high fusion rates of the vertebral body. Typically, it affords ~ 30° of lordotic correction; hence, it is often suitable for global imbalance correction without the need for anterior releases or structural grafting.[12] Anterior support may be necessary when fusing to the sacrum, but with current techniques, this can easily be achieved via a posterior-only approach.[19] The precise amount of bone resection to achieve a balanced spine is readily calculated using simple trigonometric calculations.[23] Asymmetrical pedicle subtraction osteotomies are often useful in correcting Type A biplanar deformities. The more radical vertebral column resection technique is often necessary for the rare Type B deformities.[6,21]

Fusion Levels

Proximal fusion levels should start at a neutral and stable vertebra, as defined by the center sacral vertical line.[8,9,20] The fusion should never stop at a rotatory subluxation. Furthermore, the thoracic physiological apex must be avoided.[5] Hence, the fusion should stop well below T-10 or well above T5–6. Similarly, distal fusion levels should begin at a neutral and stable vertebra and should never end at a rotatory subluxation. One could end the fusion at L-5; however, it must be extended to the sacrum if there is an oblique take-off of L-5 on the sacrum—typical with fractional curves > 15°—advanced degeneration of the L-5/S-1 intervertebral disc, L5–S1 spondylolysis, or previous decompression at this segment. Additionally, fusion at T-12 and above should be considered for extension to the ilium/S-1. Again, fractional curves > 15° must be included in the distal fusion to achieve balance.

Complications

Among spinal deformity surgeries, adult deformity corrective procedures carry a high complication rate.[3,10,32] Often this group of patients has multiple comorbidities, and the operations are more involved to achieve appropriate balance and proper load sharing on the instrumentation, the latter being particularly important in osteopenic patients. Such complications include infections, CSF leaks (especially among revision cases), implant failures, junctional kyphosis, adjacent segment degeneration, and pseudarthrosis. Systemic complications include myocardial infarction, pneumonia, ileus, urinary tract infections, deep venous thrombosis, and superior mesentery artery syndrome. Blindness is a particularly ominous but an exceedingly rare complication. Hence, even when the appropriate techniques and postoperative care are undertaken, complications can still be somewhat high; however, the clinical outcomes appear to support such risks in appropriately selected patients.[2] A comparative chart of the most helpful references for ADS evaluation and treatment is featured in Table 3.

Conclusions

Demographically and clinically, ADS is a very im-

TABLE 3: Recommended references for ADS demographics, evaluation, and treatment*

Authors & Year	No. of Patients	Study Design	Conclusion
demographics			
Benner & Ehni, 1979	14	retrospective, case report	after decompressive procedures for degenerative scoliosis, patients w/ continued back pain & possible mechanical instability should undergo augmentation w/ instrumented fusion
Grubb et al., 1988	21	review	patients w/de novo scoliosis typically present in the 6th decade of life; progression is likely due to degenerative changes, not necessarily bone demineralization
Kobayashi et al., 2006	60	prospective, community-based cohort	de novo scoliosis is becoming one of the most prevalent findings in the aging spine; vertebral index, disc index, and lateral osteophyte difference: the latter 2, and not the former, were found to be independent predictors of de novo scoliosis
Ploumis et al., 2007	NA	review	prevalence of degenerative scoliosis in aging population is increasing; the goal is the least intervention that will provide pain relief & improvement in functional lifestyle
nonoperative treatment			
van Dam, 1988	NA	instructional	this patient population presents surgical challenge; complaints of pain must be carefully investigated; the high complication rate requires careful preop evaluation & surgical skill; spinal instrumentation is a very important adjunct
Everett & Patel, 2007	NA†	review	although conservative care in general may be useful, evidence supporting this hypothesis is lacking
natural history/treatment			
Schwab et al., 2002	95	prospective	radiographic criteria should be developed to guide treatment of this patient population; olisthesis, L-3 and L-4 endplate obliquity, lumbar lordosis, & thoracolumbar kyphosis appear to correlate w/ pain development
Korovessis et al., 1994	91	retrospective, case report	lat spondylolisthesis of the apical vertebra, Harrington factor, & disc index were related to scoliosis progression
Pritchett & Bortel, 1993	200	retrospective, case report	relationship of L-5 to the intercrestal line, Cobb angle, & degree of apical rotation serve as valuable progression markers
radiographic evaluation			
Cobb, 1948	NA	instructional	gold standard & cornerstone of radiographic evaluation of patients w/ deformity
Bernhardt & Bridwell, 1989	102	retrospective	wide range of normal sagittal alignment, permitting more objective evaluation of hypokyphosis & lordosis often seen in scoliosis
O'Brien et al., 2004	NA	instructional	excellent overall guide for evaluation of pertinent radiographic parameter used in evaluation of patients w/ deformity
osteotomies			
Ahn et al., 2002	83	prospective, clinical trial	significant association is found btwn outcomes & radiographic correction; radiographic parameters should be goal of spinal osteotomies
Bradford & Tribus, 1997	24	retrospective	fixed, decompensated spinal deformity may be safely corrected via vertebral column resection, w/ transient complication not outweighing the benefits
Bridwell et al., 2004	102	retrospective	in patients w/ fixed imbalance, pedicle subtraction osteotomy is an important adjunct; however, comorbidities, pseudarthrosis at the thoracic spine, & breakdown at caudal fusion end lead to worse clinical outcomes
Lenke et al., 2009	35	retrospective review of prospectively accrued patient cohort	vertebral column resection is challenging & safe technique that permits a posterior-only approach of severe spinal deformities; motor evoked potential recording is a mandatory monitoring modality
Ondra et al., 2006	15	retrospective comparative study	simple mathematic equations permit reliable determination of the degree of pedicle subtraction; osteotomy needed for correction of sagittal imbalance
Silva et al., 2008	NA†	instructional, book chapter	overall review of generally used posterior-only osteotomies in deformity treatment

(continued)

TABLE 3: Recommended references for ADS demographics, evaluation, and treatment *(continued)**

Authors & Year	No. of Patients	Study Design	Conclusion
fusion levels			
Lenke & Bridwell, 1991	95	retrospective	careful curve analysis, including objective evaluation of curve parameters, is essential to prevent postop decompensation; standing anteroposterior radiographs important
Bridwell & Lenke, 1994	6‡	instructional/review, book chapter	careful attention should be paid when placing instrumentation at critical vertebrae btwn deformity curves; this will help to avoid decompensation; certain parameter at L-3 can help in deciding to end instrumentation at this level, saving fusion levels
Bridwell et al., 2004	7‡	data review	excellent review of overall curve analysis & decision making for choosing instrumentation & fusion levels in scoliosis/deformity surgery

* NA = not applicable.
† Total of 5225 articles.
‡ Illustrative cases.

portant entity to the deformity surgeon. An appropriate history and workup guide treatment, differentiating the therapy for stenosis from that for a deformity. Six different levels of treatment (Lenke-Silva Treatment Levels I–VI) of increasing complexity are available to the surgeon. More specifically, these levels of treatment help to decide when to address the stenosis alone and when to include the deformity. Viable options based on clinical and radiographic stability as well as balance and revision status include nonoperative management, decompression, instrumented posterior spinal fusion, ASF, and osteotomy. Restoring lumbar lordosis and sagittal balance take precedence over scoliosis correction. Although higher complication rates are expected, a beneficial outcome in properly selected patients is also anticipated.

Disclosure

Dr. Lenke was a consultant for Medtronic until January 2009, and is a patent holder with Medtronic.

Author contributions to the study and manuscript preparation include the following. Conception and design: FE Silva. Critically revising the article: LG Lenke. Reviewed final version of the manuscript and approved it for submission: LG Lenke. Administrative/technical/material support: LG Lenke.

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Virtual preoperative measurement and surgical manipulation of sagittal spinal alignment using a novel research and educational software program

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Understanding regional as well as global spinal alignment is increasingly recognized as important for the spine surgeon. A novel software program for virtual preoperative measurement and surgical manipulation of sagittal spinal alignment was developed to provide a research and educational tool for spine surgeons. This first-generation software program provides tools to measure sagittal spinal alignment from the occiput to the pelvis, and to allow for virtual surgical manipulation of sagittal spinal alignment. The software was developed in conjunction with Clifton Labs, Inc.

Photographs and radiographs were imported into the software program, and a 2D virtual spine was constructed from the images. The software then measured regional and global sagittal spinal alignment from the virtual spine construct, showing the user how to perform the measurements. After measuring alignment, the program allowed for virtual surgical manipulation, simulating surgical procedures such as interbody fusion, facet osteotomy, pedicle subtraction osteotomy, and reduction of spondylolisthesis, as well as allowing for rotation of the pelvis on the hip axis. Following virtual manipulation, the program remeasured regional and global sagittal spinal alignment.

Computer software can be used to measure and manipulate sagittal spinal alignment virtually, providing a new research and educational tool. In the future, more comprehensive programs may allow for measurement and interaction in the coronal, axial, and sagittal planes. *(DOI: 10.3171/2009.12.FOCUS09283)*

Key Words • **virtual measurement** • **computer software** • **spinal alignment** • **spinal deformity**

Increasing emphasis is being placed on understanding regional as well as global sagittal spinal alignment. Sagittal spinal alignment is becoming recognized as an important predictor of patient outcome after spine surgery.[1–3,6,9] A new educational and research software program was developed for virtual sagittal modeling and manipulation of the spine. The objective was to provide a tool that would aid in understanding measurement techniques and the effects of surgical manipulation on alignment. The system features an easy-to-use interface, including a canvas for viewing images and virtual spine models, a measurement window showing automatically calculated angles and displacements with their relationship to those calculated from the asymptomatic population, and a toolbox consisting of 4 possible virtual surgical adjustments that may be applied to the spine. As each adjustment is made, the effect on regional and global spinal alignment is immediately depicted by a graphic representation of the adjusted spine. This software system may be useful as a research and educational tool for spine surgeons.

Methods

The simulation software was developed as a graphic Windows desktop application suitable for use directly by surgeons. Building on high-level development frameworks such as .NET[7] and Spring.NET[8] allowed for a greater focus on solving domain-related issues, and less time was needed for solving low-level implementation details. To allow for maximum flexibility over the course of the project while maintaining high confidence in the validity of the domain model, all software development followed an iterative and test-driven methodology.

Because the software is user oriented, development began with a nonfunctional visual prototype used to identify the major modes of user interaction. Development

Abbreviations used in this paper: CBVA = chin-brow to vertical angle; HA = hip axis; PT = pelvic tilt; SVA = sagittal vertical axis.

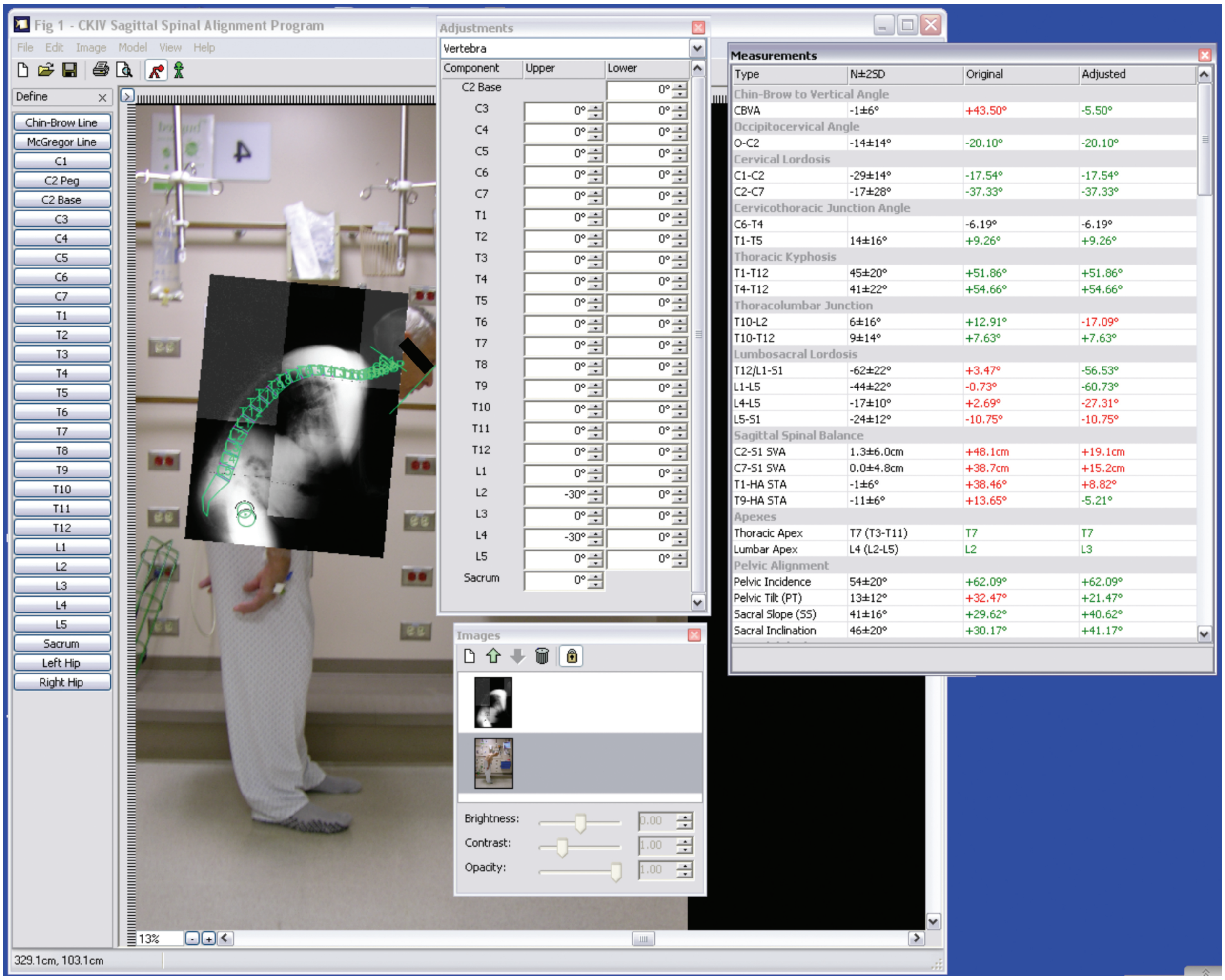

Fig. 1. Computer screen capture. The software interface contains a central canvas where imported images and the virtual spine model are displayed. The model definition window is to the left of the canvas. The measurements, images, and adjustments windows are shown to the right. STA = sagittal tilt angle.

proceeded in sprints of roughly 1 month, each followed by hands-on user acceptance testing. This iterative development model was very powerful, enabling the surgeons and developers to make significant changes and additions to the software requirements midproject.

Much of the development effort was dedicated to capturing a computational model of sagittal spinal manipulation that was both conceptually simple and powerful enough to express a wide range of 2D spinal adjustments. The final domain model consists of 4 major components: 1) a vector representation of each vertebra of the spine prior to adjustment; 2) a series of adjustments representing standard real-world surgical procedures and modeled as mathematical transformations of the vector spine model; 3) a vector representation of each vertebra of the spine following adjustment, automatically calculated by applying adjustments to the original spine model; and 4) a series of standard measurements against both spine models.

As the user makes changes to the inputs of any of the components of the model, the entire model updates in real time, with visual feedback. Consequently, minimal user effort is required to experiment with different adjustment options. The model does not require complete information, enabling adjustments and measurements based on the available data, permitting the user to focus on an arbitrary subset of vertebrae or adjustments. Last, the system has "undo" and "reset" (undo all adjustments) options to facilitate virtual surgery explorations. This first-generation software program is available to the public free of charge.

The virtual modeling and virtual adjustment procedure consists of the following workflow: 1) clinical and radiographic images are imported into the software display; 2) a virtual spine model is constructed using the images as a guide; 3) inspection and analysis of this original spine model is performed; 4) virtual adjustments are performed; and 5) the adjusted spine model is reanalyzed.

The interface consists of a central canvas for displaying images (Fig. 1). To construct the original (preoperative) spine model, the user imports a clinical photograph and lateral radiograph into the canvas. The software supports a variety of image types, including DICOM, gif, jpeg, bitmap, png, and tiff. The radiograph is overlaid

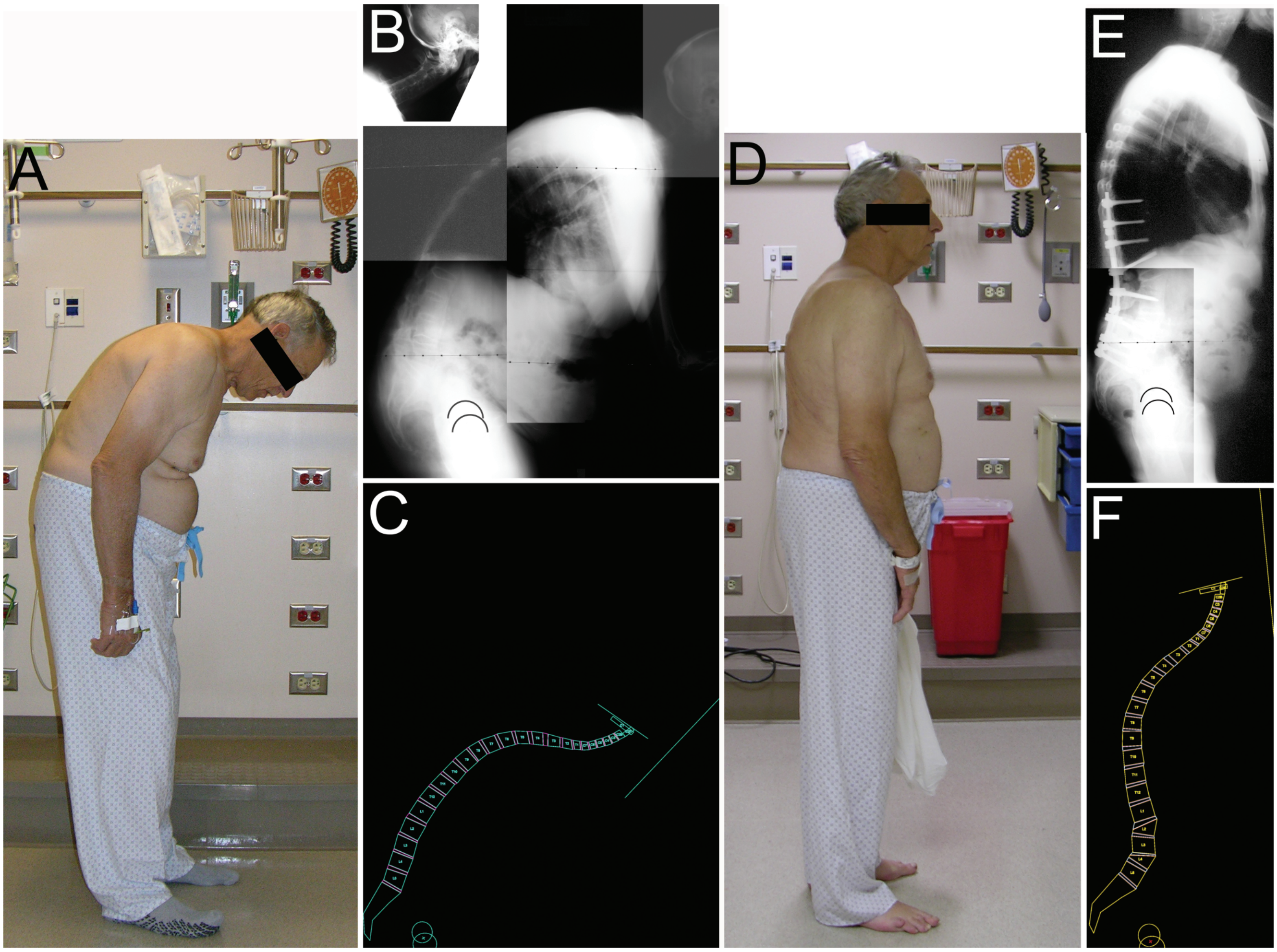

Fig. 2. A case illustrating use of the software. Preoperative lateral photographic **(A)** and lateral radiographic **(B)** images are shown. Clinical evaluation reveals a horizontal gaze sagittal imbalance. Radiographic evaluation reveals a major structural lumbar kyphotic curve and a minor structural lumbosacral kyphotic curve. Global spinal alignment (horizontal gaze and spinal balance) reveals positive sagittal imbalance. Pelvic alignment reveals posterior sagittal rotation. **C:** Virtual spine model constructed from preoperative images using the software program. Postoperative lateral photographic **(D)** and lateral radiographic **(E)** images illustrate the outcome following L-2 and L-4 pedicle subtraction osteotomies with a spinopelvic fixation and fusion. **F:** Virtual spine model following virtual surgical L-2 and L-4 pedicle subtraction osteotomies with anterior sagittal rotation of the pelvis on the HA.

on the clinical image, and soft tissue in the radiograph is used for fiduciary landmarks (for example, see Fig. 1). To get the images into register, either image can be rotated, flipped, rescaled, or cropped as necessary. The opacity, brightness, or contrast of each image can also be adjusted.

Once the images have been imported and put into register, the original spine model can be constructed. To the left of the canvas is the model definition window used to build the original model of the spine from imported images (Fig. 1). The vertebral body at each level is traced manually, each modeled as a quadrilateral. The C-2 odontoid process (designated “Peg” in the model definition window) is similarly traced and represented as a quadrilateral. The sacrum is modeled by tracing a 7-sided polygon along the borders. As adjacent vertebral bodies are defined, the intervertebral discs are automatically drawn by the software.

The hips are represented by tracing circles around the femoral heads. The chin-brow and MacGregor lines are drawn using the defining landmarks in the clinical photograph and radiograph, respectively. The dorsoventral axis is defined by specifying the patient as either right- or left-facing. Finally, to assign physical units to displacement measurements, the model is calibrated using a known length standard contained in the image.

After the original model is defined, analysis and adjustments may be performed. The software automatically measures a variety of angles and displacements from the occiput to the pelvis from the virtual spine model. These values are displayed to the right of the canvas in the measurements window; mean values ± SDs for the asymptomatic adult population are also displayed.[4,5] Values lying within 2 SDs of the mean are displayed in green; values lying outside this range are displayed in red.

Virtual adjustments to the spine may be made using the adjustments window (Fig. 1). To simulate shaving osteotomy wedges from the vertebral bodies, the angle of either the upper or lower endplate of each vertebra may be adjusted. Material can be added to either the anterior or posterior aspect of each intervertebral disc space. Listhesis can be simulated by specifying a translational shift in either direction between any two vertebrae. Finally, the hip rotation on the HA may be adjusted. This last adjustment is not intended to simulate a surgical procedure per se, but to educate the user regarding the role that hip rotation plays in global sagittal spinal alignment.

The user may toggle between the original and adjusted spine models as desired. Angle and displacement measurements are displayed for both models in the measurement window. The user may specify angles to be measured in addition to those that are hard-coded by the software system. The software also constructs a log of all adjustments that are made.

Case Illustration

A case illustrating use of the software is shown in Fig. 2. This 67-year-old man with ankylosing spondylitis presented with low-back pain and difficulty ambulating. A preoperative lateral photographic image (Fig. 2A) revealed a horizontal gaze sagittal imbalance (CBVA, +67°). Standing lateral cervical and long-cassette radiographic images (Fig. 2B) revealed a major structural lumbar kyphotic curve (L1–5, +3°) and a minor structural lumbosacral kyphotic curve (L4–S1, –3°). Global spinal alignment revealed positive sagittal imbalance (CBVA, +67°; C7–S1 SVA, +346 mm). Pelvic alignment revealed posterior sagittal rotation (PT, +37°). Postoperative lateral photographic (Fig. 2D) and long-cassette radiographic (Fig. 2E) images showed improvement in regional as well as global sagittal spinal alignment following L-2 and L-4 pedicle subtraction osteotomies with a spinopelvic fixation and fusion. With improvement in regional and global sagittal spinal alignment, the pelvis had rotated anteriorly, with an improvement in the PT.

After importing a preoperative lateral clinical image into the software program, preoperative lateral radiographic images were imported into the software program. The radiographic images' brightness, contrast, and opacity were adjusted. The radiographic images were then scaled and rotated to overlay the clinical image, using soft tissue in the radiographs as fiduciary landmarks. A virtual model of the spine was then constructed (Fig. 2C). The software program automatically measured the angles and displacements from the occiput to the pelvis based on the virtual spine model. These values were displayed to the right of the canvas in the measurements window; mean values ± SDs for the asymptomatic adult population were also displayed.[4,5] Values lying within 2 SDs of the mean were displayed in green; values lying outside this range were displayed in red. Using the adjustments window, –30° wedge osteotomies were virtually performed at L-2 and L-4 with a –11° anterior rotation of the pelvis on the HA, resulting in an adjusted model (Fig. 2F) that closely resembled the postoperative condition and confirming that the first-generation software could simulate the operative procedure and provide an educational and research tool.

Discussion

Spine surgeons are increasingly recognizing the importance of the maintenance or restoration of "normal" neutral upright sagittal spinal alignment. From occipitocervical fusion to lumbosacral fusion, preservation of neutral upright sagittal spinal alignment has been reported to prevent the postoperative development of deformity and adjacent-segment disease as well as to provide improved postoperative clinical outcomes.[1–3,6,9] Many measurement techniques for evaluating regional and global sagittal spinal alignment have come about in the recent past. For spine surgeons it can be a daunting task to begin to understand measurements of regional and global spinal alignment and the effects of surgical manipulation.

To better understand regional and global sagittal spinal alignment, we developed a first-generation, novel software program for virtual preoperative measurement and surgical manipulation of sagittal spinal alignment. By assuming that the spine is a rigid column, simple geometrical principles and fiducial representations of key vertebral segments can serve as markers within the program. Virtual surgical manipulation can then be portrayed and analyzed as it impacts regional and global alignment. Using this working model, the vertebral level selected for an osteotomy, the amount of angular bone removal required during an osteotomy, and their anticipated impact can be assessed for research and education.

Conclusions

This first-generation program is limited to the sagittal plane, and the surgical manipulation is oversimplified, treating the spine as a rigid column. Despite these limitations, the program does provide educational information to the user on measurement techniques and the effects of virtual surgical manipulation. Future software generations will be more comprehensive, allowing for measurement and interaction in the coronal, axial, and sagittal planes.

Disclosure

Dr. Kuntz is a stockholder in Mayfield Clinic, Mayfield Spine Center, Precision Radiotherapy, Priority Consult, Cincinnati Imaging, and CKIV Alignment; receives research or education funding from Synthes, Stryker, BioAxone, and AO Spine; and is a consultant for Synthes Spine. Dr. Wilsey is a consultant for Clifton Labs, Inc.

Author contributions to the study and manuscript preparation include the following. Conception and design: C Kuntz IV, CJ Morgan, RB Anderson, PA Wilsey. Acquisition of data: CJ Morgan, RB Anderson, PA Wilsey. Analysis and interpretation of data: C Kuntz IV, CJ Morgan, RB Anderson, PA Wilsey. Drafting the article: DB Pettigrew, CJ Morgan, RB Anderson. Critically revising the article: C Kuntz IV, DB Pettigrew, CJ Morgan, PA Wilsey. Reviewed final version of the manuscript and approved it for submission: C Kuntz IV, DB Pettigrew, CJ Morgan, RB Anderson, PA Wilsey. Administrative/technical/material support: RB Anderson, PA Wilsey. Study supervision: C Kuntz IV, PA Wilsey.

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Adult scoliosis surgery outcomes: a systematic review

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Object. Appreciation of the optimal management of skeletally mature patients with spinal deformities requires understanding of the natural history of the disease relative to expected outcomes of surgical intervention. Appropriate outcome measures are necessary to define the surgical treatment. Unfortunately, the literature lacks prospective randomized data. The majority of published series report outcomes of a particular surgical approach, procedure, or surgeon. The purpose of the current study was to systematically review the present spine deformity literature and assess the available data on clinical and radiographic outcome measurements.

Methods. A systematic review of MEDLINE and PubMed databases was performed to identify articles published from 1950 to the present using the following key words: "adult scoliosis surgery," "adult spine deformity surgery," "outcomes," and "complications." Exclusion criteria included follow-up shorter than 2 years and mean patient age younger than 18 years. Data on major curve (coronal scoliosis or lumbar lordosis Cobb angle as reported), major curve correction, Oswestry Disability Index (ODI) scores, Scoliosis Research Society (SRS) instrument scores, complications, and pseudarthroses were recorded.

Results. Forty-nine articles were obtained and included in this review; 3299 patient data points were analyzed. The mean age was 47.7 years, and the mean follow-up period was 3.6 years. The average major curve correction was 26.6° (for 2188 patients); for 2129 patients, it was possible to calculate average curve reduction as a percentage (40.7%). The mean total ODI was 41.2 (for 1289 patients), and the mean postoperative reduction in ODI was 15.7 (for 911 patients). The mean SRS-30 equivalent score was 97.1 (for 1700 patients) with a mean postoperative decrease of 23.1 (for 999 patients). There were 897 reported complications for 2175 patients (41.2%) and 319 pseudarthroses for 2469 patients (12.9%).

Conclusions. Surgery for adult scoliosis is associated with improvement in radiographic and clinical outcomes at a minimum 2-year follow-up. Perioperative morbidity includes an approximately 13% risk of pseudarthrosis and a greater than 40% incidence of perioperative adverse events. Incidence of perioperative complications is substantial and must be considered when deciding optimal disease management. Although the quality of published studies in this area has improved, particularly in the last few years, the current review highlights the lack of routine use of standardized outcomes measures and assessment in the adult scoliosis literature. *(DOI: 10.3171/2009.12.FOCUS09254)*

Key Words • **adult scoliosis** • **adult spine deformity** • **pooled analysis** • **outcome**

The number of surgical treatment options for skeletally mature patients with spine deformities has expanded over the past several decades.[1] Advances in operative techniques, along with an understanding of biomechanics and advances in instrumentation, has allowed for the development of many surgical approaches to adult scoliosis. To determine the "best" approach to treat patients with adult deformity, clinicians must be familiar with risks and benefits of surgical intervention. Unfortunately, randomized controlled trials comparing operative with nonoperative management are lacking.[13] Outcomes for adult deformity surgery are largely reported in reference to a specific surgical technique or in relation to a particular surgeon or surgical group. Investigators have used varying classifications of clinical outcomes and procedure-related complications, making analysis of the literature difficult.

Abbreviations used in this paper: ODI = Oswestry Disability Index; SRS = Scoliosis Research Society; USPSTF = U.S. Preventive Services Task Force.

The purpose of this systematic review was to synthesize existing data on the outcomes of surgical intervention for adult spine deformity. Four specific questions regarding outcome were proposed as follows: 1) What is the benefit of surgery for adult scoliosis in terms of correction of curve at a minimum 2-year follow-up? 2) What is the benefit of surgery for adult scoliosis based on standard clinical outcomes measures at a minimum 2-year follow-up? 3) What is the rate of complication with adult scoliosis surgery? 4) What is the rate of pseudarthrosis with adult scoliosis surgery?

Methods

Literature Review

A query of the PubMed and MEDLINE databases was performed to identify articles pertinent to the aforementioned clinical questions. First, a search of PubMed using the key words "adult scoliosis surgery outcomes" and "adult spine deformity surgery outcomes" was per-

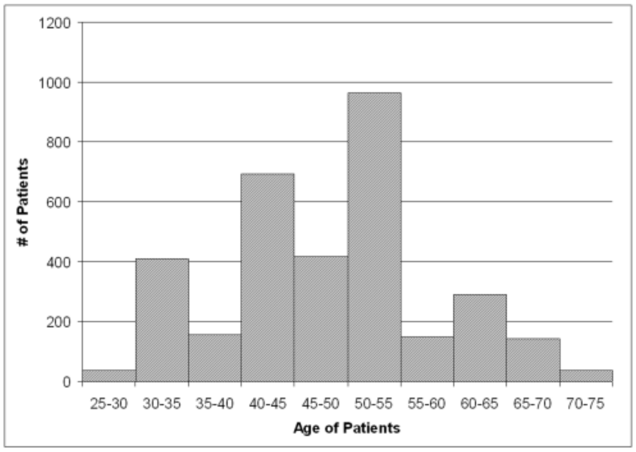

Fig. 1. Bar graph illustrating age distribution (in years) of patients in 49 reviewed series encompassing 3299 patients.

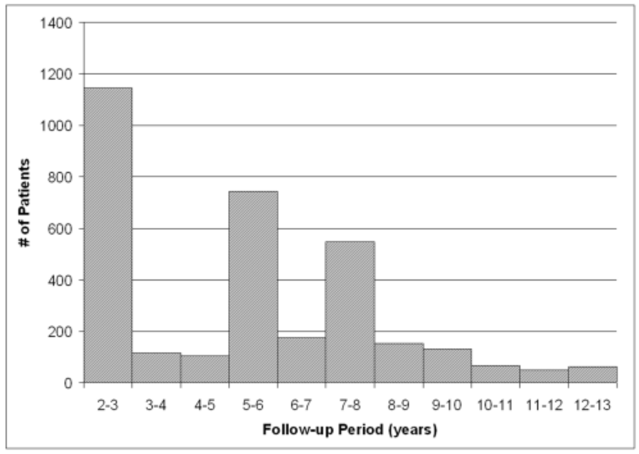

Fig. 2. Bar graph illustrating distribution of average follow-up period of patients in 49 reviewed series including data from 3299 patients.

formed and returned 361 articles. The query was further limited to the English-language literature (341 articles) and a patient age of 19 years or older (334 articles). Abstracts from these articles were reviewed, and those that reported a minimum 2-year follow-up, average patient age older than 18 years, or did not specify either parameter in the abstract were retained for more detailed review. This yielded 44 articles for detailed review. A minimum 2-year follow-up was specified to include chronic or subacute complications (for example, pseudarthrosis) and to account for any loss of curve correction.

Next, a search of MEDLINE was performed to identify any pertinent articles published between 1950 and 2009 that were not identified in the previous PubMed search. A search for the key words "adult scoliosis and outcomes" (29 articles), "adult spine deformity and outcomes" (31 articles), and "adult scoliosis and complications" (59 articles) was performed. Abstracts from these searches yielded 14 additional articles for detailed review that were not identified previously in the PubMed search. Thus, 58 articles were identified by abstract for detailed review of methods and results. Nine of these articles were excluded from analysis due to failure to meet the minimum follow-up, patient age criteria, or report postoperative outcomes. Forty-nine articles were ultimately included in the analysis (Table 1).[2,4,8–11,15–27,29,30,34–43,45–49,51–63]

The quality of evidence in the selected articles was classified using the USPSTF system for ranking evidence.[31] Articles were reviewed for data on methodology (retrospective vs prospective), number of patients, mean patient age, and mean follow-up. Data regarding change in major curve at last follow-up in degrees and as a percentage of the initial curve were recorded if available. A major curve was defined as the coronal scoliosis Cobb angle or lumbar lordosis Cobb angle as reported in the study. Clinical outcomes data based on postoperative ODI scores, change in ODI scores from preoperative, postoperative SRS instrument scores, and change in SRS scores from preoperative was also recorded when available. Finally, the number of complications and pseudarthroses were tallied.

Statistical Analysis

Descriptive statistics were calculated using the JMP statistical package (version 7.02, SAS Institute). Because of variability in the type of SRS instrument used by different investigators (SRS-22, SRS-24, SRS-29, or SRS-30), SRS scores were converted to SRS-30 score equivalents for purposes of statistical analysis. Weighted averages of age, length of follow-up, ODI, change in ODI, SRS-30 equivalent score, change in SRS-30 equivalent score, curve reduction in degrees, and curve reduction as a percentage of the original curve were calculated. Complications were not uniformly reported; classification (that is, minor vs major) was variable as was reporting of multiple complications in the same patient. Therefore, complication incidence was calculated by tallying the total number of complications reported divided by total number of patients in those studies that reported complications. The incidence of pseudarthrosis was calculated in a similar fashion: the number of pseudarthroses reported divided by total number of patients in those studies reporting pseudarthroses.

Results

A total of 49 articles reporting data in 3299 patients were reviewed. Of the 49 articles reviewed, none were classified as Level I evidence according to USPSTF criteria. Four articles met criteria for Level II evidence as well-designed matched cohort studies or multiple time series with and without intervention. The remaining 45 articles were descriptive studies and therefore classified as Level III evidence. Eight studies were conducted in a prospective fashion, and the other 41 series were conducted in a retrospective manner. Only 4 articles reported on all specified outcome measures.

The average age of the patients included in this review was 47.7 years (Fig. 1). The average length of follow-up was 3.6 years (Fig. 2). Thirty-nine studies reported preoperative and postoperative major curve Cobb angles (for 2188 patients). At a minimum 2-year follow-up, the average reduction of the major curve was 26.6° (Fig. 3), or 40.7% as a percentage of the original curve (where this calculation was available; for 2129 patients).

TABLE 1: Literature review of postoperative radiographic and clinical outcomes for adult patients undergoing surgery for scoliosis with a minimum 2-year follow-up

Authors & Year	Level of Evidence	Study Design	Total No. of Patients	Mean Age (yrs)	Mean FU (yrs)	Mean ODI	SRS-30 Equivalent	Major Curve Reduction (°)	Major Curve Reduction (%)	No. of Complications	No. of Pseudarthroses
Bridwell et al., 2009	II	prospective, matched cohort	85	60	2	20	114	29	52	31	—
Smith et al., 2009	II	prospective	147	51	2	35	93	—	—	—	—
Khan et al., 2009	III	retrospective	14	65	3.7	—	108	40	87	4	1
Rose et al., 2009	II	prospective, matched cohort	34	38.3	3	—	111	29.5	47	0	0
Kim et al., 2009	III	retrospective	62	47.9	10.3	25	—	—	—	4	—
Glassman et al., 2009	III	prospective cohort	283	50	2	22.8	111	—	—	—	—
Peelle et al., 2008	III	retrospective	30	40	3.3	—	90	18	50	0	0
Wu et al., 2008	III	retrospective	26	64.2	3	25.8	—	9.1	55	2	—
Weistroffer et al., 2008	III	retrospective	50	54	9.7	—	—	—	—	35	12
Chang et al., 2008	III	retrospective	83	66.1	2	—	98.4	42.2	1	26	3
Deviren et al., 2008	III	retrospective	15	37.5	3.9	—	69	34	67	4	0
Kim et al., 2008	III	retrospective	48	49.6	3.7	—	74.4	25	42	10	4
Wang et al., 2008	III	retrospective	13	31	2.54	—	76.9	53.9	59	4	0
Kim et al., 2007	III	retrospective	125	57.1	4.5	—	67.5	12	51	—	21
Buchowski et al., 2007	III	prospective	108	54.8	2	29.5	97.1	32.2	65	15	0
Daubs et al., 2007	III	retrospective	46	67	4.2	25	—	—	—	26	—
Kim et al., 2007[37]	III	retrospective	35	53.1	5.8	26	48	37	73	13	8
Bomback et al., 2007	III	retrospective	17	30	2	24	123	44	52	22	—
Pateder et al., 2007	III	retrospective	180	60.5	4.5	—	—	25.3	50	42	20
Bess et al., 2007	II	retrospective, matched cohort	56	49	3.6	—	114	19.3	35	21	7
Kim et al., 2006[39]	III	retrospective	144	52	3.9	—	107.1	15	29	—	34
DeWald & Stanley, 2006	III	retrospective	38	72.4	2.5	—	—	—	—	24	4
Yang et al., 2006	III	prospective	35	40.8	2	—	74.4	20.6	18	16	0
Kim et al., 2006[38]	III	retrospective	232	40.8	2	90.6	—	—	—	—	40
Boachie-Adjei et al., 2006	III	retrospective	24	48	4	—	—	40	40	17	0
Tsuchiya et al., 2006	III	retrospective	67	36.2	6	20.1	—	—	—	23	—
Suk et al., 2005	III	retrospective	25	38	2	—	—	23	60	5	1
Glattes et al., 2005	III	retrospective	81	45	5.3	—	114.1	—	—	—	—
Chang et al., 2005	III	retrospective	66	34.8	3.6	—	96.7	39.2	42	44	0
Kim et al., 2005	III	retrospective	96	42.2	5.9	—	91.9	37	39	—	16
Brown et al., 2004	III	retrospective	16	49	2.7	—	—	23	43	—	—
Rhee et al., 2003	III	retrospective	42	47	2	—	117.5	25	23	3	0
Bridwell et al., 2003[16]	III	prospective	33	53.4	2	34.2	91.2	32.9	31	24	8
Berven et al., 2003[8]	III	retrospective	25	58	4.5	—	102	19	17	9	5
Ali et al., 2003	III	retrospective	28	48.5	2	—	—	38	61	5	0

(continued)

TABLE 1: Literature review of postoperative radiographic and clinical outcomes for adult patients undergoing surgery for scoliosis with a minimum 2-year follow-up *(continued)*

Authors & Year	Level of Evidence	Study Design	Total No. of Patients	Mean Age (yrs)	Mean FU (yrs)	Mean ODI	SRS-30 Equivalent	Major Curve Reduction (°)	Major Curve Reduction (%)	No. of Complications	No. of Pseudarthroses
Bridwell et al., 2003[17]	III	retrospective	27	52.4	2	51.21	—	34.1	33	24	7
Shapiro et al., 2003	III	retrospective	16	29.5	3.4	44.3	74.4	36	50	12	0
Murrey et al., 2002	III	retrospective	59	47	4.5	—	—	20.7	—	10	0
Ahn et al., 2002	III	prospective	83	54.4	4.6	—	—	40.1	38	83	6
Wang et al., 2002	III	retrospective	22	26.8	4.7	—	—	26.6	48	4	1
Emami et al., 2002	III	retrospective	54	54.9	4.75	—	69.2	19.5	38	48	10
Smith et al., 2002	III	retrospective	15	37.5	5.1	—	106.9	34	66	6	0
Eck et al., 2001	III	retrospective	58	43	5	—	—	14	27	13	5
Lapp et al., 2001	III	retrospective	44	42.6	3.5	—	—	21	38	13	5
Buttermann et al., 2001	III	retrospective	105	44	4.1	60	—	—	—	65	43
Simmons et al., 1993	III	retrospective	49	41	2.8	—	—	32	47	20	0
van Dam et al., 1987	III	retrospective	91	31	3.5	—	—	21	32	13	22
Kostuik & Hall, 1983	III	retrospective	45	44.3	3.5	—	—	19.5	34	65	10
Swank et al., 1981	III	retrospective	222	30.7	3.6	—	—	27	33	117	26

Fifteen studies, including data from 1289 patients, used total ODI as a measure of clinical outcomes. The average ODI for patients in these studies was 41.2. Eleven studies including data from 911 patients reported both preoperative and postoperative ODIs. The average decrease in ODI from preoperative testing to latest follow-up in these studies was 15.7.

Twenty-six studies with data from 1700 patients used an SRS instrument to measure clinical outcomes at follow-up. Scores were converted to SRS-30 equivalent scores for purposes of comparison and analysis. The average SRS-30 score of patients in these series was 97.1. Ten studies, with data from 999 patients, reported both preoperative and postoperative SRS scores. The average decrease in SRS-30 scores in these patients was 23.1.

Forty-one articles reported on complications associated with surgery; 897 complications were reported in 2175 patients, giving a pooled incidence of 41.2% for patients in these series. Thirty-nine articles (2469 patients) reported on pseudarthroses. There were 319 pseudarthroses in these articles, giving a rate of 12.9%.

Discussion

An adult spine coronal deformity may develop de novo in the mature skeleton or progress from untreated adolescent scoliosis. Estimates of prevalence vary from 1 to 9% of the adult population.[12] Adult patients present more often with pain or neurological symptoms than their adolescent counterparts, and surgery is generally indicated for patients with significant deformity-related pain or progressive curves.[32] Several authors have reported high rates of patient satisfaction and functional improvement with operative treatment.[3,4,23,32]

Historically, outcomes in the adult deformity literature have been reported in reference to specific procedures, pathology, or primary surgeon.[10,11,27,57] This is reflected in the current review in that the majority of studies included were classified as Level III evidence (descriptive studies) according to USPSTF criteria. Although several prospective and matched cohort studies have been performed, definitive randomized controlled trials are lacking.[13,15,63] There has been a trend toward increasing quality in evidence and methodology of publications in this area, particularly in the past few years. Three of 4 Level II studies included in the current review were published in 2009. In addition, 5 of 8 prospective studies in this review were published in 2007 or later; all 8 were published in 2002 or later.

The aim of the current study was to review different series to generate more powerful estimates of the effect of surgery for adult scoliosis. The current review focuses on the ODI and the SRS outcome instruments because these were the most consistently used measures. Complications and pseudarthroses, a significant cause of pain and reoperation in these patients,[38,39] were included in the review rather than limiting it to only potential benefits of surgery. The inclusion criterion of a 2-year minimum follow-up was specified to increase the capture of subacute and chronic events (for example, pseudarthrosis or loss of curve correction).

Correction of Curve

Cobb angle correction varied from 9.1 to 53.9° (mean

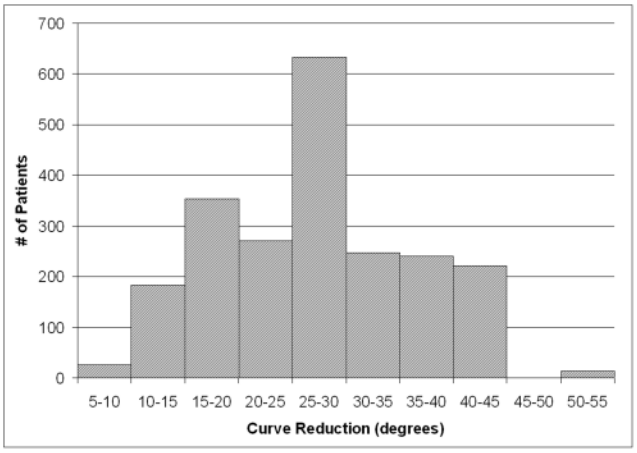

Fig. 3. Bar graph illustrating distribution of average curve reduction of patients as reported in 39 reviewed series with data from 2188 patients at a minimum 2-year follow-up.

correction 26.6°). As a percentage of the original curve, correction ranged from 1 to 87% (mean 40.7%). The natural history of untreated spinal deformity is progression of the curve, and this has been illustrated by several comparative series.[15,44] Unlike adolescent scoliosis in which bracing can prevent progression of the curve, no such utility has been found in the skeletally mature patient.[33]

Clinical Outcome Measurements

There was no consensus in the reviewed literature on the measurement of clinical outcomes. At least 9 separate formal instruments were used in the reviewed series. The most commonly used instruments were the ODI (15 studies) and SRS outcomes instrument (26 studies). Several versions of the SRS instrument were used, including SRS-24, SRS-29, SRS-30, and the SRS-22 (the modified SRS instrument). However, only 21 studies (42.9%) reported both preoperative and postoperative scores.

The ODI is a widely used and validated instrument for outcomes measurement of a variety of pathological conditions.[28] The average postoperative ODI in the 15 series that reported them was 41.2. This correlates with a clinical picture of moderate to severe disability. In their review of 947 adults with spinal deformity, Schwab et al.[50] found a mean ODI score of 30 suggesting that the patients in the current review were more disabled by their disease than the general adult scoliosis population.

The difference in ODI scores that correlates with significant clinical improvement ranges from 4 to 15 points.[28] Eleven studies in the current review reported both preoperative and postoperative ODI scores. For the 911 patients in these 11 studies, there was an average decrease of 15.7 points (range 3.1–32.3 points) after surgery, suggesting that significant clinical improvement did occur in patients in those series.

Several versions of the SRS are commonly used and have been previously validated in adults and children with scoliosis.[5,7,14] Several variations of the SRS format were used by investigators to report outcomes; the difference in SRS versions is primarily inclusion or exclusion of certain groups of questions. For purposes of comparison, it was necessary to convert scores to the SRS-30 scale. To our knowledge, there has been no previous validation of such a conversion. Using this method, the average SRS-30 equivalent score of patients in the 26 studies using a version of the SRS instrument was 97.1. In the aforementioned study by Schwab et al., the average SRS-22 score was 67, which is equivalent to a score of 100.5 on the SRS-30 scale, suggesting minimal difference between patients in these series and the general adult scoliosis population.

Bago et al.[6] recently reported that the minimal important difference, the difference in score correlating to a patient's self-perceived improvement in outcome for raw SRS scores is approximately 13 points. The average decrease in SRS-30 equivalent score found in the 10 studies that reported both pre- and postoperative SRS scores was 23.1 points. This difference represents a significant improvement in patient-reported outcome at a minimum 2-year follow-up for patients who underwent surgery in those series.

Eight series reported use of both ODI and SRS score as measures of outcome, 14 reported ODI alone, 25 reported SRS score alone, and 13 reported neither. The ability to compare outcomes in the scoliosis literature is limited by the lack of consensus on which measurement instrument to use, a consistent method of pre- and postoperative assessment, and whether to include clinical outcomes data in such series at all. An agreement on these standards seems overdue as performance measures in surgery become increasingly important.

Complications and Pseudarthroses

The incidence of reported complications in the reviewed articles ranged from 0 to 53%. There was no consensus regarding the classification or categorization of complications. Several authors divided complications into major or minor categories while others reported early versus late complications.[15,16,52,63] The method used in this systematic review may overestimate the true incidence of complications. Several series reported only the number of complications and did not specify whether multiple complications occurred in the same patient. For analysis, the incidence of complication was calculated as the total number of complications divided by the number of patients in those series reporting complications. This formula implicitly assumes that multiple complications did not occur in the same patient. Therefore, this approach may not accurately reflect overall incidence of perioperative adverse events in these series.

The rate of pseudarthroses in the reviewed series ranged from 0 to 41%.[20,45] This range is slightly broader than other estimates, although the overall rate in the current review of 12.9% is similar to previously published rates.[12]

Conclusions

The current review analyzes outcomes data for adult spine deformity surgery with a minimum 2-year follow-up. The average major curve correction in these series was 26.6°, or about 40.7% correction of the original curve. Based on the most commonly reported clinical outcomes measures, the ODI and SRS instrument, surgery for adult scoliosis appears to improve clinical outcomes at a minimum 2-year follow-up. Although the quality of studies in this area has improved, particularly in the past few years, this review highlights the lack of routine use of standardized outcome measures and methods for preoperative and postoperative assessment in the current literature. Such standardization should be expanded to include methods of complication classification and reporting.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Osteotomies in the posterior-only treatment of complex adult spinal deformity: a comparative review

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In addressing adult spinal deformities through a posterior approach, the surgeon now may choose from among a variety of osteotomy techniques. The Ponte or Smith-Petersen osteotomy provides the least correction, but it can be used at multiple levels with minimal blood loss and a lower operative risk. Pedicle subtraction osteotomies provide nearly 3 times the per-level correction of Ponte/Smith-Petersen osteotomies but carry increased technical demands, longer operative time, and greater blood loss and associated morbidity. Vertebral column resections serve as the most powerful method, providing the most correction in the coronal and sagittal planes, but posing both the greatest technical challenge and the greatest risk to the patient in terms of possible neurological injury, operative time, and potential morbidity. The authors reviewed the literature relating to these osteotomy methods. They also provided case illustrations and suggestions for their proper application. *(DOI: 10.3171/2009.12.FOCUS09259)*

Key Words • **spinal osteotomy** • **pedicle subtraction** • **vertebral column resection** • **Ponte** • **Smith-Petersen** • **adult deformity** • **posterior-only approach** • **kyphosis correction**

Posterior-only approaches for the correction of adult kyphotic or kyphoscoliotic deformities have become increasingly common in recent years. The reason for this change in practice has been the advent of polysegmental 3-column fixation through the use of pedicle screws, as well as the use of posterior osteotomies to effect greater curve correction without the need for anterior releases or corpectomies. The status of surgical techniques and technology in adult deformity surgery is now such that essentially any kyphotic deformity can be addressed through a posterior-only approach, which obviates the morbidity of an anterior approach while obtaining equivalent correction to what a combined anterior-posterior approach can provide.

The surgeon treating patients with kyphotic deformities must be versed in the relative merits of the various osteotomy techniques. Three major techniques are currently used for the posterior-only correction of kyphotic deformities in adults as follows: Ponte or Smith-Petersen osteotomy (SPO), PSO, or pVCR. The indications, surgical techniques, anatomical characteristics, kyphotic correction afforded, complications, outcomes, and relative benefits of each osteotomy technique will be described in turn, with an illustrative case provided for each.

Ponte or Smith-Petersen Osteotomy

Although it is a commonly used osteotomy technique, much confusion surrounds the nomenclature and technique of the Ponte or Smith-Petersen osteotomy. Smith-Petersen and colleagues[38] first described the technique of posterior element osteotomy and posterior compression. In this technique, they used the disc space as a fulcrum to effect anterior column lengthening and posterior column shortening in the treatment of flexion deformities in individuals with "rheumatoid arthritis" and autofused (that is, ankylosed) spines. This method involved violation of the anterior longitudinal ligament and entailed significant risk of injury to vascular structures anterior to the spine. Hehne et al.[15] also described a "polysegmental lordosis osteotomy" with resection of a portion of the posterior elements at each level, producing a per-segment correction of about 10°. More recently, Ponte et al.[35] further elaborated on the use of wide segmental osteotomies and posterior compression along unfused regions of the kyphotic deformity in patients with Scheuermann kyphosis. Although the description by Ponte et al. more directly captures the technique most commonly used today for

Abbreviations used in this paper: PSO = pedicle subtraction osteotomy; pVCR = posterior vertebral column resection; SPO = Smith-Petersen osteotomy; SRS = Scoliosis Research Society; VB = vertebral body.

TABLE 1: Osteotomy techniques for treatment of deformity*

Authors & Year	No. of Patients	Average OR Time (minutes)			Mean EBL (ml)			Neurological/Overall Complication Rate (%)			Kyphosis Correction at Final Follow-Up (°)			Sagittal Balance Correction at Final Follow-Up (cm)		
		SPO	PSO	VCR	SPO	PSO	VCR	SPO	PSO	VCR	SPO (per level)	PSO (per level)	VCR (coronal/sagittal plane)	SPO	PSO	VCR
Cho et al., 2005	30 SPO, 41 PSO	756	726		1392	2617		3.3/46.6†	7.3/58.5†		10.7	31.7		5.49	11.19	
Geck et al., 2007	17 SPO	270			808			0/29.4			9.3					
Lehmer et al., 1994	38 PSO		294			1850			19.5/51.2†							
Danisa et al., 2000	11 PSO								36.4/54.5			40.1				
Berven et al., 2001	13 PSO								30.8/69.2†			29.9			9.1	
Chen et al., 2001	78 PSO		225			1150			1.3/14.1			34.5				
Kim et al., 2002	45 PSO								11.1/NR						8.6	
Murrey et al., 2002	37 PSO					2874			NR/16.9			25				
Bridwell et al., 2003[6]	27 PSO		744‡			2396‡			3.7/35§			34.5			13.5	
Bridwell et al., 2003[5]	66 PSO		732			2386			7.6/48.5†			36.1			12.7	
Lazennec et al., 2006	13 PSO		128			1850			15.4/61.5†			38.5				
van Loon et al., 2006	11 PSO		250			3800			0/18.1			26.9				
Yang et al., 2006	35 PSO		948			5800			3.6/45.7†			24.6¶			7.7¶	
Buchowski et al., 2007	108 PSO								11.1/NR						10.8	
Ikenaga et al., 2007	67 PSO		277			1988			8.96/40			34.2			4.9	
Mummaneni et al., 2008	10 PSO								10/70							
Kiaer & Gehrchen, 2009	36 PSO		180			2450			5.5/25†							
Kawahara et al., 2001	7 VCR**			576			2386			0/NR			NR/49			1.7
Suk et al., 2002	70 VCR			271††			2604††			17/34			61.9/45.2			2.4
Suk et al., 2005	25 VCR			280			2810						23/40			4.7
Lenke et al., 2009[26]	35 VCR (peds)			460			691			11.4/40			36/36			
Lenke et al., 2009[27]	43 VCR			577			1103			NR/48.8			50/59			
Wang et al., 2008	13 multi-VCR			266			2411			15.3/30.7			33.7/53.9			2.1
mean		580	341	385	1181	1831	1928	2.1/40.4	9.1/38.5	14.3/39	10.2	32.6	47.1/46.7	5.5	9.8	2.8

* EBL = estimated blood loss; NR = not reported; peds = pediatric patients.
† This value represents total complications divided by total number of patients; some patients experienced multiple complications.
‡ Some procedures involved 2 stages.
§ Estimated.
¶ Includes thoracic and lumbar PSOs.
** "Closing-opening wedge osteotomy."
†† Average extrapolated from data in paper.

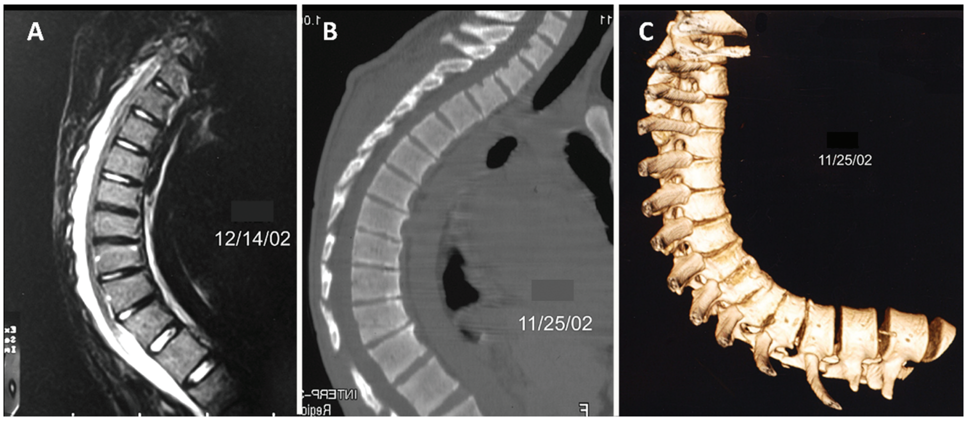

Fig. 1. Case 1. Preoperative T2-weighted sagittal MR image **(A)**, sagittally reconstructed CT scan **(B)**, and 3D CT reconstruction **(C)**. Note the gradual, sweeping kyphosis, ideally suited to a series of SPOs.

posterior column osteotomies, the name Smith-Petersen osteotomy seems to have taken hold to describe the spectrum of posterior column osteotomies and will be used in this manuscript.

Surgical Technique

The technique typically involves removal of the posterior ligaments (supraspinous, intraspinous, and ligamentum flavum) and facets to produce a posterior release, thereby aiding in coronal correction and sagittal plane realignment. Compression of the osteotomy brings about kyphosis correction, although it does require a mobile disc space anteriorly. Additionally, compression leads to contraction of the neural foramina, which necessitates a preceding wide facetectomy to prevent nerve root impingement. As previously noted, although some descriptions depict the method as resulting in correction through rupture of the anterior tension band and resultant profound anterior lengthening,[38,47] this is not how the procedure is commonly used; rather, the disc space typically compresses posteriorly and expands anteriorly with a fulcrum between. Anything more would present a significant risk of vascular or gastrointestinal complications, as noted in the literature on extension osteotomies.[29,46]

Indications for Surgery

The classic indication for an SPO would be a long, gradual, rounded kyphosis as in Scheuermann kyphosis.[4] The degree of kyphotic correction afforded by an SPO has been reported to be in the range of 9.3–10.7° per level,[9,13] with another general guideline being 1°/mm of bone resected. Because these osteotomies could practically be used at every level within a fusion construct, they lend themselves to powerful correction globally across a kyphotic segment; for focal regions of kyphosis, however, other osteotomies may be more appropriate. Other common indications for the technique include application along the apex of a rigid coronal curve to enhance curve flexibility and correction. Furthermore, the technique may contribute to greater technical ease and speed when

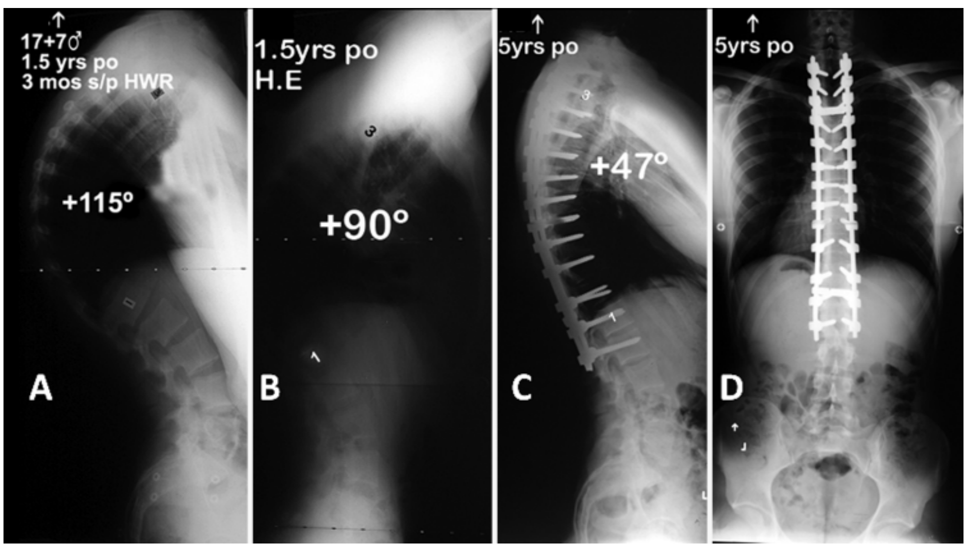

Fig. 2. Case 1. Preoperative standing lateral **(A)**, preoperative supine hyperextension lateral **(B)**, postoperative standing lateral **(C)**, and postoperative standing anteroposterior **(D)** 36-inch radiographs. H.E = hyperextension; HWR = hardware removal; po = postoperative; s/p = after.

used in conjunction with thoracic pedicle screw placement, as the osteotomy creates a window through which the pedicles can be palpated for more confident screw insertion.[14]

With respect to safety and efficacy, SPOs compare favorably with other osteotomy techniques. Blood loss tends to be less with SPOs. Cho et al.[9] found that using at least 3 SPOs (to achieve a comparable degree of correction with a single PSO) resulted in an average blood loss of 1392 ml, versus nearly twice as much for a PSO (2617 ml). In that same study, no difference was noted in fusion rates or the ODI, although patients undergoing PSO experienced greater sagittal plane imbalance correction (≥ 3 SPOs 5.49 ± 4.5 vs PSO 11.19 ± 7.2 [$p < 0.01$]) and reduced risk of coronal decompensation. Further data on the safety and efficacy of the technique came from a study by Geck et al.,[13] in which the authors successfully treated 17 patients using a posterior-only approach and Ponte osteotomy, achieving an average correction of 61% of kyphosis across instrumented levels and 49% for the largest Cobb angle, with no reoperations for pseudarthrosis/instrumentation failure; they reported 1 proximal junctional kyphosis and 1 distal junctional kyphosis that were essentially asymptomatic, 1 late wound infection, and 2 minor, transient, nonneurological complications.

Overall, the SPO is a versatile technique that can be performed safely and rapidly to aid in the correction of gradual kyphotic or scoliotic curves. Compared with the PSO, the SPO offers a reduction in operative time, blood loss, and risk of neurological complications, but it has the drawbacks of reduced sagittal plane correction, possibly a greater likelihood for coronal decompensation, reduced effectiveness for sharp, angular kyphoses, and inapplicability when the disc space lacks flexibility. A collection of recent published findings relating to the SPO can be found in Table 1.

Illustrative Case

Case 1. This 17-year-old boy had a history of Scheuermann kyphosis with an 84° thoracic kyphosis. At the age of 15 years, he underwent a T4–L1 video-assisted thoracoscopic fusion with a hybrid hook/rod construct. He suffered instrumentation failure with screw pullout at the distal end, which was revised with laminar wiring; this construct also failed, and he developed an infection requiring instrumentation removal. He then was referred with a progressing 115° of thoracic kyphosis that bent out to 90° when he was lying supine over a hyperextension bolster (Figs. 1 and 2A and B). He underwent a T2–L2 instrumented fusion with a posterior-only, pedicle screw construct as well as a total of 9 apical SPOs. Five years postoperatively, he has maintained correction at 47° of thoracic kyphosis with evidence of solid fusion at all levels (Figs. 2C and D and 3).

Pedicle Subtraction Osteotomy

Surgical Technique

Pedicle subtraction osteotomy was first described by Thomasen in 1985.[42] Like the SPO, the PSO has been called by various names, including transpedicular wedge procedure, closing wedge osteotomy, and eggshell osteotomy, which are used more or less interchangeably throughout the literature. The technique involves removal of the posterior ligaments and facets—as though one were performing an SPO—followed by resection of the pedicles and decancellation of a wedge of the VB via a transpedicular corridor. More aggressive resections include the disc space above the decancellated segment. Following the osteotomy, closure occurs in a wedge fashion, which brings about kyphosis correction through posterior shortening. This closure also creates a large contact area of cancellous bone, which proves beneficial for fusion of the PSO body (although the effect on fusion at neighboring levels remains less clear). If performed in an asymmetric fashion, the osteotomy can also lead to significant coronal correction.

Fig. 3. Case 1. Preoperative and postoperative clinical photographs.

Indications for Surgery

The indications for a PSO overlap somewhat with the use of multiple SPOs, but they diverge in key ways. Typically, the PSO is used for patients with sharp or angular kyphosis, as well as at levels lacking anterior flexibility at which effective SPOs would be precluded.[4] Furthermore, patients with greater than 10 cm of sagittal imbalance would be more likely to benefit from a PSO than SPOs.[4,9] A PSO may be of particular use in the treatment of lumbar flat-back syndrome in which significant lumbar kyphosis can be safely treated, and because of the long moment arm of the resultant sagittal rotation, a tremendous degree of correction in sagittal balance can be obtained.

Numerous recent cadaveric, radiographic, and clinical studies have evaluated the degree of deformity correction one can produce with a PSO. In a cadaveric model, Li et al.[28] obtained 36.4° of kyphotic correction with a standard decancellation closing wedge osteotomy, versus 48.5° for modified closing wedge osteotomy involving resection of part of the superior endplate of the decancellat-

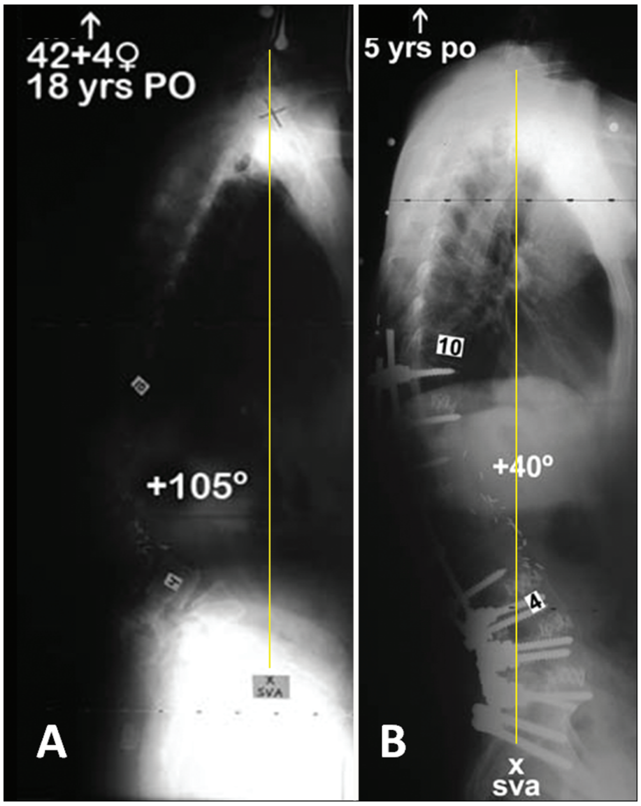

Fig. 4. Case 2. Preoperative (that is, before the SPO; **A**) and postoperative **(B)** lateral standing 36-inch plain radiographs. Note improvement in sagittal balance as evident by C-7 plumbline *(yellow line)*. sva = sagittal vertical alignment.

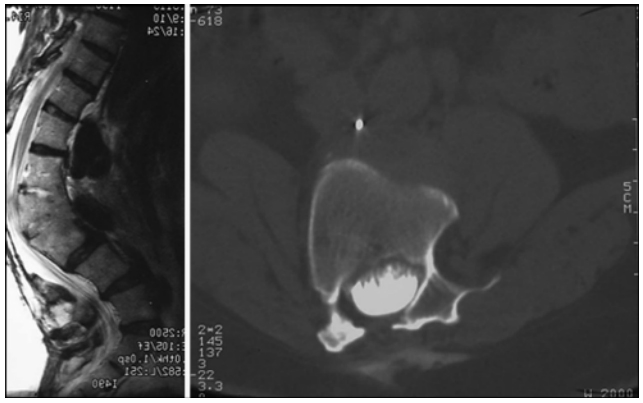

Fig. 5. Case 2. Preoperative sagittal **(left)** and axial **(right)** T2-weighted MR images. Note the cauda equina draped over posterior aspect of VB at the apex of the curve. This focal lumbar kyphosis is well suited to a PSO at the apex.

ed vertebra. Clinical studies to date have shown relative uniformity for the degree of kyphosis correction obtained at the osteotomized level, ranging from 26.2 to 40.1° with an average of 32° across recent studies,[2,6,8,11,18,21–25,32,33,43,48] although the expected correction is likely less for the thoracic spine.[34] Additionally, Ondra et al.[34] have created a mathematical model to determine the degrees of correction needed via PSO in the lumbar spine to bring a patient back into proper sagittal balance.

Outcomes After Surgery

Several recent studies have also highlighted outcomes from PSO procedures. A study by Bridwell et al.[6] in 27 patients who underwent PSOs for fixed sagittal imbalance showed highly significant improvements in final postoperative sagittal balance (from 17.74 ± 7.95 cm to 4.23 ± 6.73 cm, $p < 0.0001$), thoracic kyphosis (from 21.59 ± 18.37° to 31.70 ± 16.58°, $p < 0.0001$), lumbar lordosis (from −14.52 ± 21.82° to −48.63 ± 19.01°, $p < 0.0001$), and height (from 156.87 ± 8.18 cm to 160.30 ± 7.09 cm, $p < 0.0001$). Patients also experienced significant improvements in pain scale scores (from 6.96 to 4.41, $p = 0.0002$) and the ODI (from 51.21 to 35.75, $p < 0.0001$). Early complications varied in severity and were associated with patient comorbidities. Late complications included 1 case of neurogenic urinary retention and 7 pseudarthroses (all but 1 occurred either cephalad or caudad to the site of the PSO procedure, and none when a PSO was used through the site of a previous fusion mass). The neurological complication rate was 3.7%, with no permanent deficits. In expanding this group of patients who had undergone PSO to 66 patients (33 with 2 or more years of follow-up), Bridwell et al.[5] found a 7.6% rate of transient neurological complications, all of which improved; meanwhile these patients had significant improvements in pain scale, ODI, and SRS score outcomes. When follow-up was extended to 5 years in 35 patients, SRS scores and the ODI remained statistically unchanged, as did radiographic measures such as proximal junctional change, thoracic kyphosis, lumbar lordosis, and global sagittal balance—although a trend toward an increasingly anterior sagittal vertical axis was noted.[23] A more extensive complication review by the same group in 2007 showed that, in 108 adults treated with PSO for kyphotic deformity, the rate of intraoperative and postoperative neurological deficits was 11.1%, with a 2.8% rate of permanent deficits.[7] However, the ODI still improved in the study population (from 51.5 ± 16.2 to 29.5 ± 18.7, $p < 0.001$), as did SRS-22 scores (from 48.4 ± 15.3 to 71.2 ± 15.3, $p < 0.001$). Of note, none of the neurological complications were predicted by intraoperative monitoring, thus emphasizing the importance of performing a wake-up test before leaving the operating room.

Other centers have noted similar effectiveness and complication rates with PSOs. An early report by Lehmer et al.[25] in 38 patients with either posttraumatic or iatrogenic deformity showed a 19.5% rate of new neurological deficits, including a case of permanent paraplegia, although 76% of patients were satisfied enough to state that they would repeat the surgery. In a more recent study of PSO in 45 patients with ankylosing spondylitis and a minimum 5-year follow-up, neurological complications occurred in 11.1% while sagittal imbalance improved from 9.4 to 0.8 cm, and the modified Abnormal Involuntary Movement Scale (AIMS) assessment improved significantly.[22] Another review of 59 transpedicular "eggshell" osteotomies (37 for deformity) showed a 16.9% overall complication rate but no cases of neurological worsening.[33] Significant improvement was noted in pooled 36-Item Short Form

Fig. 6. Case 2. Preoperative and postoperative clinical photographs.

Health Survey scores, and 74.1% of patients were "completely satisfied" with the surgery. A somewhat higher rate of complications was noted by Ikenaga et al.;[18] of 67 patients who underwent PSO for thoracolumbar kyphosis, 27 (40%) had some type of complication. There were 48 total complications, including 7 pseudarthroses and 6 neurological complications (2 hematomas requiring reoperation) for a neurological complication rate of 8.96%. High complication rates were also found in a study by Mummaneni et al.,[32] with 70% of those in a 10-patient PSO cohort experiencing some major or minor perioperative complication; this study highlights an important point, however, which is that this subset of patients carries many medical comorbidities (90% in this cohort) and frequently has undergone multiple revision surgeries (80% in this cohort), both of which can contribute to worse operative outcomes.

Although the aforementioned studies focused largely on the use of PSOs in the lumbar spine, the technique may also be effective in the thoracic region. A study by Yang et al.[48] compared lumbar and thoracic PSOs for fixed sagittal imbalance and found no difference in outcomes between the 2 groups for modified Prolo scale scores or SRS-22 scores. Here again, there is a fairly high early and late complication rate ranging between 10 and 30% for the thoracic and lumbar cohorts.

Overall, PSO offers several benefits with respect to other osteotomy choices. First, it addresses focal kyphosis more effectively than SPO, although not as effectively as a VCR.[19,44] Furthermore, the ability to perform an asymmetric bone resection may aid in the attainment of coronal correction. A PSO may also be particularly useful in addressing sagittal imbalance, especially when used in the lumbar spine to recreate lordosis and restore the C-7 plumbline over the sacrum. However, these benefits do not come without associated drawbacks. Most notably, the PSO procedure is more technically demanding and carries with it greater operative time and blood loss than the SPO. Multiple studies have also shown a rather high complication rate following PSO procedures, which, although they may not result directly from the technique itself, highlight the medical fragility of this subset of patients in whom prior procedures and a multiplicity of comorbidities lead to a propensity for perioperative difficulties. Please refer to Table 1 for a collection of recent published findings relating to PSO.

Illustrative Case

Case 2. At the age of 23 years, this 42-year-old woman suffered a flexion-distraction injury that resulted in an 88° thoracolumbar kyphosis. At that time she underwent an instrumented fusion via an anteroposterior approach, with correction to 59° of thoracolumbar kyphosis. In the intervening years, she underwent implant removal and ultimately had progression of her kyphosis to 105° with a sagittal balance of +5 cm (Fig. 4A). Meanwhile she complained of symptoms of neurogenic claudication, and an MR imaging study (Fig. 5) demonstrated her lumbar nerve roots draped anteriorly over the posterior aspect of the vertebrae at the apex of the curve. Because her kyphosis was focal and largely centered over the L-2 VB, she underwent posterior spinal fusion with an L-2 PSO. This was followed by a second-stage anterior spinal fusion due to extension of the fusion to her sacrum. At the 5-year follow-up, her thoracolumbar kyphosis was reduced to

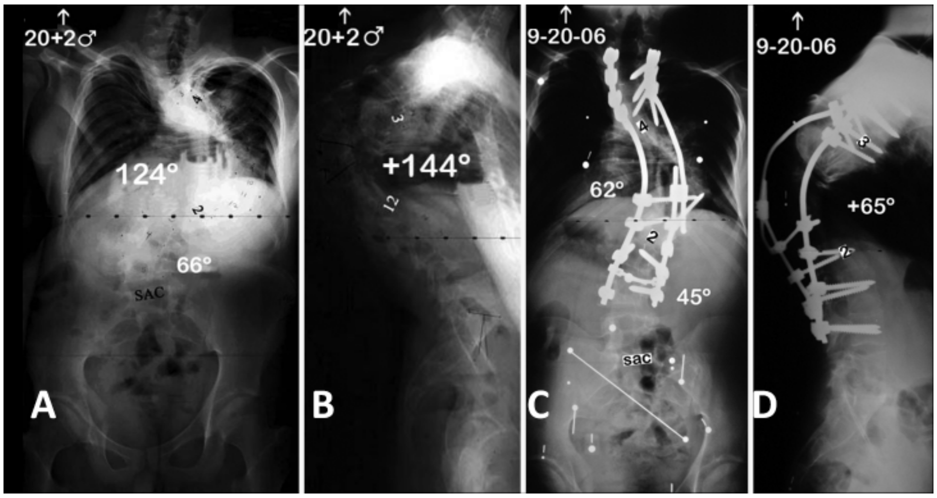

Fig. 7. Case 3. Preoperative standing anteroposterior **(A)**, preoperative standing lateral **(B)**, postoperative standing anteroposterior **(C)**, and postoperative standing lateral **(D)** 36-inch radiographs. A 2-level VCR enabled profound correction of a very severe kyphoscoliosis. sac = sacrum.

40°, and her sagittal balance was restored to 0 cm (Fig. 4B). Preoperative and postoperative clinical photographs are depicted in Fig. 6.

Vertebral Column Resection

Surgical Technique

Although vertebral corpectomy has been used for the treatment of scoliosis for many years,[3,30] the procedure known currently as pVCR has only recently been promoted by Suk et al.[41] as an option for posterior-only deformity correction. The procedure involves the resection of all posterior elements, the facet joints at the levels above and below, and essentially the entire VB and supra-adjacent/subjacent discs. The spine is then disarticulated, and the proximal and distal limbs are slowly brought together. In most cases, an anterior fusion is performed with structural support via an anterior cage in all cases; this allows

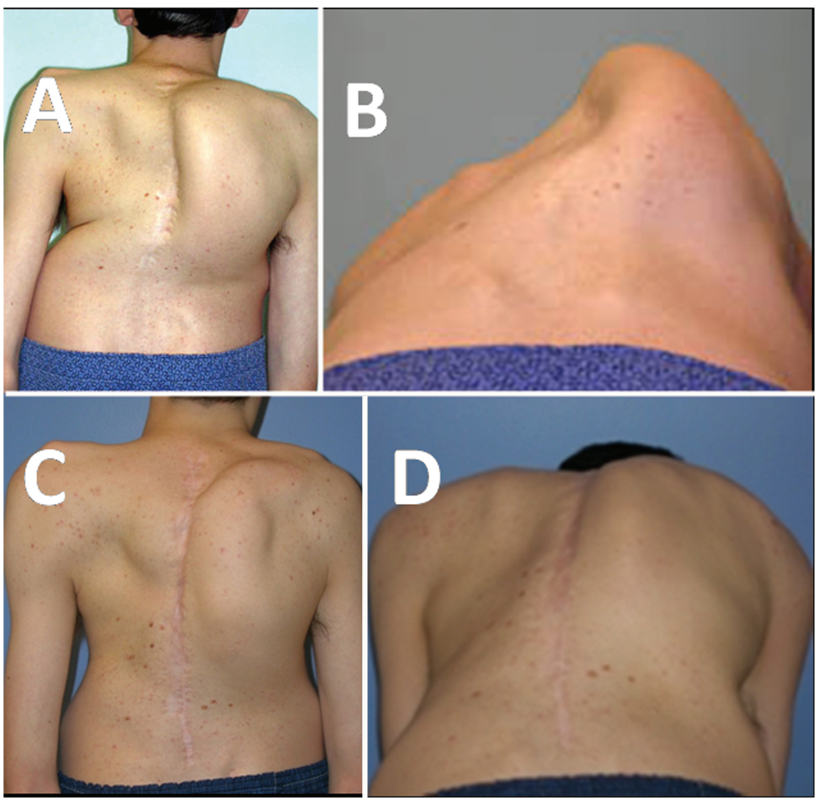

Fig. 8. Case 3. Preoperative **(A and B)** and postoperative **(C and D)** clinical photographs.

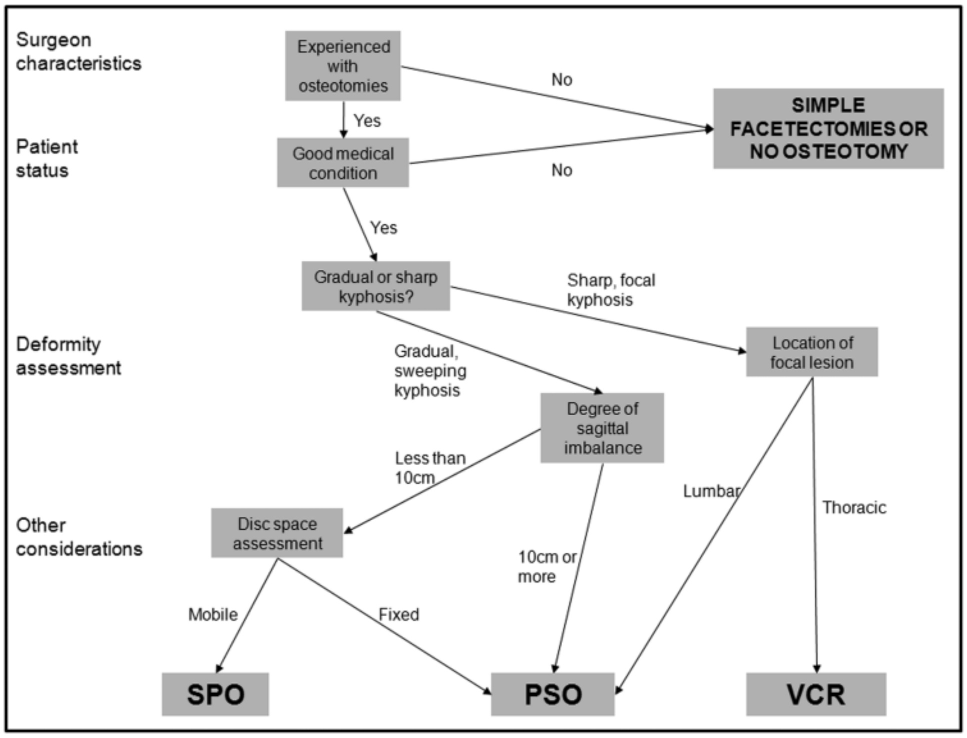

Fig. 9. General algorithm for decision making in osteotomy selection. Surgeon experience and good medical status of the patient are 2 prerequisites to proceeding with advanced osteotomy techniques. A gradual, sweeping kyphosis favors an SPO or PSO, with the latter preferable in cases with severe positive sagittal balance. A mobile disc space is required for SPOs. For sharp or focal kyphoses, VCRs are typically used in the thoracic spine and PSOs in the lumbar spine. However, individual patient characteristics and surgeon judgment must supersede any general algorithmic approach.

for relative anterior lengthening, perhaps through the use of an expandable cage implant,[36] which enhances the degree of correction. Kawahara et al.[20] have also described essentially the same technique as involving a closing-opening wedge osteotomy, which is to say that a kyphotic deformity is reduced by resection of the vertebra through a costotransverse approach, followed by "closing" of the gap with posterior compression and then "opening" of the anterior column with cage insertion. In any case, the aggressive VCR technique provides tremendous potential for deformity correction.

Posterior VCR primarily finds use in the thoracic and thoracolumbar spine for the treatment of sharp, angular kyphotic deformity. Other indications include the resection of hemivertebrae[4,16] or intravertebral spinal tumors,[1,10,31,37,39] or even, as has recently been described, the shortening of the spine proximal to a tethered region as a novel method of treating tethered spinal cord without the risks of dissection around adhesed nerve roots.[4,12,17]

Outcomes After Surgery

Studies of pVCR to date have demonstrated it to be a powerful method of focal deformity correction. Suk et al.[41] noted a correction of 61.9° in the coronal plane and 45.2° in the sagittal plane in their series of 70 patients with adult scoliosis, congenital kyphoscoliosis, and postinfectious kyphosis. In a series of 35 children, Lenke et al.[26] noted major curve improvements that averaged 61° (51%) in scoliosis cases, 56° (55%) in global kyphosis cases, 51° (58%) in angular kyphosis cases, 98° (54%) in kyphoscoliosis cases, and 24° (60%) in congenital scoliosis cases; in a slightly larger series of adults and children, the average major curve improvements were 57° (69%) for scoliosis, 45° (54%) for global kyphosis, 49° (63%) for angular kyphosis, and a combined 109° (56%) for kyphoscoliosis.[27]

Despite its effectiveness, however, pVCR poses significant operative times and blood loss, and its use can be fraught with complications. Reported operative times have ranged from 266 to 577 minutes, and blood loss has ranged from 691 to 2810 ml for this technique.[26,41,45] Regarding complications, in a series of 70 patients, Suk et al.[41] found a 34.3% overall rate of complications and a 17.1% rate of neurological complications was encountered, including 2 complete cord injuries (albeit in patients with preexisting neurological deficits), 6 hematomas with cauda equina syndrome requiring reoperation, 4 nerve root injuries, and 5 fixation failures. For these reasons, Suk noted, "Theoretically very appealing, the vertebral column resection is, in fact, a challenging procedure and is an ordeal for both the patient and the surgeon, requiring an exhaustively lengthy operation with a great risk of major complications at every turn en route." In a study in children, Lenke et al.[26] found a similar 40% overall rate of complications as well as an 11.4% rate of neurological complications; however, half occurred intraoperatively and were noted during osteotomy closure with loss of monitoring data, allowing for reparative measures that prevented subsequent deficits, thereby highlighting the importance of neuromonitoring during these cases. Finally, a recent study by Wang et al.[45] reported on 13 adults with severe rigid kyphoscoliosis who underwent a modified combined multilevel eggshell osteotomy and pVCR. These authors found a 30.7% rate of complications and a 15% rate of temporary neurological complications. They did, however, note substantial improvements in postoperative pain and SRS-24 scores at 2-year follow-up.

Overall, pVCR appears to be the most powerful posterior osteotomy method, but it carries a significant risk of complications, including potentially permanent neurological lesions. It also likely entails longer operating room time and blood loss than less invasive osteotomy techniques. This method, as emphasized by multiple authors, should be used at high-volume centers by surgeons highly experienced with the technique, and even then patients and families must be counseled to expect a difficult perioperative course. That being said, success with vertebral column resection can be optimized by following several key principles: There is no reason for a circumferential approach; more severe sagittal deformities thrust the anterior portions of the spine further posteriorly, thereby optimizing the anatomy for a posterior VCR approach. Stable pedicle screw fixation above and below is vital. A posterior VCR allows 360° access to the spinal cord to confirm/obtain decompression. From the standpoint of neurological risk, pVCR is safer for severe scoliosis than kyphosis/kyphoscoliosis. It is imperative to use somatosensory evoked potential or motor evoked potential monitoring throughout the period of correction, as well as to maintain normotension with mean arterial pressures of at least 75 to 80 mm Hg during osteotomy closure. Temporary rod placement must precede a pVCR to avoid potential catastrophic intraoperative subluxation. Placement of an anterior structural cage prevents buckling of the spinal cord and excessive segmental shortening. Extensive laminectomy one level above and below the VCR area is necessary to avoid spinal cord impingement. Rib struts can serve as "bridge grafts" to provide a bony surface for fusion over the laminectomized region following osteotomy closure. Table 1 contains a collection of recent published findings relating to VCR.

Illustrative Case

Case 3. This 20-year-old man had a history of congenital kyphoscoliosis for which he had undergone fusion in situ as a child. He presented many years later with a severe, progressive deformity with a rigid main thoracic curve with 124° of scoliosis in the coronal plane and 144° of kyphosis in the sagittal plane. He underwent VCR at T-8 and T-9 with posterior spinal fusion from T-2 to L-4. On the 2-year follow-up radiographs, reductions were noted in the main thoracic coronal curve to 62° and sagittal curve to 65° (Fig. 7). Preoperative and postoperative photographs are shown in Fig. 8.

Conclusions

The addition of several osteotomy techniques to the surgeon's armamentarium, along with the advent of 3-column posterior pedicle screw fixation, have made it such that essentially all kyphotic deformities can be treated via a posterior-only approach. A general algorithm for the selection of osteotomy techniques is provided in Fig. 9.

An understanding of the relative merits of each of the osteotomy techniques is imperative so that the deformity surgeon can use these methods to greatest effect. It is equally imperative, however, to respect the great potential for complications, even catastrophic neurological events, when these techniques are used.

Disclosure

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Spinal deformity and Parkinson disease: a treatment algorithm

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Object. The authors review the literature on the treatment of spinal deformity in patients with Parkinson disease (PD) and formulate a treatment algorithm.

Methods. The authors provide representative cases of patients with PD and spinal deformity who underwent deep brain stimulation (DBS) or spinal surgery.

Results. In patients with PD and spinal deformity who undergo spinal surgery there is a high rate of acute and delayed complications. Patients who undergo DBS, while having significantly fewer complications, often do not regain sagittal balance.

Conclusions. Cases involving PD and camptocormia have a high rate of complications when spinal surgery is performed. The authors prefer to offer spinal surgery only to patients with coexisting spinal stenosis causing radiculopathy or myelopathy. Patients with PD and camptocormia without spinal stenosis may be considered for DBS, but the results are mixed. *(DOI: 10.3171/2010.1.FOCUS09288)*

Key Words • **Parkinson disease** • **camptocormia** • **spinal deformity** • **Pisa syndrome**

Parkinson disease is a neurodegenerative disorder that affects over 1 million people in the US.[19] It is estimated that the lifetime risk of developing PD is 1.5%.[7,10] With the aging of the US population, the prevalence of PD will likely continue to grow.[35] A recent estimate of the prevalence of deformities (involuntary trunk flexion/camptocormia, anterocollis, scoliosis) in PD was 33.5%.[2]

The cardinal motor signs of PD are 4–6-Hz resting tremor, rigidity, bradykinesia, and gait disorder/postural instability. Other symptoms include stooped posture, hypophonia, and paucity of facial expression. However, it can be difficult to diagnose PD correctly, and the early signs of PD can often be subtle. This has particular relevance when trying to understand the impact of surgical interventions on this population.[19] In the later stages of PD, the patients have a risk of developing dementia.[1,22] The dementia may contribute to death due to PD.[21]

Patients with PD may present with postural deformities. Several factors can contribute to postural instability including axial rigidity, poor trunk coordination, orthostatic hypotension, and difficulty integrating various sensory inputs. The postural instability contributes to increasing difficulty with transfers, gait, ability to live independently at home, and falls.[5]

Abbreviations used in this paper: DBS = deep brain stimulation; GPi = globus pallidus internus; PD = Parkinson disease; STN = subthalamic nucleus.

A number of spinal deformities have been described in association with PD. The stooped posture classically associated with PD is the most common abnormality. Other disorders include camptocormia, myopathy-induced postural deformity, Pisa syndrome, and degenerative scoliosis. Here, we review the literature on surgical treatment of spinal deformity in patients with PD, including effects of DBS and spinal instrumentation.

Camptocormia

Camptocormia, or "bent spine syndrome," is an extreme forward flexion of the thoracolumbar spine, which often worsens during standing or walking, but completely resolves when supine. The term itself is derived from the Greek "kamptos" (to bend) and "kormos" (trunk). While the condition was described as early as 1818, the term camptocormia was first proposed in 1914 to describe the forward flexion posture of some soldiers in World War I who had to move through the trenches in a bent posture to avoid injury.[8,18,28,31]

Camptocormia is used to describe the extreme forward flexion of the spine associated with a number of causes including dystonia, Tourette syndrome, amyotrophic lateral sclerosis, myopathy, myositis, multiple system atrophy, PD, and conversion disorder. While initially thought to be a rare manifestation of PD, recent estimates of the prevalence of camptocormia in patients with PD vary from 3–12.9%.[2,20,33] It is unclear if the prevalence of camptocormia varies with the severity of the PD.[3,6,11,20,33]

Medical management of camptocormia in PD remains suboptimal. Azher and Jankovic[3] have reviewed the cases of 16 patients with camptocormia associated with PD (11 patients), dystonia (4 patients), and Tourette syndrome (1 patient). Twelve patients received levodopa therapy with minimal or no improvement in camptocormia. In 9 patients botulinum toxin Type A was administered into the rectus abdominus muscle, with improvement in 4 patients. Ho et al.[17] have described a single patient in whom camptocormia improved after adjustments in dopaminergic therapy. Von Coelln and colleagues[37] reported on 4 patients with PD who received ultrasound-guided injections of botulinum toxin Type A into the iliopsoas muscle. While they found the technique to be safe, with only patients receiving the highest doses reporting mild weakness of hip flexion, they also found no significant postural improvement. Bloch et al.[6] have reported a case control study (8 patients in each arm) and found that patients with PD and camptocormia responded poorly to levodopa treatment and had levodopa-unresponsive axial symptoms.

Subthalamic nucleus DBS has been reported to improve camptocormia associated with PD. Sako et al.[27] have reported on 6 patients in whom they documented a mean improvement of 78 ± 9.1% in thoracolumbar angle after bilateral STN stimulation. Hellmann et al.,[16] Yamada et al.,[39] and Micheli et al.[23] each reported on a single case of PD and camptocormia in which the patient improved after bilateral subthalamic DBS or GPi stimulation. Reports on the responsiveness of camptocormia in PD patients have been inconsistent. Of the 16 patients reported on by Azher and Jankovic,[3] one underwent placement of bilateral STN electrodes with no improvement in camptocormia. Most recently, Umemura et al.[34] reported on a retrospective analysis of 18 patients (8 with camptocormia, 10 with Pisa syndrome) who underwent subthalamic DBS placement. In 13 patients with a moderate postural abnormality, 11 patients ultimately improved. In the 5 patients with severe postural abnormality, 2 patients improved slightly. Deep brain stimulation has also been reported to improve camptocormia associated with other movement disorders. Fukaya et al.[13] reported improvement of camptocormia in 3 patients with primary dystonia who underwent placement of bilateral GPi DBS. Nandi et al.[24] published a case report of a patient with tardive dyskinesia and camptocormia who responded to the placement of bilateral GPi electrodes for DBS. However, it is unclear if the pathophysiology of camptocormia in PD is similar to that of camptocormia associated with primary dystonia.

Babat et al.[4] reported on 14 patients with PD who underwent spinal surgery (mostly short-segment laminectomies/fusions; 1 patient underwent multiple-level cervical corpectomy, 1 underwent deformity correction, and 1 underwent L-1 transpedicular decompression for burst fracture). They noted that 11 patients underwent 22 additional operations at the same or adjacent levels for instability. Four of these patients had hardware failure or pullout, requiring 10 additional operations. Their conclusion was that the primary cause of failure was persistent kyphosis or segmental instability. Peek et al.[26] recently described the case of a patient with PD and camptocormia who underwent posterior T7–ilium fixation. The patient required several surgical revisions, prolonged hospitalization, and rehabilitation. Although they were ultimately successful in restoring spinal balance, their conclusion was to consider surgical intervention only after subthalamic nucleus DBS has been performed and then only in patients who were highly motivated to walk.

Myopathy Associated Postural Deformity in PD

Inflammatory myopathy of the paraspinal muscles can mimic the appearance of camptocormia in PD. Wunderlich et al.[38] have described a 63-year-old man with PD in whom a camptocormia-like deformity developed. They noted hyperintensity (consistent with edema) within the paraspinal muscles and histopathological features consistent with myositis. The patient was treated with steroids and they noted marked improvement in forward flexion.

Myopathy with nemaline rods, end-stage myopathy with autophagic vacuoles, mitochondrial myopathy, and necrotizing myopathy have all been associated with camptocormia in patients with PD.[15,25,30] Gydnia et al.[15] have studied 19 consecutive muscle biopsies obtained in patients with PD and either camptocormia or dropped-head syndrome (anterocollis), finding abnormal muscle biopsies in all patients. Although MRI images were not abnormal in all patients, MR imaging generally showed fatty degeneration of the paravertebral musculature or neck extensor musculature in many of them. Electromyography was also generally consistent with myopathy changes.

Pisa Syndrome

Pisa syndrome is characterized by a lateral flexion of the trunk when sitting or standing.[5] In addition, there is an associated backward axial rotation of the spine. The term itself is derived from the image of the patient leaning much like the Leaning Tower of Pisa. The condition was first described by Ekbom et al.[12] in 1972. It is generally associated with the use of neuroleptics, antiemetics, and/or cholinesterase inhibitors.[32,36] Treatment generally consists of removing the offending medication or reducing the dosage. Gambarin et al.[14] reported on one patient with PD in whom Pisa syndrome developed without having received neuroleptic drugs, antiemetic medications, antipsychotics, selective serotonin reuptake inhibitors, or benzodiazepines. Cannas et al.[9] described 8 patients with PD and Pisa syndrome whose symptoms were brought on by the introduction of or increase in a dopaminergic medication. In a single case report Santamato et al.[29] described a patient with PD and Pisa syndrome who benefited from a rehabilitation program and botulinum toxin Type A therapy after medication adjustments were made.

We present representative cases from our experience of treating camptocormia in patients with PD. We then propose a treatment algorithm incorporating a multimodality treatment strategy.

Case Reports

Case 1: Bilateral STN DBS

This patient was a 59-year-old man with advanced idiopathic PD and motor fluctuations. Preoperatively it was noted that he had severe camptocormia (Fig. 1 left). He underwent placement of bilateral STN deep brain stimulators and a right chest dual channel pulse generator. He was discharged to an acute rehabilitation facility on postoperative Day 6 in good condition for several weeks after his hospitalization. At 2-year follow-up, his gait and ease of ambulation had improved, but he had no significant improvement in his camptocormia posture (Fig. 1 right).

Case 2: Bilateral GPi DBS

This patient was a 59-year-old man with PD and severe camptocormia. Parkinson disease was diagnosed based on the initial presenting symptoms of a severe stooped posture, decreased fine finger movements, and bilateral hand tremor. The patient's camptocormia only minimally responded to dopaminergic medications, and he would fall several times a day. He had begun wearing kneepads to prevent further injury from his frequent falls. He underwent placement of bilateral GPi DBS electrodes to alleviate his parkinsonian symptoms as well as treat his camptocormia. He was discharged to an acute rehabilitation facility on postoperative Day 5 in good condition. At 15-month follow-up, while having some improvement in his parkinsonian symptoms, he continued to suffer from severe camptocormia.

Case 3: Short-Segment Spinal Fusion

This patient was a 68-year-old man with PD, severe camptocormia, chronic low-back pain, bilateral lower-extremity pain, and severe spinal stenosis (Fig. 2 left). He had previously undergone a left L4–5 hemilaminotomy that gave him 6 weeks of relief. Lumbar MR imaging demonstrated multilevel high-grade stenosis at L2–3, L3–4, and L4–5. He also had mobile Grade 1 L4–5 anterolisthesis. He underwent an L1–5 posterior spinal fusion with Smith-Petersen osteotomies at L2–3, L3–4, and L4–

Fig. 1. Case 1. Preoperative image of patient with severe camptocormia prior to DBS **(left)**, and postoperative image obtained after DBS at 24-month follow-up **(right)**.

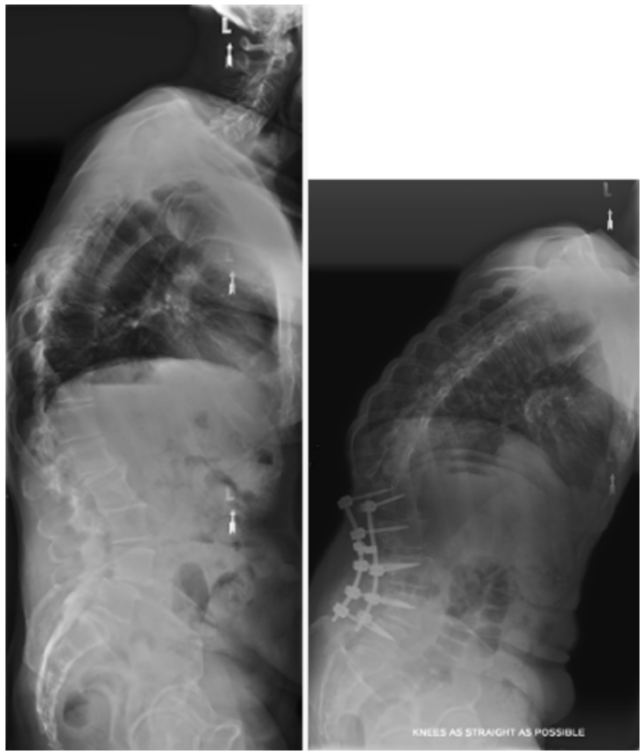

Fig. 2. Case 3. Standing 36-in radiographs. Preoperative image demonstrating severe camptocormia **(left)**, and postoperative image revealing progression of kyphosis above the construct **(right)**.

5. In addition, a transforaminal lumbar interbody fusion was performed at L2–3, L3–4, and L4–5. Postoperatively, a marked bradykinesia and rigidity developed, which ultimately improved over the following several days. Furthermore, he remained confused during much of his acute inpatient course and was treated for diarrhea due to *Clostridium difficile*. He was ultimately discharged to rehabilitation in good condition with a thoracolumbosacral orthosis brace on postoperative Day 17. At 6-week follow-up he remained in a skilled nursing facility. Imaging studies caused concern regarding the progression of postural kyphosis above his construct (Fig. 2 right). At 3 months, CT scanning of the lumbar spine demonstrated hollowing of the L-1, L-2, and L-5 screws. At 6 months, imaging studies suggested pseudarthrosis at L3–4 and L4–5, and we were concerned by the possibility of discitis at these levels. The patient underwent CT-guided biopsy of these levels and the cultures grew *Enterobacter cloacae*. He was started on long-term antibiotic therapy.

Case 4: Long-Segment Spinal Fusion

This patient was a 65-year-old woman with PD who complained of back pain and worsening capacity to ambulate due to her sagittal imbalance (Fig. 3). She required a wheelchair when outside of her home. She had no significant spinal stenosis. She underwent a T3–4 posterior spinal fusion. After 7 days of hospitalization, she was discharged to rehabilitation. Initially she was ambulatory with a walker and was weaned off oral narcotics. She returned to clinic 4 months postoperatively with recur-

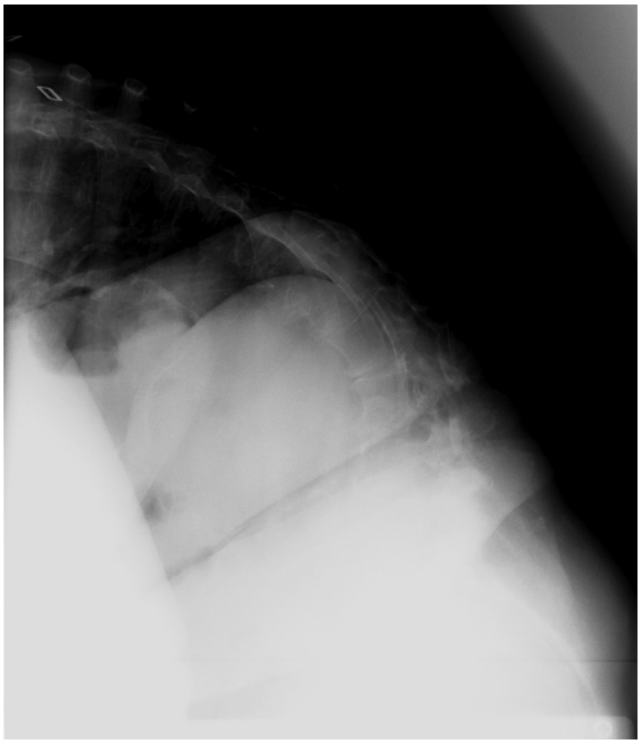

Fig. 3. Case 4. Preoperative radiograph showing significant sagittal imbalance.

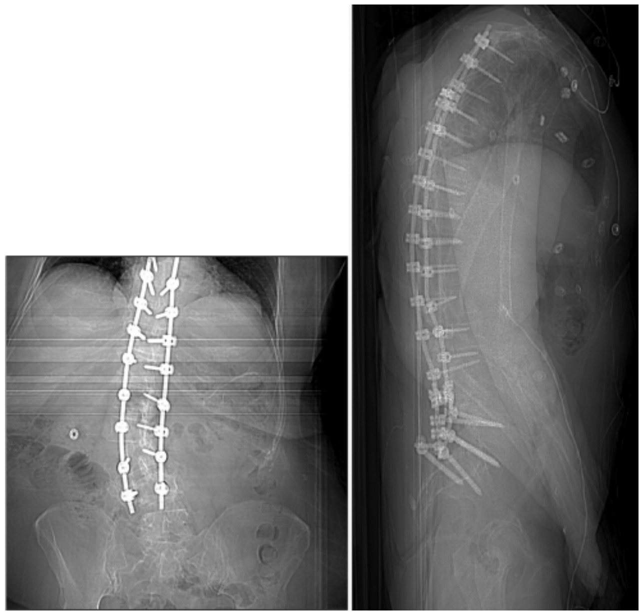

Fig. 4. Case 4. **Left:** Four-month postoperative radiograph demonstrating pseudarthrosis and lateral fixed listhesis at L4–5. **Right:** Postoperative radiograph demonstrating extension to S-1 and the ilium.

rent back pain and was found to have pseudarthrosis due to partial screw pullout at L3–4 as well as a new lateral fixed listhesis at L4–5 (below her fusion) (Fig. 4 left). She underwent posterior spinal revision surgery in which the fusion extended to the sacrum and pelvis (Fig. 4 right). Again she was discharged to rehabilitation after 7 days of hospitalization and regained her ability to ambulate with a walker. She returned to clinic 2 years later in a wheelchair. She reported that she ambulated short distances in her home, but she was not motivated to ambulate outside her home and preferred to be in a wheelchair. She reported her back pain was improved and her capacity to sit upright was improved. A radiographic fusion was achieved.

Discussion

The surgical management of patients with PD and spinal deformity is difficult for a number of reasons. First, a number of conditions that can be treated nonsurgically must be considered. For example, patients with severe motor fluctuations and transient abnormal truncal postures associated with wearing-on or wearing-off dystonia could respond to changes in antiparkinsonian medications. Patients with myopathy of the paraspinous muscles should also be excluded from surgical consideration. Patients with severe anterocollis or "dropped head" may suffer from a form of atypical parkinsonism that does not respond to DBS. Second, our experience, as well as the limited published surgical experience of spinal surgery in patients with PD, suggests that there is a high postoperative complication rate. Furthermore, the symptoms of postural instability, depression, and cognitive impairment, which are common features of later-stage PD, can make postoperative rehabilitation a challenge. Table 1 summarizes the current literature regarding camptocormia and either spinal surgery or DBS.

The role of DBS in the management of severe spinal deformity associated with PD is not yet known. Given that there is limited evidence that some patients' spinal deformities may improve after DBS, the presence of spinal deformity should not be considered a contraindication for DBS as long as other standard criteria for DBS surgery exist. The standard criterion for DBS in PD is the presence of motor fluctuations in the setting of optimal medical management by a movement disorders neurologist (in patients who do not have dementia).

Our proposed algorithm attempts to classify the range of spinal deformity in patients with PD (Fig. 5). In any patient with PD and a spinal deformity, an appropriate history and physical examination, along with imaging studies, should be obtained. Furthermore, consultation with a movement disorders neurologist is essential in ensuring an accurate diagnosis of idiopathic PD and in ensuring that the patient's medical regimen is optimized. Imaging studies should be acquired to evaluate for the possibility of myopathy, noted in particular with high T2 signal on MR imaging. If there is doubt, then a muscle biopsy can also be considered. Myopathy does not respond well to spinal surgery or DBS.

In patients in whom symptoms meet standard criteria for DBS (debilitating motor fluctuations in the setting of optimal medical management), DBS can be considered. However, it should be noted that in the experience of one of the authors (P.A.S.), at most 50% of the patients experience persistent benefit in their postural deformity following DBS of either the STN or GPi. Thus, if all parkinsonian motor symptoms other than abnormal posture are

TABLE 1: Summary of reports on the treatment of camptocormia with medical management, DBS, or spinal surgery*

Authors & Year	No. of PD Patients w/ Deformity	Type of Study	Intervention	Camptocormia Outcomes	Complications
Azher & Jankovic, 2005	11 with PD, 1 w/ generalized dystonia	case series	12 treated w/ dopaminergic medication adjustment; 9 w/ clinical evidence of contractions of rectus abdominus received botox; 2 received intrathecal baclofen infusion; 1 patient received bilat STN DBS	patients treated w/ medication adjustment only had minimal to no effect on camptocormia; 4 treated w/ botox noted moderate to marked improvement; no benefit to intrathecal baclofen infusion; no improvement in single patient who received DBS	none reported
Ho et al., 2007	1	case report	medical management	reported improvement w/ adjustments to dopaminergic therapy	none reported
von Coelln et al., 2008	4	case series	botox injection into iliopsoas	no improvement	transient & mild itching at injection site in 1 patient
Bloch et al., 2006	16	case control	dopaminergic treatment	poor response	no significant difference between groups
Sako et al., 2009	6	case series	bilat STN stimulation	reported improvement	none reported
Hellmann et al, 2006	1	case report	bilat STN stimulation	reported improvement	none reported
Yamada et al., 2006	1	case report	bilat STN stimulation	reported improvement	none reported
Micheli et al., 2005	1	case report	bilat GPi stimulation	reported improvement	none reported
Umemura et al., 2009	8 w/ camptocormia, 10 w/ Pisa syndrome	case series	bilat STN stimulation	early: 4/8 patients reported improvement; late: 5/8 patients reported improvement	1 had severe skin erosion at site of internal pulse generator requiring op repair; 1 suffered from prolonged depression
Peek et al., 2009	1	case report	spinal surgery	ultimately improved	multiple revision ops, percutaneous gallbladder drainage, prolonged hospital & rehabilitation course
Babat et al., 2004†	14	case series	spinal surgery	NA	12 (86%) had reops; 4 (29%) had hardware pullout, requiring 10 additional ops

* Botox = botulinum toxin Type A; NA = not applicable.

† This study did not specifically address camptocormia.

adequately treated medically, there is limited evidence to support DBS for camptocormia as the primary surgical indication.

In patients with camptocormia, one must also evaluate for the presence of myelopathy or radiculopathy due to spinal stenosis (Fig. 6). Patients with spinal stenosis and camptocormia who are candidates for DBS may first undergo DBS placement. In these patients, if the camptocormia does improve following DBS, a short-segment spinal decompression can be considered to treat spinal stenosis. If the patient does not meet standard criteria for DBS implantation (and does not undergo DBS), then spine surgeons may consider short-segment decompression and fusion alone. Long-segment spinal deformity correction and decompression should only be considered in patients who have minimal other comorbidities and are very well motivated to walk. It should be noted that long-segment spinal fixation in camptocormic patients is associated with a very high complication rate (essentially 100%).

In patients with camptocormia who do not have spinal stenosis, treatment follows a similar algorithm. If they have typical indications for DBS surgery in addition to their spinal deformity, then DBS can be offered. If they do not have indications for DBS, then long-segment deformity correction should probably not be offered because of the very high complication and revision surgery rate.

In patients who have a camptocormic posture with coexistent rigid degenerative scoliosis our recommendations are to consider short-segment decompression/fusion in patients with symptomatic stenosis, and to reserve long-segment deformity correction (with osteotomies) only for those patients who are motivated to walk, given

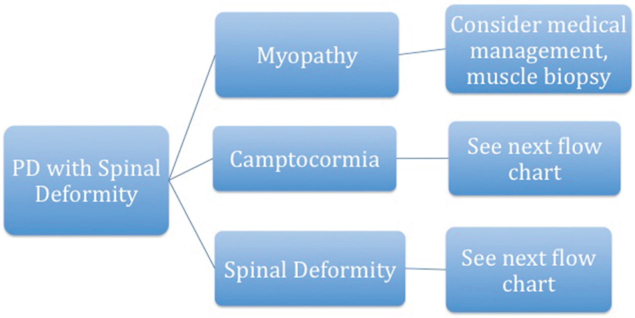

Fig. 5. Proposed surgical algorithm for the management of spinal deformity in patients with PD.

our experience with a high complication rate (> 50% major complications) (Fig. 7).

Conclusions

We present our algorithm for the management of patients with PD and spinal deformity. In our experience, patients with PD who undergo spinal surgery have a high rate of both acute and delayed complications. Nonsurgical management is preferred in this patient population. In addition, DBS can be considered in the correctly selected patient as an option for the treatment of some spinal deformities associated with PD. However, DBS is not universally effective in treating camptocormia.

Short-segment spinal decompression and fusion may be considered in patients with coexistent camptocormia and spinal stenosis with myelopathy or radiculopathy. Long-segment spinal fixation procedures should be performed sparingly due to the very high complication rates reported in the literature.

Disclosure

Author contributions to the study and manuscript preparation include the following. Conception and design: PV Mummaneni.

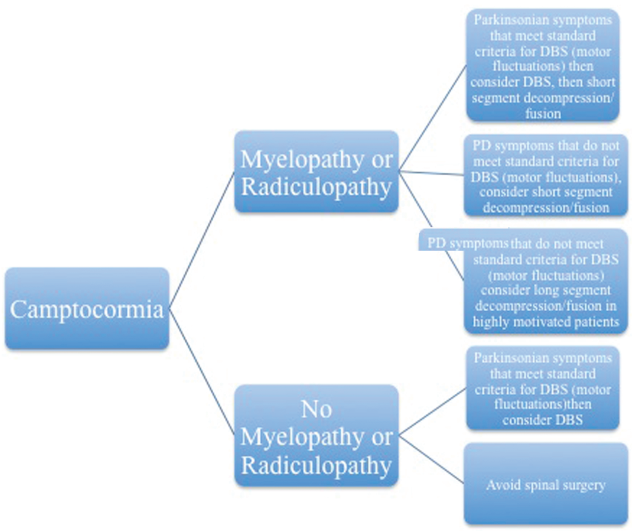

Fig. 6. Proposed surgical algorithm for the management of camptocormia in patients with PD.

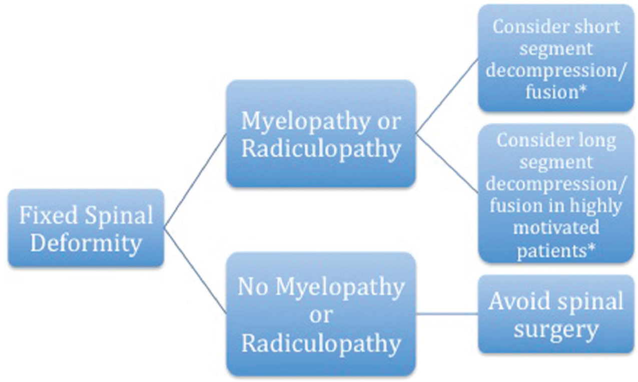

Fig. 7. Proposed surgical algorithm for the management of fixed spinal surgery in patients with PD. Spinal surgery is associated with a greater than 50% risk of early and late complications in patients with PD. *Asterisk* indicates that the correction of fixed spinal deformity with either a short- or long-segment fusion (with osteotomies) should be tailored to the individual patient, taking into account the patient's spinal balance and medical comorbidities.

Acquisition of data: PV Mummaneni, CD Upadhyaya, PA Starr. Analysis and interpretation of data: PV Mummaneni, CD Upadhyaya, PA Starr. Drafting the article: CD Upadhyaya. Critically revising the article: PV Mummaneni, PA Starr. Reviewed final version of the manuscript and approved it for submission: PV Mummaneni, PA Starr.

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Mid-term to long-term clinical and functional outcomes of minimally invasive correction and fusion for adults with scoliosis

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Object. The goal of this study was to assess the operative outcomes of adult patients with scoliosis who were treated surgically with minimally invasive correction and fusion.

Methods. This was a retrospective study of 28 consecutive patients who underwent minimally invasive correction and fusion over 3 or more levels for adult scoliosis. Hospital and office charts were reviewed for clinical data. Functional outcome data were collected at each visit and at the last follow-up through self-administered questionnaires. All radiological measurements were obtained using standardized computer measuring tools.

Results. The mean age of the patients in the study was 67.7 years (range 22–81 years), with a mean follow-up time of 22 months (range 13–37 months). Estimated blood loss for anterior procedures (transpsoas discectomy and interbody fusions) was 241 ml (range 20–2000 ml). Estimated blood loss for posterior procedures, including L5–S1 transsacral interbody fusion (and in some cases L4–5 and L5–S1 transsacral interbody fusion) and percutaneous screw fixation, was 231 ml (range 50–400 ml). The mean operating time, which was recorded from incision time to closure, was 232 minutes (range 104–448 minutes) for the anterior procedures, and for posterior procedures it was 248 minutes (range 141–370 minutes). The mean length of hospital stay was 10 days (range 3–20 days). The preoperative Cobb angle was 22° (range 15–62°), which corrected to 7° (range 0–22°). All patients maintained correction of their deformity and were noted to have solid arthrodesis on plain radiographs. This was further confirmed on CT scans in 21 patients. The mean preoperative visual analog scale and treatment intensity scale scores were 7.05 and 53.5; postoperatively these were 3.03 and 25.88, respectively. The mean preoperative 36-Item Short Form Health Survey and Oswestry Disability Index scores were 55.73 and 39.13; postoperatively they were 61.50 and 7, respectively. In terms of major complications, 2 patients had quadriceps palsies from which they recovered within 6 months, 1 sustained a retrocapsular renal hematoma, and 1 patient had an unrelated cerebellar hemorrhage.

Conclusions. Minimally invasive surgical correction of adult scoliosis results in mid- to long-term outcomes similar to traditional surgical approaches. Whereas operating times are comparable to those achieved with open approaches, blood loss and morbidity appear to be significantly lower in patients undergoing minimally invasive deformity correction. This approach may be particularly useful in the elderly. *(DOI: 10.3171/2010.1.FOCUS09272)*

Key Words • **minimally invasive spine surgery** • **adult deformity** • **transpsoas approach**

Scoliosis has been estimated to occur in approximately 6% of the population older than 50 years of age.[32] In adults, scoliosis may arise secondary to untreated adolescent idiopathic scoliosis, failed surgical or nonsurgical treatment, or de novo spinal deformity occurring when the patient is an adult; for example, lumbar degenerative scoliosis.[10] Adults with scoliosis typically present with back pain.[10] Furthermore, 15% of the population with low-back pain and older than 60 years of age has been noted to have scoliosis.[28]

Among the most common forms of adult scoliosis seen in the elderly is lumbar degenerative scoliosis. It has been postulated to develop because of asymmetrical degeneration of discs, osteoporosis, and vertebral body compression fractures.[7,21] The treatment of adult scoliosis remains controversial. Although nonsurgical management is the mainstay of treatment for this condition, its efficacy is not well supported in the literature.[31] When surgery is performed, little consensus exists for optimal

Abbreviations used in this paper: AxiaLIF = axial lumbar interbody fusion; DBM = demineralized bone matrix; DLIF = direct lateral interbody fusion; HRQOL = health-related quality of life; ODI = Oswestry Disability Index; PLIF = posterior lumbar interbody fusion; rhBMP-2 = recombinant human bone morphogenetic protein–2; SF-36 = 36-Item Short Form Health Survey; TIS = treatment intensity scale; VAS = visual analog scale; XLIF = extreme lateral interbody fusion.

management because of the heterogeneous presentation of the disorder, controversial surgical indications, numerous surgical options, and heterogeneous outcomes in reported series. Surgery is also associated with considerable complication rates, especially in the elderly.[31]

Minimally invasive spine surgery theoretically allows for less tissue damage and blood loss, and as a result less morbidity in the treatment of adult scoliosis.[4,27] Earlier we reported the feasibility and technique of using 3 novel minimally invasive methods for circumferential deformity correction and fusion of scoliosis.[4] In this paper we report on a consecutive series of patients with adult scoliosis in whom 3 or more levels were treated with instrumentation and fusion according to minimally invasive methods, and in whom more than 1 year of clinical and radiographic follow-up was available.

Methods

A research associate identified all patients who had undergone minimally invasive circumferential adult scoliosis deformity correction through a review of the database of surgical cases performed by the senior author (N.A.). Seventy-two consecutive patients were identified who had undergone minimally invasive percutaneous instrumentation and fusion for adult scoliosis. Only patients with fusions of 3 or more levels were included, and all had to have a minimum of 1 year of follow-up. Additionally, all had to have a minimum 15° Cobb angle to be included. Twenty-eight patients were identified who met the selection criteria. All patients had severe predominantly low- to middle-back pain, worsening over the day with any loading activity. Sitting was the worst position for pain, with stiffness in the morning being a ubiquitous symptom in all. Eighteen of these patients had associated radiculopathy; 10 had severe radiculopathy that worsened with standing and walking. These patients had central and lateral recess stenosis documented on MR imaging. The other 8 had intermittent radiculopathy and foraminal stenosis on MR imaging. There were 13 men and 15 women (mean age 67.7 years, range 22–81 years), and the mean follow-up time was 22 months (range 13–37 months). All patients had participated in extensive conservative therapies without adequate relief of their symptoms before being considered for surgery.

Data for this study were obtained through retrospective chart review with Internal Review Board approval. Outcome data were prospectively collected at each visit through self-administered patient questionnaires, with 100% follow-up. All surgery was performed by the senior spine surgeon at a single institution.

Surgical Technique

Fusion levels were based on the extent of degeneration and segmental instability. All degenerated discs in the Cobb angle were fused, and fusion extent was up to the first parallel normal disc on MR imaging. The techniques used for minimally invasive percutaneous correction and fusion for adult scoliosis have been described by us previously.[4] In summary, the patients in this study underwent a single or a combination of the following surgical interbody disc release and fusion procedures: 1) XLIF (NuVasive, Inc); 2) DLIF (Medtronic Sofamor Danek, Inc.); or 3) AxiaLIF for L5–S1 fusion, or in some cases L4–5 and L5–S1 fusion (TranS1, Inc.). Posteriorly, all patients underwent multilevel percutaneous pedicle screw instrumentation, for which the Medtronic CD Horizon Longitude system was used. If 3 or more levels were being treated, the surgeries were staged 2 to 3 days apart, with the lateral interbody discectomies and fusions being performed in the first stage, followed by the second stage, in which the axial interbody fusion and the posterior instrumentation and fusion were done.

The techniques of lateral lumbar interbody fusion procedures (XLIF and DLIF) have been well described.[3,6,16,23,25,26] The technique was nearly identical for both the XLIF and DLIF procedures, with the exception of access to the disc space and use of different retractor systems. Proprietary instrumentation was used for disc space access, in addition to continuous neurophysiological monitoring, including free-running and triggered electromyography. In degenerative scoliosis, the side selected for access to the disc space was determined by the side where the L4–5 disc space was more readily accessible given the morphological features of the iliac crest. If L4–5 was not being fused, then access was always obtained on the side of the convexity. In adult idiopathic scoliosis, the MR imaging study was carefully reviewed with regard to the vascular anatomy, and access was obtained from the convex side. The disc was released all the way to the contralateral side to obtain maximal coronal correction at that segment. After endplate preparation, lordotic polyetheretherketone spacers supplemented with rhBMP-2/ACS (Infuse, Medtronic Sofamor Danek) and Grafton putty DBM (Osteotech) were then used to maintain the correction and perform fusion. A single large Infuse sponge (infused with 12 mg rhBMP-2) was equally divided among all the levels being fused, and placed within the polyetheretherketone cage in the DLIF procedure, augmented with Grafton putty DBM. This averaged to 3.5 mg of rhBMP-2 (range 2–4 mg/level) per disc space fused via the transpsoas technique. The lowest level was always treated first, with sequential segmental discectomy and fusion being performed from a caudal to rostral direction.

The TranS1 AxiaLIF procedure was used as the percutaneous interbody fusion technique for L5–S1, and in some cases L4–5 and L5–S1 (when access to the L4–5 interspace via the transpsoas approach was not feasible because the patient's iliac crest was relatively high). The general technique for this approach has also been described in detail elsewhere.[23] The AxiaLIF nondistracting screws were placed across the L5–S1 disc space (and in some cases also L4–5). Lordosis was obtained by positioning the patients' legs in extension, and by performance of discectomies. Fusion was obtained with local bone, Grafton putty DBM, and use of one-half of a small sponge of Infuse (from an additional kit) per level. This amounts to 2.1 mg of rhBMP-2 per disc space fused with this technique.

Posterior multilevel percutaneous pedicle screw stabilization was obtained using the Medtronic CD Horizon

Longitude system. All screws were placed percutaneously with the aid of fluoroscopic guidance. Cannulated screws were placed over guide wires. All screws had extenders attached to them containing a slot to receive an unconstrained rod. Rods were shaped according to the sagittal contour desired, and then passed freehand through the slots under direct fluoroscopic control. After they were passed into all the screw extenders, the rods were reduced to seat them into the tulips of pedicle screw heads. Once reduced, a top locking nut was inserted to fix the rod to the screw, starting from the caudal screw and working proximally in a sequential manner. After all the nuts were placed in the screw heads, extenders were unseated and detached from the screws. Posterior fusion was then performed in long fusions at the levels that were not done anteriorly, and at all levels that underwent transsacral procedures. This was done through the same incision used for screw placements, via a Wiltse-style approach with an expandable tubular retractor. Facet joints and pars were identified, then decorticated with a high-speed bur and grafted with local bone augmented with Grafton putty DBM and rhBMP-2. Approximately 1.62 mg of rhBMP-2 was used per facet–pars complex fused with this technique. In patients in whom segments had already been treated with anterior lumbar fusion, pedicle screw instrumentation was used as a posterior tension band for increased stability and correction; there was no posterolateral fusion at these levels.[4]

Study Measures

Study measures included operative data consisting of blood loss and operating time. Length of hospital stay was noted, as were perioperative complications.

Clinical and functional outcome was evaluated using the VAS, the ODI and TIS questionnaires, and the SF-36 health survey. These were collected prospectively preoperatively and at 6-week, 3-month, 6-month, 1-year, 2-year, and 3-year intervals. The TIS questionnaire[5] was administered to document objectively the amount of treatment for pain that patients received postsurgery. It consists of 5 questions with 6 choices each. The questionnaire is scored 0 to 100, and it objectively quantifies the basic postoperative treatment received by each patient, and assigns a score at follow-up.[5] The self-administered questionnaires and radiographic data were scored and tabulated in a database. Patients were asked to rate the surgery as excellent, good, fair, or poor, and to state whether they would recommend the surgery to another patient or friend.

Results

The demographic data of the patients in the cohort are listed in Table 1, along with the levels treated and the number of anterior and posterior levels fused. Seventeen patients underwent a TranS1 AxiaLIF procedure at L5–S1 or at L4–5 and L5–S1.

Surgical and Clinical Data

Surgical data are shown in Table 2. For anterior procedures (transpsoas discectomy and interbody fusions), the estimated blood loss was 241 ml (range 20–2000 ml). A single patient incurred a 2000-ml blood loss subsequent to retrocapsular renal bleeding, which tamponaded off without any sequelae. Estimated blood loss for posterior procedures, including L5–S1 transsacral interbody fusion and percutaneous screw fixation, was 231 ml (range 50–400 ml). The mean operating time, which was recorded from time of incision to closure, was 232 minutes (range 104–448 minutes) for the anterior procedures, and for posterior procedures it was 248 minutes (range 141–370 minutes). The mean length of stay was 10 days (range 3–20 days).

All patients had a solid arthrodesis documented at 1 year. This was confirmed on plain radiographs, and further documented on CT scans in 21 patients. The mean Cobb angle preoperatively was 22.3° (range 15–62°), and postoperatively it was 7.47° (range 0.6–22°) ($p < 0.0001$; see Figs. 1 and 2).

Clinical results were all found to be statistically significant, and are shown in Table 3. The mean preoperative VAS and TIS scores were 7.05 and 53.5; postoperatively these were 3.03 and 25.88, respectively. The mean preoperative SF-36 and ODI scores were 55.73 and 39.13; postoperatively these were 61.50 and 7, respectively.

Postoperative Complications

Seventeen patients were noted to have immediate postoperative thigh dysesthesias, which resolved within 6 weeks. Transient hip flexor weakness and pain was also noted in several patients, which completely resolved again within 6 weeks of surgery. All patients showed fusion on imaging studies, with no evidence of pseudarthrosis. One patient required removal of the proximal screw at T-12 once fusion was confirmed on CT scans; the screw had to be removed because of its prominence. Another patient had an asymptomatic proximal screw fracture at L-2, with solid fusion confirmed on imaging studies. Two patients developed quadriceps palsy with weakness of the vastus medialis, and these patients went on to achieve complete recovery by 6 months. There were no vascular or permanent neurological issues. One patient had an intraoperative retrocapsular renal hematoma, which tamponaded off and needed no further intervention. She did lose 2000 ml of blood, and received appropriate transfusions, with no untoward sequelae. Another patient had an unrelated cerebellar hemorrhage that presented as lethargy 2 days postoperatively. The patient required emergency craniectomy, clot evacuation, and ventriculostomy placement. She recovered well without long-term sequelae: she has no dysarthria, dysmetria, ataxia, or other cerebellar signs and symptoms. No durotomy occurred during surgery, and the extensive cardiac and neuroimaging workup was negative for an embolic, ischemic, or aneurysmal/vascular malformation source (Table 4).

Discussion

Adult scoliosis remains a challenge for the spine surgeon. Given the patients' age and the often-associated medical comorbidities in this population, surgical treatment can be particularly challenging.[14] In their series of

TABLE 1: Demographic characteristics, surgical data, and follow-up time in 28 patients with adult scoliosis*

		No. of Procedures					EBL (ml)		OR Time (min)	
Indication	Levels Treated	Transpsoas Lat Interbody Fusion	Pst Perc Screws & Rods	AxiaLIF	LOS (days)	FU (mos)	Stage 1	Stage 2	Stage 1	Stage 2
DLS	L2–5	3	3		17	37				
DLS	L2–5	3	3		6	33	100		167	276
DLS	L1–S1	4	5	1	11	32	100	50	366	208
DLS	L1–S1	3	3		3	31	100		156	
DLS	T12–S1	5	6	1	10	30	150	350	425	267
DLS	T10–S1	3	8	1	11	29	20	150	225	336
DLS	L1–S1	4	5	1	5	29	500		448	
DLS	L2–S1	3	4	1	6	28	100	100	124	263
AIS	T12–S1	5	6	1	7	26	300	300	225	227
DLS	L2–S1	3	4	1	10	26	150	150	137	261
DLS	L1–5	3	3		6	26	100	300	208	270
DLS	L2–5	3	3		6	24	300	200	248	186
postlami	T12–S1	1	6		4	23	300		250	
AIS	T12–S1	5	6	1	7	21	100	300	257	310
DLS	L1–S1	4	5	1	9	21	100	150	206	178
AIS	L1–S1	4	5	1	4	20	300	200	255	308
DLS	T12–S1	4	6	2	9	18	100	300	193	296
DLS	L2–5	3	3		15	18	250		313	
AIS	L2–S1	2	4		7	17	150	100	104	191
AIS	T12–S1	4	6	2	10	17	100	400	150	221
AIS	T12–S1	4	6	2	20	16	200	300	169	370
AIS	L1–5	3	3		9	16	150	200	139	141
DLS	L2–S1	2	4	2	9	16	100	300	114	192
postlami	T10–S1	5	8	1	9	16	250	200	197	354
DLS	L3–S1	2	3	1	17	15	200		296	
DLS	L1–S1	4	6		8	15	100	150	431	165
AIS	T12–L5	5	5		16	14	2000	400	255	153
AIS	T12–S1	5	6	1	17	13	200	250	196	276

* AIS = adult idiopathic scoliosis; DLS = degenerative lumbar scoliosis; EBL = estimated blood loss; FU = follow-up; LOS = length of stay; OR = operating room; Perc = percutaneous; postlami = after laminectomy; Pst = posterior.

28 patients undergoing surgery for adult scoliosis, Ali et al.[2] noted that 18% of patients experienced a perioperative complication. The average blood loss was reported as 1600 ml, with patients receiving a transfusion of 2.4 U on average. Similarly, Shapiro et al.[30] reported outcomes in 16 patients undergoing circumferential deformity correction for adult scoliosis with concurrent low-back pain and spinal stenosis. In patients undergoing combined surgery as an index procedure, they noted a mean blood loss of 3665.7 ml, and they reported a complication rate of 75%. Daubs et al.[15] reported complications in 46 patients with arthrodesis of 5 or more levels undergoing adult deformity correction surgery. Among these patients, 28 (60%) had the diagnosis of lumbar degenerative scoliosis or adult idiopathic scoliosis. These authors noted a mean blood loss of 2056 ml, and an average transfusion of 5 U packed red blood cells per patient. They noted an overall complication rate of 37%, with 20% of patients sustaining a major complication.

Historically, complication rates ranging from 20 to 80% have been reported in the treatment of lumbar degenerative scoliosis.[1,12,29,36] Recent series have reported similar complication rates. Cho et al.[13] reviewed their experience with 47 patients undergoing PLIF with instrumentation for lumbar degenerative scoliosis. They noted an overall complication rate of 68%, with 30% of patients having early perioperative complications and 38% having late complications. These authors concluded that abundant blood loss was a significant risk factor for early perioperative complications. They noted a mean blood loss per patient of 2.1 ± 1 L, with an average hospital stay of 20.7 ± 9.6 days. They further noted that patients with degenerative lumbar scoliosis often require long-segment fusion, which may increase the risk of complications re-

TABLE 2: Surgical data in 28 patients with adult scoliosis

Parameter	Anterior Procedures*	Posterior Procedures†
EBL	241 ml (range 20–2000 ml)	231 ml (range 50–400 ml)
op times (time in OR to time out)	232 min (range 104–448 min)	248 min (range 141–370 min)

* Transpsoas discectomy and interbody fusion.
† Percutaneous pedicle screw and rod placement; possible transsacral L5–S1 interbody fusion.

lated to instrumentation. An overall pseudarthrosis rate of 4.3% was noted.

The surgical environment of degenerative lumbar scoliosis remains challenging for patients, especially given the hypolordosis associated with this condition, osteoporosis, and the advanced patient age. Thus, interbody fusion has been suggested for achieving a higher fusion rate and theoretically achieving better alignment than posterolateral instrumented fusion alone.[35] Wu et al.[35] reported on 29 consecutive patients with degenerative scoliosis who underwent a PLIF procedure. They noted a mean blood loss of 1.7 L ± 129 ml, with an average hospital stay of 11.7 ± 8.3 days. They noted no major medical complications, except for 1 patient who had a superficial infection. The ODI scores were noted to improve from 58 ± 11.5 preoperatively to 25.8 ± 19 postoperatively. Lumbar scoliosis improved considerably with this technique, with a preoperative Cobb angle measuring 16.5 ± 5.7° and postoperatively measuring 7.4 ± 3.4°. The authors concluded that PLIF, performed after laminectomy in patients with degenerative lumbar scoliosis, is a safe and effective procedure.

Bono and Lee[9] pooled 78 articles regarding spinal fusion for lumbar degenerative disc disorders, and they

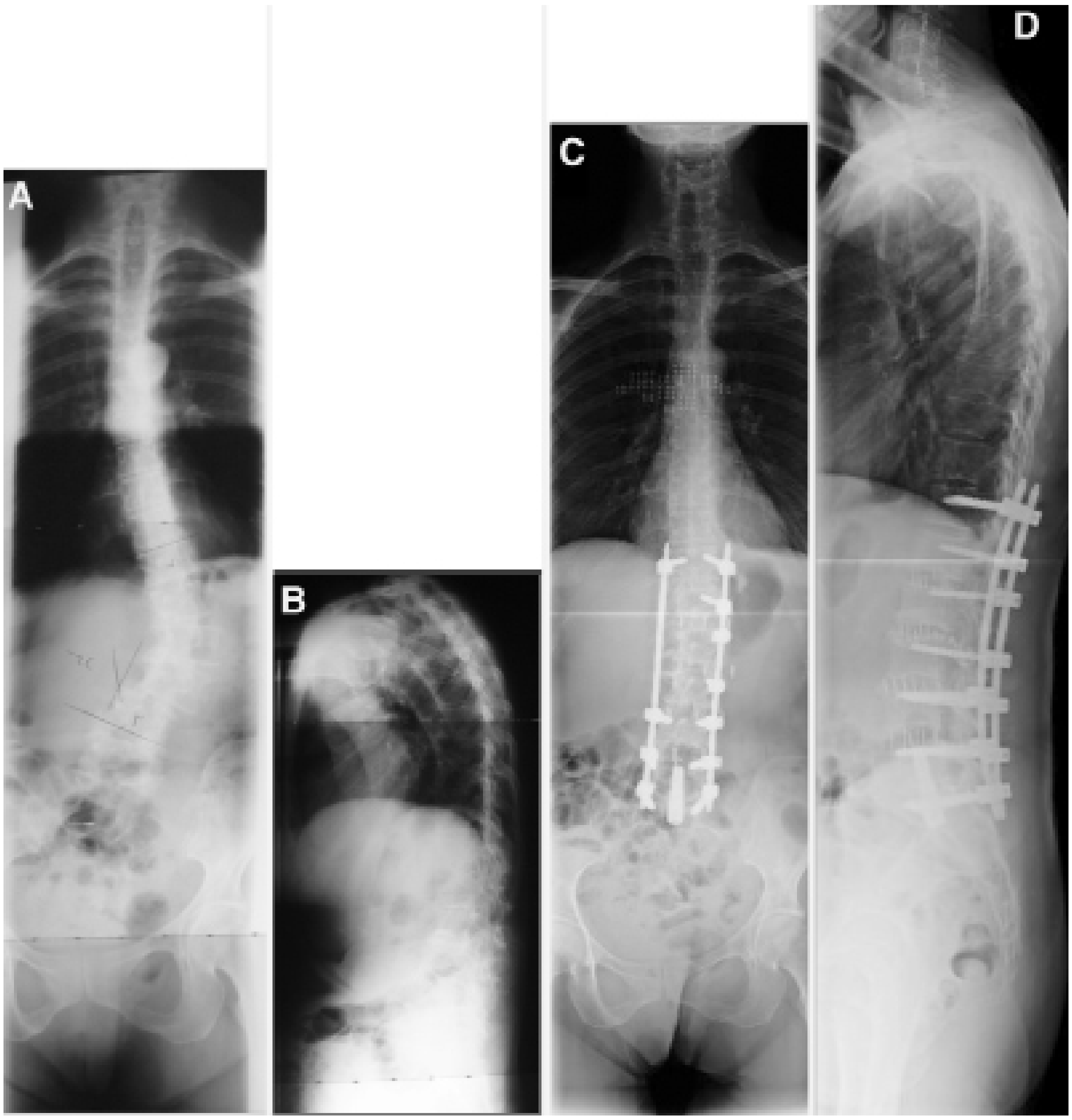

Fig. 1. **A and B:** Preoperative anteroposterior and lateral long-cassette standing radiographs demonstrating ~ 35° adult lumbar scoliosis, with the apex to the left, in a 61-year-old woman. **C and D:** The 1-year postoperative anteroposterior and lateral radiographs reveal excellent correction (Cobb angle of 4°), with good sagittal balance.

Fig. 2. Postoperative CT scans, sagittal **(A and B)** and coronal **(C)** reconstruction images, demonstrating a solid arthrodesis.

reported the pooled outcomes for lumbar decompression and fusion for degenerative scoliosis. They reported an overall good-to-excellent outcome in 82% of patients; the fusion rate was reported at 87%. Nevertheless, complication rates for scoliosis based on the pooled data were 55%. Clearly, surgery for a subset of patients with lumbar degenerative scoliosis appears to be of benefit, but perioperative complications remain a major problem. Blood loss is a major concern. Given that the average blood loss for adult deformity correction has been reported as 1.5 L, and has been reported to range from 360 ml to 7 L for instrumented fusion, such operative interventions may be considered very risky in elderly patients, given their increased risk for cardiovascular morbidity.[21,24] Weidenbaum[34] recommended consideration of focal surgical intervention rather than long-segment deformity correction within this patient population.

Our operative results are particularly attractive when comparing complications and blood loss to historical controls. Clearly, the total blood loss for circumferential procedures averages < 500 ml, which is considerably less than any of the abovementioned series for treatment of similar patients. Additionally, operating times were comparable to those for open procedures, and the length of stay was considerably shorter than those reported by the above-named authors. The clinical outcomes, in terms of both VAS and TIS scores, which are measures of patient narcotic use and pain intervention requirements,[5] demonstrate excellent results for these procedures.

Nevertheless, the utility of such an approach needs to be analyzed by studying clinical outcomes data. The HRQOL measures such as the SF-36, the ODI, and VAS scores allow the clinician to achieve better understanding of the degree of patient improvement for any given intervention, and have become standard instruments for studying outcome for lumbar degenerative conditions.[18,19] In our study, the mean ODI improvement was 32.13 points at 1 year, the mean SF-36 improvement was 5.77, and the mean VAS improvement was 4.02 points. This compares quite favorably to the data reported by Glassman et al.[18] in a study in which they assessed patients who had undergone posterolateral instrumented lumbar fusion. In their

TABLE 3: Clinical and radiological outcomes at 1 year in 28 patients with adult scoliosis*

Outcome	Preop	Postop	Average Change	p Value†
clinical				
VAS	7.05	3.03	−4.02	<0.0001
TIS	53.5	25.88	−27.62	0.02
SF-36	55.73	61.50	5.77	0.014
ODI	39.13	7.00	−32.13	0.02
radiological				
Cobb angle (range)	22.3° (15–62°)	7.47° (0.6–22°)	−14.9°	<0.0001

* All values are presented as means unless otherwise indicated. All patients had fusion confirmed on plain and flexion-extension radiographs; 21 patients had confirmed solid arthrodesis on CT scans.

† According to paired t-tests.

TABLE 4: Surgery-related complications in 23 patients with adult scoliosis

Complication	No. of Patients
minor	
transient dysesthesia	17 (recovered w/in 6 wks)
major	
quadriceps palsy	2 (recovered w/in 6 mos)
retrocapsular renal hematoma	1
cerebellar hemorrhage	1
miscellaneous	
screw prominence	1
asymptomatic proximal screw fracture	1

series, 17 patients with degenerative scoliosis were noted to have a 1-year improvement in ODI scores of 21.2, and an improvement in the SF-36 physical component score of 6.8. These results are consistent with achieving a minimally and clinically important difference for each outcome measure, where a value change of 10 points for the ODI and 5.42 points for the SF-36 physical component score are considered an important difference.[17,33] In the same series, Glassman et al. noted an overall complication rate of 41.2% for patients undergoing surgery for degenerative scoliosis.

In our series, all patients had a solid arthrodesis on plain radiographs, which was further confirmed on CT scans in 21 patients at 1 year. In terms of dosing of rhBMP-2, we used between 2 and 4 mg per interbody level fused, and approximately 1.62 mg per facet–pars complex (3.24 mg per posterolateral level) fused. In terms of interbody fusion technique, these doses were considerably lower than the 12–18 mg per level used in 3 different clinical trials in which rhBMP-2 was used with anterior lumbar interbody fusion.[11] Similarly, much less rhBMP-2 was used posteriorly than the 10–40 mg per level reported by other groups performing instrumented posterolateral fusions.[8,22] Given the successful fusion achieved in our series with much lower dosing of rhBMP-2 per level, further studies are probably warranted to determine the minimum effective dose of rhBMP-2 necessary to achieve a successful arthrodesis.

There was only 1 case noted of screw fracture, and another with screw prominence due to inadequate contouring of the rod. Longer-term follow-up will determine whether there are long-term problems. Although not reported in this series, sagittal balance correction achieved via this technique was excellent. Additionally, no pseudarthrosis at L5–S1 was seen, and no sacral stress fractures or sacral screw loosening were noted. Patients did not receive instrumentation to the ilium. Longer-term follow-up will address the issue of whether techniques such as the ones described by us may obviate the need for iliac bolts.

Conclusions

Circumferential minimally invasive correction and fusion for adult scoliosis represents a newer method of achieving long-term outcomes similar to those obtained with open methodologies in terms of clinical improvement, but has considerably lower morbidity and complication rates. Blood loss and hospital stays are significantly lower than those reported in earlier literature. The HRQOL measures revealed that clinical outcomes achieved with these techniques at > 1 year of follow-up were comparable to those of historical open controls. Recently, Glassman et al.[20] noted that HRQOL parameters stabilized at 1 year postoperatively: they noted no statistically significant differences when comparing 1- and 2-year outcomes in 283 adult patients with deformity who underwent surgery. Given all this, minimally invasive circumferential deformity correction remains attractive, especially in elderly patients and in patients with medical comorbidities who are being considered for deformity correction, decompression, and fusion.

Disclosure

Dr. Anand serves as a consultant for NuVasive, TranS1, and Medtronic; owns stock in TranS1; and receives royalties from Medtronic. Dr. Baron is a member of the Speakers Bureau for TranS1.

Author contributions to the study and manuscript preparation include the following. Conception and design: EM Baron, N Anand, R Rosemann. Acquisition of data: N Anand, R Rosemann, B Khalsa. Analysis and interpretation of data: N Anand, R Rosemann, B Khalsa. Drafting the article: EM Baron. Critically revising the article: EM Baron, N Anand. Reviewed final version of the manuscript and approved it for submission: N Anand. Statistical analysis: N Anand, R Rosemann.

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Complications and radiographic correction in adult scoliosis following combined transpsoas extreme lateral interbody fusion and posterior pedicle screw instrumentation

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Object. The authors recently used a combined approach of minimally invasive transpsoas extreme lateral interbody fusion (XLIF) and open posterior segmental pedicle screw instrumentation with transforaminal lumbar interbody fusion (TLIF) for the correction of coronal deformity. The complications and radiographic outcomes were compared with a posterior-only approach for scoliosis correction.

Methods. The authors retrospectively reviewed all deformity cases that were surgically corrected at the University of Pittsburgh Medical Center Presbyterian Hospital between June 2007 and August 2009. Eight patients underwent combined transpsoas and posterior approaches for adult degenerative thoracolumbar scoliosis. The comparison group consisted of 4 adult patients who underwent a posterior-only scoliosis correction. Data on intra- and postoperative complications were collected. The pre- and postoperative posterior-anterior and lateral scoliosis series radiographic films were reviewed, and comparisons were made for coronal deformity, apical vertebral translation (AVT), and lumbar lordosis. Clinical outcomes were evaluated by comparing pre- and postoperative visual analog scale scores.

Results. The median preoperative coronal Cobb angle in the combined approach was 38.5° (range 18–80°). Following surgery, the median Cobb angle was 10° ($p < 0.0001$). The mean preoperative AVT was 3.6 cm, improving to 1.8 cm postoperatively ($p = 0.031$). The mean preoperative lumbar lordosis in this group was 47.3°, and the mean postoperative lordosis was 40.4°. Compared with posterior-only deformity corrections, the mean values for curve correction were higher for the combined approach than for the posterior-only approach. Conversely, the mean AVT correction was higher in the posterior-only group. One patient in the posterior-only group required revision of the instrumentation. One patient who underwent the transpsoas XLIF approach suffered an intraoperative bowel injury necessitating laparotomy and segmental bowel resection; this patient later underwent an uneventful posterior-only correction of her scoliotic deformity. Two patients (25%) in the XLIF group sustained motor radiculopathies, and 6 of 8 patients (75%) experienced postoperative thigh paresthesias or dysesthesias. Motor radiculopathy resolved in 1 patient, but persisted 3 months postsurgery in the other. Sensory symptoms persisted in 5 of 6 patients at the most recent follow-up evaluation. The mean clinical follow-up time was 10.5 months for the XLIF group and 11.5 months for the posterior-only group. The mean visual analog scale score decreased from 8.8 to 3.5 in the XLIF group, and it decreased from 9.5 to 4 in the posterior-only group.

Conclusions. Radiographic outcomes such as the Cobb angle and AVT were significantly improved in patients who underwent a combined transpsoas and posterior approach. Lumbar lordosis was maintained in all patients undergoing the combined approach. The combination of XLIF and TLIF/posterior segmental instrumentation techniques may lead to less blood loss and to radiographic outcomes that are comparable to traditional posterior-only approaches. However, the surgical technique carries significant risks that require further evaluation and proper informed consent.
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Key Words • **adult scoliosis** • **extreme lateral interbody fusion** • **spinal deformity** • **Cobb angle**

The benefits of anterior approaches for arthrodesis in deformity correction surgery are well known and include load sharing and increased fusion rates when compared with posterior-only fusion constructs. The application of anterior interbody fusion—initially developed for the treatment of spinal tuberculosis—to the treatment of spondylolisthesis was first reported by Burns in 1933.[3] Lane and Moore[13] first described its use in the treatment of intervertebral disc degeneration in 1948, and interbody arthrodesis has seen increasingly widespread use ever since.

Cloward[4] introduced the technique of posterior interbody fusion in 1953, in his classic paper arguing for the

Abbreviations used in this paper: A/P = anterior/posterior; AVT = apical vertebral translation; CSVL = center sacral vertebral line; PA = posterior-anterior; PLIF = posterior lumbar interbody fusion; TLIF = transforaminal lumbar interbody fusion; VAS = visual analog scale; VB = vertebral body; XLIF = extreme lateral interbody fusion.

TABLE 1: Patients undergoing combined XLIF and posterior instrumentation*

Case No.	XLIF Levels	Posterior Interbody Levels	Instrumented Levels	XLIF Allograft	TLIF Graft
1	L2–4	L5–S1	T10–ilium	AF	IC, BMP
2	L1–4	L5–S1	T10–ilium	AF	IC, BMP
3	L2–5	L5–S1	T9–ilium	AF	IC
4	L1–4	L4–S1	T8–ilium	AF	BMP
5	L1–4	L5–S1	T11–ilium	AF	IC
6	L1–5	L5–S1	T10–ilium	DBM	IC, BMP
7	L1–3	L5–S1	T6–ilium	DBM	IC, BMP
8	L2–5	L5–S1	L1–S1	DBM	local bone only

* AF = Actifuse bone graft; BMP = bone morphogenetic protein; DBM = demineralized bone matrix; IC = autologous iliac crest.

superiority of an approach that offered the spine surgeon the ability to accomplish decompression of the neural elements and circumferential arthrodesis, all from a single, posterior approach, and without the inherent risk to the abdominal viscera and retroperitoneal structures incurred by a transperitoneal approach.

In 2001, Pimenta[17] introduced a novel approach to the anterior lumbar spine, using a lateral, transpsoas approach that was later popularized by Ozgur et al.[15] in 2006 as "extreme lateral interbody fusion." The extreme lateral approach offers several advantages over traditional interbody approaches. It obviates the need for mobilization of the great vessels—thereby avoiding the associated risk of sexual dysfunction—and does not require the assistance of a general surgeon. Similarly, it avoids transgression of the nerve roots and thecal sac and, therefore, places these structures at a lower theoretical risk. The extreme lateral approach has also been reported to decrease operating time when compared with other approaches to the anterior lumbar spine, including even mini-open and laparoscopic techniques. The lateral approach also offers the advantage of decreased blood loss, both through the avoidance of the epidural venous plexus, and through shorter operating times. For these reasons, transpsoas XLIF is a promising alternative to traditional interbody techniques in the treatment of adult degenerative scoliosis, because those affected by this condition are often more advanced in age and suffer from multiple medical comorbidities that make them less ideal candidates for traditional, "open" multilevel interbody fusions.

The application of transpsoas XLIF to adult lumbar degenerative scoliosis was first reported by Pimenta in 2001,[17] and thus is still in its infancy, with a dearth of published results on the effectiveness of the technique for this indication. Over the past 18 months at our institution, we have applied the extreme lateral approach to the treatment of adult degenerative scoliosis. Herein we report our initial radiographic results and perioperative complications, and compare them to those achieved using traditional interbody techniques for the same indication during the same time period.

Methods

Study Design

We retrospectively reviewed all deformity corrections performed at the University of Pittsburgh Medical Center Presbyterian Hospital between June 2007 and August 2009. The purpose of the study was to evaluate radiographic deformity correction parameters and perioperative complications following posterior instrumented fusion supplemented with transpsoas interbody fusion, and to compare these results to those achieved following posterior-only correction in which TLIF or PLIF techniques were used. Eight patients underwent deformity correction via a combined A/P approach. Anterior interbody fusion was performed via an extreme lateral transpsoas approach, and 4 patients underwent deformity correction via a posterior-only approach. Laterally placed interbody spacers contained either Actifuse synthetic bone graft material (ApaTech, Inc.) or demineralized bone matrix (Table 1). All posterior instrumentation was placed via an open posterior approach. Posterior arthrodesis was performed at all instrumented levels by using a combination of decortication, local autograft, autologous iliac crest, and bone morphogenetic protein (Tables 1 and 2). In all patients, both pre- and postoperative standing PA and lateral long-cassette scoliosis series plain radiographs were available for review in our computerized radiographic archives. Medical records and patient interviews conducted at follow-up evaluations were used to document intra- and postoperative complications and to establish the VAS score in each treatment group.

TABLE 2: Patients undergoing posterior-only correction

Case No.	Posterior Interbody Levels	Instrumented Levels	Interbody Allograft
1	L2–5	L1–5	AF
2	L5–S1	T9–ilium	BMP
3	none	L1–S1	BMP
4	L3–4	T7–ilium	IC, BMP

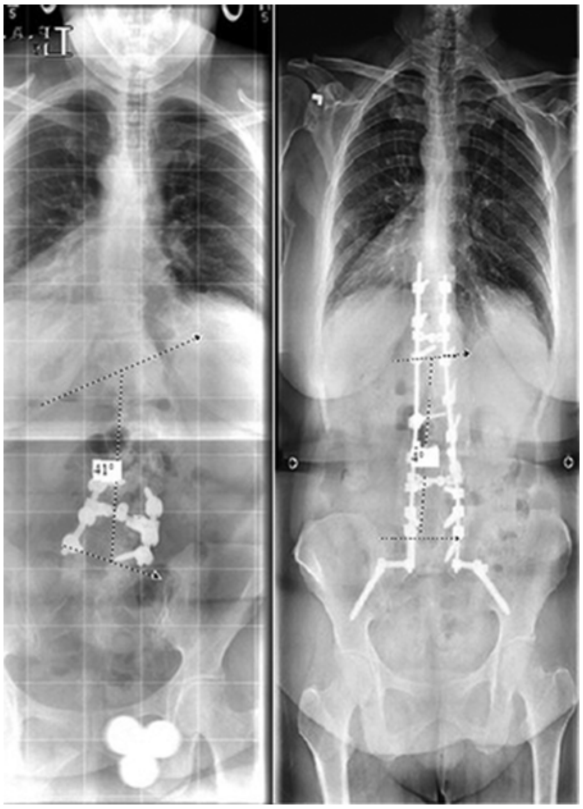

Fig. 1. Preoperative **(left)** and postoperative **(right)** standing PA long-cassette scoliosis series radiographs in a patient who underwent a combined approach with minimally invasive transpsoas XLIF and revision open posterior segmental pedicle screw instrumentation for correction of adult degenerative scoliosis. Interbody grafts were placed via a transpsoas approach from L-1 to L-4. The patient had 90% correction of her coronal Cobb angle.

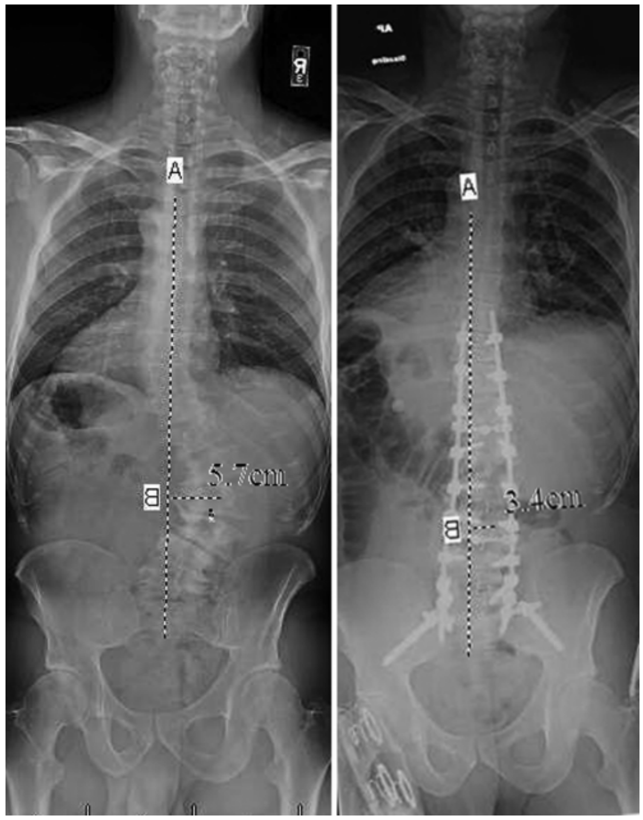

Fig. 2. Preoperative **(left)** and postoperative **(right)** standing PA long-cassette scoliosis series radiographs in a patient who underwent a combined approach with minimally invasive transpsoas XLIF and open posterior segmental pedicle screw instrumentation for correction of adult degenerative scoliosis. A satisfactory correction in coronal Cobb angle, AVT, and sagittal balance (not depicted) was achieved.

Radiographic Evaluation

All patients had pre- and postoperative standing PA and lateral scoliosis series radiographs available on our hospital's radiographic archival system. The software on this archival system provides measurement tools for the determination of distances and angles on the radiographs. Coronal Cobb angles, as well as the AVT, were measured. Preoperative and postoperative radiographs were compared to determine the degree of correction achieved following surgery.

The Cobb angle is used frequently to assess the severity of coronal and sagittal deformity. For coronal deformity, it is determined from the standing PA radiograph by drawing a line parallel to the superior endplate of the most superior VB, and a second line parallel to the inferior endplate of the most inferior VB of the scoliotic curve (Fig. 1). A second set of lines is drawn perpendicular to these first lines, and the angle subtended by these perpendiculars is the Cobb angle.

The AVT is the distance from the CSVL to the midpoint of the apical VB of the curve. The CSVL is a line that extends superiorly from the midpoint of the sacral promontory on a standing PA radiograph (Fig. 2).

Lumbar lordosis was measured using the Cobb method, with the superior endplate of L-1 and the inferior endplate of L-5. Hyperlordosis was defined as any Cobb angle > 60°, and hypolordosis as any angle < 20°. Return to normal lordosis after surgery was evaluated.

Statistical Analysis

Statistical analysis of correction of radiographically evaluated parameters was performed using SPSS software to evaluate statistical significance between pre- and postoperative radiographic measurements. Analysis was also performed to determine if there was any significant difference between the combined transpsoas and posterior and the posterior-only approach groups.

Results

Combined Lateral Transpsoas and Posterior Group

Eight patients underwent combined lateral transpsoas and posterior approaches for deformity correction. The average age of patients in this group was 60 years (range 48–69 years). Twenty-three interbody spacers were placed from a lateral approach (mean 2.8 spacers per patient), and in all patients an L5–S1 interbody spacer was placed from a posterior approach. The L5–S1 interbody space is not accessible from a lateral approach due to the iliac crest.

TABLE 3: Preoperative and postoperative radiographic parameters for combined and posterior-only approaches

	Coronal Cobb Angle		AVT		Lumbar Lordosis	
Case No.	Preop (°)	Postop (°)	Preop (cm)	Postop (cm)	Preop (°)	Postop (°)
combined approach						
1	26	7	2.8	1.7	84	43
2	41	4	1.9	1.1	69	45
3	39	24	3.7	3.2	79	40
4	38	16	2.5	1.9	50	46
5	18	2	1.2	0	37	39
6	48	8	5.7	2.4	22	41
7	80	46	10.0	4.0	2	38
8	21	0	1.0	0	35	42
posterior-only approach						
1	17	14	2.0	1.3	26	37
2	10	2	0	0	44	43
3	25	18	4.2	1.9	31	36
4	21	8	2.5	1.2	19	35

Posterior lateral arthrodesis was performed in all patients. This was accomplished with the combination of transpedicular instrumentation, along with local autograft and allograft placement. Two patients had the posterior procedure on the same day as the lateral procedure, whereas the other 6 had the second stage within 1 week of the lateral procedure.

In all patients, pre- and postoperative standing PA and lateral scoliosis series radiographs were available for assessment of deformity. Preoperative and postoperative coronal Cobb angles were compared (Table 3). The median preoperative Cobb angle was 38.5° (range 18–80°). Following surgery, the median Cobb angle was 10°. The mean percent of curve correction was 70.2%. According to paired t-test analysis, curve correction was statistically significant between pre- and postoperative Cobb angles ($p < 0.0001$).

The AVT is measured as the distance from the CSVL to the center of the apical VB in the curve. The mean preoperative AVT was 3.6 cm, and it was 1.8 cm postoperatively ($p = 0.031$).

The mean preoperative lumbar lordosis in this group was 47.3 ± 28.7° (mean ± SD, range 2–84°). Three patients had a hyperlordotic lumbar spine, defined as a Cobb angle > 60°, and 1 patient had a loss of lumbar lordosis, defined as a Cobb angle < 20°. The mean postoperative lordosis was 40.4 ± 2.8° (range 38–46°). Postoperatively, all patients either maintained lumbar lordosis or attained restoration of their previous hyper- or hypolordotic curvatures.

Posterior-Only Group

Four patients during the study time period underwent a posterior-only approach that combined TLIF and PLIF techniques with transpedicular instrumentation and posterolateral fusion. The average age in this group was 61 years (range 48–81 years). A total of 5 interbody grafts were placed via TLIF or PLIF approaches.

The mean preoperative coronal Cobb angle was 19° (range 17–25°), and postoperatively the mean coronal Cobb angle was 11° (Table 3). The mean percent curve correction was 44.7%, a statistically significantly difference from preoperative values ($p = 0.05$). The mean preoperative AVT for the posterior-only group was 2.2 cm, and it changed to 1.1 cm postoperatively. This change was not significant ($p = 0.114$). The mean preoperative lumbar lordosis in this group was 30 ± 10.5° (range 19–44°). No patient had preoperative hyperlordosis, and 1 patient had a loss of lumbar lordosis. The mean postoperative lordosis was 37.7 ± 3.5° (range 35–43°). All patients had a normal lumbar lordosis postoperatively.

Comparison of Approaches

The percentage of curve correction and the AVT correction were used to compare efficacy of the 2 approaches. The mean values for curve correction were higher for the combined approach than for the posterior-only approach. Conversely, the mean AVT correction was higher in the posterior-only group. An independent-samples t-test revealed no significant difference between percentage of curve correction for either of the Cobb angles, or in AVT correction (Table 4).

Postoperative Complications

Of the 8 patients who underwent combined lateral transpsoas and posterior approaches for deformity correction, 2 (25%) sustained motor radiculopathies, and 6 (75%) experienced postoperative thigh paresthesias or dysesthesias. Motor radiculopathy resolved in 1 patient after 2 months, whereas the other patient had a persistent radiculopathy 3 months postoperatively. All but 1 of the sensory radiculopathies persisted at the most recent follow-up evaluation. One patient had resolution of the postoperative numbness approximately 2 months postsurgery. One additional patient was originally scheduled for a combined lateral transpsoas and posterior instrumentation approach; however, during the transpsoas approach,

TABLE 4: Comparison of approaches

Parameter	Approach: Combined	Approach: Posterior-Only	p Value
no. of patients	8	4	
% change, Cobb angle	70.2	44.7	0.08
% change, AVT	54.6	60.4	0.763
mean follow-up (mos)	10.5	11.5	

a cecal perforation occurred, necessitating an emergency exploratory laparotomy and segmental bowel resection. This patient underwent a posterior-only approach for correction of her scoliotic deformity 6 months later, without incident. (This patient's radiographic outcomes were excluded from the analysis.) There were no instances of hardware failure or pseudarthrosis at the most recent follow-up in the combined group.

Additional postoperative complications in the combined-approach group included incidental durotomy during posterior decompression, pleural effusions necessitating chest tube placement, pulmonary embolism, and postoperative ileus (Table 5). Also, one patient had a wound infection that progressed to meningitis and sepsis. This patient required wound debridement and application of a vacuum dressing, and he eventually underwent primary closure of his wound.

Complications in the posterior-only group included 1 patient who required a total colectomy for toxic megacolon secondary to *Clostridium difficile* colitis. This patient had undergone an uneventful scoliosis surgery without complication. One patient in this group also had an incidental durotomy that was closed primarily. At a mean of 11.5 months of follow-up, there have been no infections or evidence of hardware failure in this group. One patient in the posterior-only group developed a junctional kyphosis requiring superior extension of her instrumentation as well as pelvic instrumentation.

Clinical Outcomes

In the combined XLIF and posterior group, follow-up VAS scores were available in 6 patients, with a mean follow-up period of 10.5 months (range 3–16 months). The mean preoperative VAS score was 8.8, and the mean postoperative VAS score for the combined group was 3.5.

The mean follow-up duration for the 4 posterior-only patients was 11.5 months (range 10–12 months). The mean preoperative VAS score was 9.5, and the mean postoperative VAS score was 4 for the posterior-only group.

There was not a significant difference between preoperative ($p = 0.379$) or postoperative VAS scores ($p = 0.835$) between the two operative groups.

Discussion

Adult scoliosis may be defined as a coronal deformity with a Cobb angle > 10° in a skeletally mature patient. It arises from degeneration of adolescent scoliosis, or may occur de novo in a previously straight spine. Several authors have correlated radiographic parameters with clinical symptoms in adults.[7,10,18,22] Restoration of sagittal and global spinal balance leads to improvements in quality of life measures.[7,14] Loss of normal lumbar lordosis has also been associated with increases in pain and decreases in quality of life measures.[18,22]

TABLE 5: Complications arising from the combined approach for deformity correction with XLIF in 8 patients

Complication	No. of Patients
bowel perforation	1
infection/meningitis	1
postop sensory radiculopathy	6
postop motor radiculopathy	2
pleural effusion necessitating chest tube placement	2
intraop hemodynamic instability	1
pulmonary embolism	1
ileus	1
durotomy (during posterior stage)	1

The use of interbody grafts in deformity correction surgery has gained popularity as a means of providing anterior column structural stability, increased fusion rates, and restoration and preservation of lumbar lordosis.[9,11,19,20] Graft placement has traditionally been achieved through either an anterior (anterior lumbar interbody fusion) or posterior (PLIF or TLIF) approach. The introduction of the transpsoas interbody technique has offered the surgeon treating deformity a new approach to interbody placement,[1,2,15] whose theoretical advantages of decreased blood loss, shorter operating time, and lower risk to the neural elements make it attractive for deformity correction in adults.

Restoration of balance and a return to near-normal anatomical alignment are associated with improved outcome and are the principal goals of most deformity correction surgeries. Traditional approaches to deformity correction include A/P approaches and posterior-only approaches, both of which have been shown to be effective.[5,16] However, the anterior approach is associated with complications such as vascular injury, ileus, and retrograde ejaculation.[21] Posterior approaches (PLIF and TLIF) place the nerve roots and thecal sac at greater risk because these structures must necessarily be exposed, and then protected, during graft insertion.

The transpsoas approach provides an alternative to these traditional interbody approaches. Although it is not entirely without risk—the most serious approach-related complication being injury to the bowel or other abdominal viscera—the technique uses a corridor that is designed to protect the vital structures both anterior and posterior to the VB.

Nevertheless, as our initial experience reported here demonstrates, these theoretical advantages of extreme lateral approaches have not translated without incident into practical application in our scoliosis practice. We had an 11% bowel perforation rate, and moreover, during a second procedure, at-risk bowel was clearly identified, causing us to abort a level in that procedure. Subsequent review of these cases has revealed to us that the rotatory component of scoliotic spines significantly increases the risk of injury to intra- and retroperitoneal structures. (Of note, we have performed transpsoas XLIFs in more than 60 patients for indications other than scoliosis, and have not had a bowel perforation in that series.)

The choice of approach may also influence the biomechanical soundness of the final construct. In general, anteriorly placed grafts have been viewed as more biomechanically stable.[23] This is due mostly to the destabilizing effect of the posterior facetectomy required for appropriate posterior graft placement, as well as to disruption of the tension band provided by the posterior longitudinal ligament.[6,25] However, anterior graft placement involves disruption of the anterior longitudinal ligament, also a stabilizing structure.[19] Placement of grafts via a lateral approach allows for preservation of the anterior longitudinal ligament, and has been shown in cadaver studies to be biomechanically equivalent to grafts placed via an anterior approach.[8]

Pateder and colleagues,[16] in a large series of patients, showed comparable outcomes in curve correction for those undergoing A/P or posterior-only correction. They achieved 54% correction in the posterior-only group and 46% correction in the A/P group. The mean correction rate in our combined posterior and transpsoas approach was higher (~ 70%); however, we had a smaller number of patients, and thus, no definitive conclusions can be drawn, other than that adequate correction appears to be achievable with this approach. In comparison with our posterior-only group, there was no significant difference in correction, and thus, the 2 techniques appear to be at least equivalent in terms of radiographic outcome.

Apical vertebral translation is a measure of coronal balance, defined as the distance from the CSVL to the midpoint of the apical vertebra. The transpsoas group in this study showed a significant change in the AVT, suggesting a return to coronal balance ($p = 0.031$). Restoration of coronal balance has been shown to improve pain-related outcomes and may have an additional cosmetic benefit.[7,18]

Degenerative changes in the lumbar spine may lead to changes in lumbar lordosis and contribute to global spinal imbalance in complex deformity. In their most extreme forms, these changes may result in hyperlordosis or, alternatively, in flat-back syndrome.[12,24] Schwab and colleagues[22] showed that patients with near-normal lordosis had lower VAS pain scores than patients with severe aberrations from the norm.

Conclusions

The purpose of the current study was to evaluate the efficacy of transpsoas interbody fusion, in combination with posterior release, transpedicular instrumentation, and posterior fusion, in achieving deformity correction in adults. It is readily apparent that the complication risk for extreme lateral approaches for scoliosis is higher than this approach for other spinal disorders. Although long-term radiographic outcomes, combined with validated clinical measures of pain and quality of life, are the gold standard by which this new technique will be judged, these data are not yet available because the transpsoas approach is still in its infancy. We hope, as our experience grows, to provide these data in the near future, and to correlate radiographic outcomes with validated clinical outcome measures and to further delineate the risk spectrum of the transpsoas extreme lateral approach in scoliosis surgery.

Disclosure

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Author contributions to the study and manuscript preparation include the following. Conception and design: AS Kanter, MJ Tormenti, MB Maserati. Acquisition of data: AS Kanter, MJ Tormenti, MB Maserati, CM Bonfield. Analysis and interpretation of data: MJ Tormenti, MB Maserati, CM Bonfield, DO Okonkwo. Drafting the article: MJ Tormenti, MB Maserati. Critically revising the article: AS Kanter, MJ Tormenti, MB Maserati, CM Bonfield, DO Okonkwo. Reviewed final version of the manuscript and approved it for submission: AS Kanter, MJ Tormenti, MB Maserati, CM Bonfield, DO Okonkwo. Statistical analysis: MJ Tormenti.

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Early outcomes and safety of the minimally invasive, lateral retroperitoneal transpsoas approach for adult degenerative scoliosis

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Object. The object of this study was to evaluate an alternative surgical approach to degenerative thoracolumbar deformity in adults. The authors present their early experience with the minimally invasive, lateral retroperitoneal transpsoas approach for placing interbody grafts and providing anterior column support for adult degenerative deformity.

Methods. The authors retrospectively reviewed a prospectively acquired database of all patients with adult thoracolumbar degenerative deformity treated with the minimally invasive, lateral retroperitoneal transpsoas approach at our institution. All patient data were recorded including demographics, preoperative evaluation, procedure used, postoperative follow-up, operative time, blood loss, length of hospital stay, and complications. The Oswestry Disability Index and visual analog scale (for pain) were also administered pre- and postoperatively as early outcome measures. All patients were scheduled for follow-up postoperatively at weeks 2, 6, 12, and 24, and at 1 year.

Results. The authors identified 25 patients with adult degenerative deformity who were treated using the minimally invasive, lateral retroperitoneal transpsoas approach. All patients underwent discectomy and lateral interbody graft placement for anterior column support and interbody fusion. The mean total blood loss was 53 ml per level. The average length of stay in the hospital was 6.2 days. Mean follow-up was 11 months (range 3–20 months). A mean improvement of 5.7 points on visual analog scale scores and 23.7% on the Oswestry Disability Index was observed. Perioperative complications include 1 patient with rhabdomyolysis requiring temporary hemodialysis, 1 patient with subsidence, and 1 patient with hardware failure. Three patients (12%) experienced transient postoperative anterior thigh numbness, ipsilateral to the side of approach. In this series, 20 patients (80%) were identified who had more than 6 months of follow-up and radiographic evidence of fusion. The minimally invasive, lateral retroperitoneal transpsoas approach, without the use of osteotomies, did not correct the sagittal balance in approximately one-third of the patients.

Conclusions. Degenerative scoliosis of the adult spine is secondary to asymmetrical degeneration of the discs. Surgical decompression and correction of the deformity can be performed from an anterior, posterior, or combined approach. These procedures are often associated with long operative times and a high incidence of complications. The authors' experience with the minimally invasive, lateral retroperitoneal transpsoas approach for placement of a large interbody graft for anterior column support, restoration of disc height, arthrodesis, and realignment is a feasible alternative to these procedures. *(DOI: 10.3171/2010.1.FOCUS09282)*

Key Words • minimally invasive surgery • thoracolumbar • retroperitoneal • adult scoliosis • extreme lateral interbody fusion • direct lateral interbody fusion

De novo or degenerative scoliosis in the adult spine is a 3D deformity that affects the spine in the coronal, sagittal, and axial planes. Degenerative scoliosis is believed to develop because of asymmetrical degeneration of discs, osteoporosis, and vertebral body compression fractures.[15] The primary presenting symptom of this condition is chronic back pain in the majority of patients. Patients can also present with neurogenic claudication caused by the concurrent stenosis with a structural degenerative deformity.[20,37]

The goals of adult deformity surgery are to obtain sagittal and coronal balance, pain relief, and solid fusion.[4,14] In many cases, these patients require treatment strategies that address both the anterior and posterior columns. An interbody graft placement allows for restoration of anterior column height, arthrodesis, and correction of the deformity. Anterior column support, by way of interbody graft placement, can be achieved using an

Abbreviations used in this paper: BMP = bone morphogenetic protein; EMG = electromyography; ODI = Oswestry Disability Index; VAS = visual analog scale.

TABLE 1: Clinical summary of 25 patients with adult degenerative deformity treated using the minimally invasive, lateral retroperitoneal transpsoas approach*

Case No.	Age (yrs), Sex	Interbody Levels	Instru-mentation	Fixation Levels	Fusion	Follow-Up (mos)	Coronal Angle (°) Preop	Coronal Angle (°) Postop	Sagittal Balance	Complications
1	74,F	L2–3, L3–4	LP	L2–4	yes	20	13	8	no	
2	68,M	L3–4, L4–5	LP	L3–5	yes	20	10	5	yes	subsidence
3	65,F	L1–2, L2–3, L3–4, L4–5	PS	T10–Ilia	yes	20	25	4	no	
4	64,M	L2–3, L3–4, L4–5	LP	L2–5	yes	20	11	4	yes	
5	77,F	L2–3, L3–4, L4–5	LP	L2–5	yes	18	16	7	yes	
6	51,F	L3–4, L4–5	LP	L3–5	yes	17	22	2	yes	
7	50,M	L3–4, L4–5	none	L3–5	yes	17	17	7	yes	
8	72,F	L2–3, L3–4, L4–5	LP	L2–5	yes	13	NA	12	yes	numbness
9	50,M	L1–2, L2–3, L3–4, L4–5	LP	L1–5	yes	13	23	19	no	hardware failure
10	65,M	L1–2, L2–3, L3–4, L4–5	LP	L1–5	yes	13	22	1	yes	
11	65,F	L2–3, L3–4, L4–5	LP & PS	L2–S1	yes	11	20	7	yes	
12	65,M	L2–3, L3–4, L4–5	LP	L2–5	yes	10	18	2	yes	
13	70,M	L3–4, L4–5	LP	L3–5	yes	10	13	4	yes	
14	64,M	L3–4, L4–5	LP	L3–5	yes	10	21	10	yes	
15	55,F	L3–4, L4–5	LP	L3–5	yes	10	24	2	yes	
16	56,F	L2–3, L3–4, L4–5	LP	L2–5	yes	9	12	4	yes	
17	53,F	L4–5	LP	L4–5	yes	9	11	3	no	
18	70,F	T12–L1, L1–2, L2–3, L3–4, L4–5	PS	T10–Ilia	yes	9	48	8	no	numbness
19	35,F	T12–L1, L1–2, L2–3, L3–4, L4–5	PS	T10–Ilia	yes	8	49	12	yes	
20	75,M	L2–3, L3–4, L4–5	PS	T12–S1	yes	7	19	2	no	
21	60,M	T10–11, T11–12, T12–L1, L1–2, L2–3, L3–4	none	T10–L4	no	5	34	24	NA	rhabdomyolysis
22	72,F	L2–3, L3–4, L4–5	PS	L2–5	no	4	18	3	no	
23	52,F	L3–4, L4–5	LP	L3–5	no	4	15	1	yes	
24	75,F	L2–3, L3–4, L4–5	PS	L2–5	no	4	10	3	yes	numbness
25	59,F	L1–2, L2–3, L3–4, L4–5	PS	T11–Ilia	no	3	36	6	no	

* LP = lateral plate; NA = not available; PS = pedicle screws.

anterior, posterior, or lateral approach. The minimally invasive, lateral retroperitoneal transpsoas approach allows for interbody graft placement and anterior column support, while avoiding the potential complications associated with anterior or posterior approaches.[26] In this paper, we describe our early experience with the minimally invasive, lateral retroperitoneal transpsoas approach for discectomy and interbody graft delivery for adult degenerative scoliosis.

Methods

We retrospectively reviewed a prospectively acquired database of all patients with adult thoracolumbar degenerative deformity treated via the minimally invasive, lateral retroperitoneal transpsoas approach at our institution. All patient data were recorded, including demographics, preoperative evaluation, procedure used, postoperative follow-up, operative time, blood loss, length of hospital stay, and complications. We also administered the ODI and the VAS (for pain) pre- and postoperatively as early outcome measures. All patients were scheduled for follow-up postoperatively at weeks 2, 6, 12, and 24, and at 1 year.

All patients presented with mechanical back pain and/or radicular pain that was refractory to at least 12 months of conservative management. Patients with idiopathic curves or scoliosis secondary to neurological or neuromuscular conditions were excluded from the study. The surgical procedure, as previously described,[26] consisted of placing patients in the lateral decubitus position, performing fluoroscopic localization of the affected level, and using lateral retroperitoneal blunt dissection to expose the lateral surface of the spine. Once an arm-mounted expandable retractor was placed, discectomies and placement of interbody grafts were performed laterally. The discectomies were performed across the midline to the contralateral annulus, while preserving the anterior and posterior longitudinal ligaments. The interbody grafts were made from polyetheretherketone and filled with recombinant human BMP-2, tricalcium phosphate, and hydroxyapatite. The amount of BMP that was used was approximately 0.7 cm^3 of recombinant human

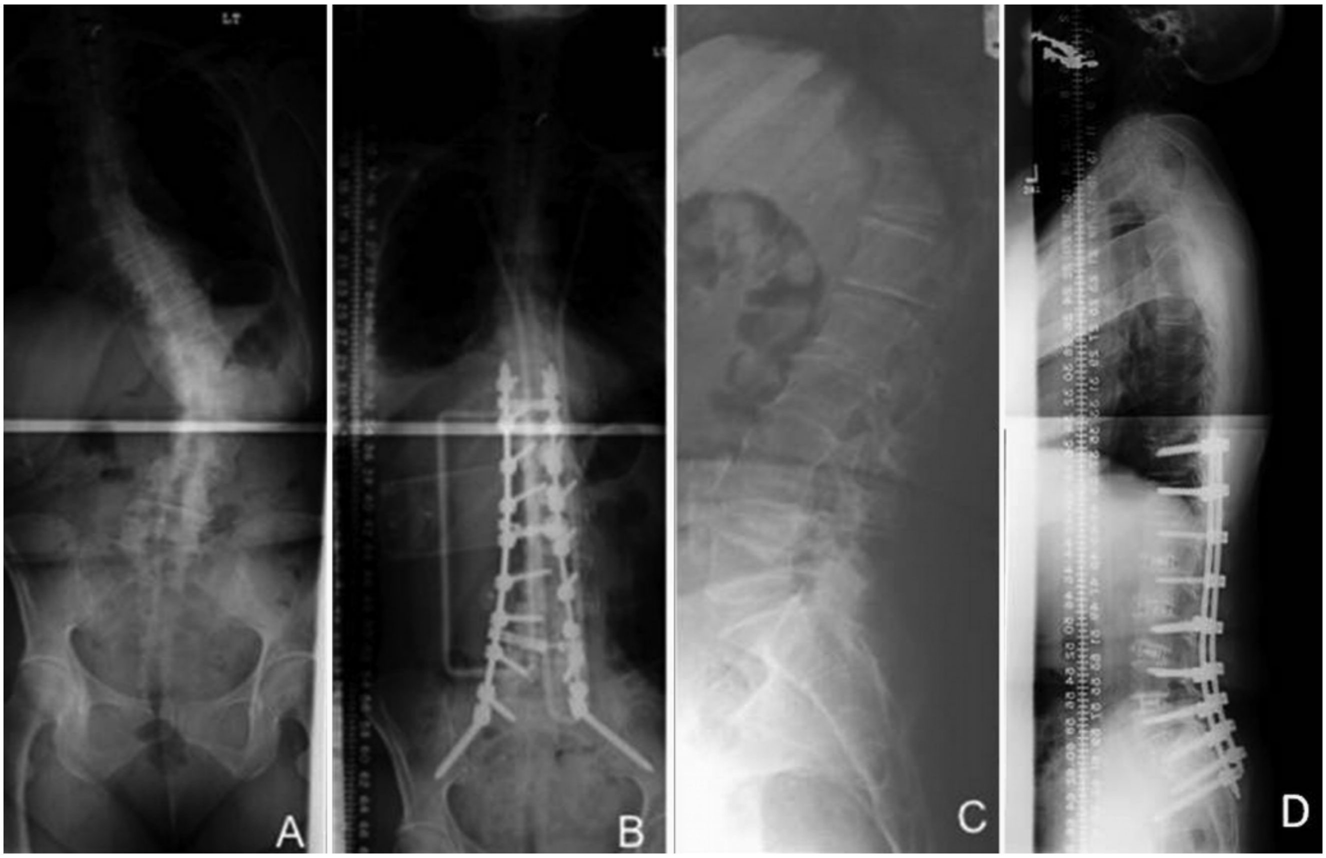

Fig. 1. Standing radiographs obtained in a patient who underwent a 5-level lateral transpsoas lumbar interbody fusion, and posterior instrumentation from T-10 to the ilia. Views shown are anteroposterior preoperative **(A)** and postoperative **(B)**, and lateral preoperative **(C)** and postoperative **(D)**.

BMP-2/absorbable collagen sponge per interbody level. The interbody cages were positioned on the apophyseal ring and measured 18 mm wide, 8–12 mm in height, and 55–60 mm in length. Interbody grafts were augmented with lateral plates or posterior pedicle screws for stability and completion of the deformity correction. Additionally, EMG neuromonitoring was used throughout the procedure to aid in localizing the motor nerves and roots of the lumbar plexus and potentially prevent injury.

Results

Between 2007 and 2009, 25 patients (15 women, 10 men) underwent a minimally invasive, lateral retroperitoneal transpsoas approach for the placement of interbody grafts in the treatment of adult degenerative deformity (Table 1). The mean patient age was 62.5 years (range 35–77 years). All patients successfully underwent lateral discectomies and placement of interbody grafts for anterior column support and interbody fusion (Figs. 1 and 2). Seventy-six lateral interbody grafts were placed. Twenty-three patients underwent additional instrumentation, 7 with pedicle screws, 15 with lateral plates, and 1 with both. The mean operative time from induction to extubation was 108 minutes per level. A significant portion of this time was devoted to patient positioning and fluoroscopic localization of the targeted levels. The mean total blood loss was 53 ml per level. The average length of stay in the hospital was 6.2 days. Mean follow-up was 11 months (range 3–20 months). No patient required a blood transfusion. There were no intraoperative CSF leaks, wound infections, or postoperative weaknesses identified. There were no injuries to the peritoneal or retroperitoneal structures. There were no deep venous thromboses, urinary tract infections, or ileus identified. Perioperative complications include 1 patient with rhabdomyolysis requiring temporary hemodialysis, 1 patient with asymptomatic subsidence, and 1 patient with asymptomatic hardware failure. Three patients (12%) experienced transient postoperative anterior thigh numbness ipsilateral to the side of approach in the distribution of the anterior femoral cutaneous nerve. Evidence of fusion was assessed radiographically in all patients with more than 6 months of follow-up. In our series, we identified 20 patients (80%) who underwent more than 6 months of follow-up; all of these patients demonstrated radiographic evidence of fusion on CT scans or flexion-extension radiographs.

Outcome measures assessed include the VAS pain score and the ODI (Fig. 3). Mean improvement of 5.7 points in VAS scores and 23.7% in the ODI was observed. The VAS score averaged 8.1 preoperatively and improved to 2.4 at the last follow-up visit. The ODI averaged 53.6% preoperatively and improved to 29.9% at the last follow-up visit.

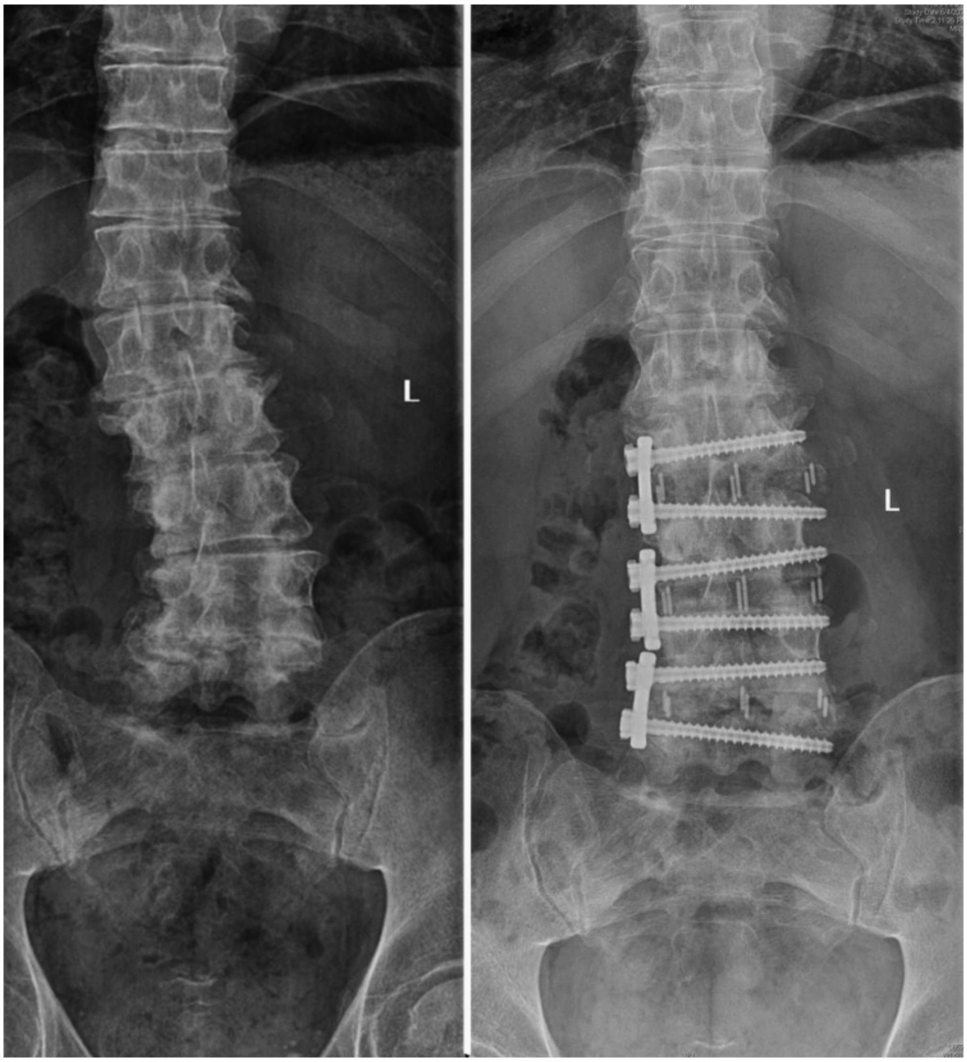

Fig. 2. Preoperative **(left)** and postoperative **(right)** standing radiographs obtained in a patient who underwent a 3-level lateral transpsoas lumbar interbody fusion with lateral plate fixation.

Discussion

Adult degenerative or de novo scoliosis is believed to develop as a result of asymmetrical degeneration of the spine. It most often occurs in the lumbar spine and typically presents with pain as the primary complaint in 90% of patients.[20,37] The pain may be axial, radicular, or both.[33] Axial pain is more prevalent among older patients with spinal deformity, as compared with younger patients.[19] This pain occurs most commonly from a combination of muscle fatigue, trunk imbalance, facet arthropathy, and degenerative disc disease.[5] All patients should first undergo conservative treatment prior to being considered for surgical intervention.[4] However, surgically treated patients with adult scoliosis had a significantly greater improvement in back pain and quality of life when compared with nonoperatively treated patients.[7,34] Once a patient has failed to respond to conservative treatment or has met the indications for surgery,[14] the surgeon is faced with the decision to approach the spine from the anterior or posterior aspect, or a combination of both.

The goals of adult deformity surgery are to obtain sagittal and coronal balance, pain relief, and solid fusion. Typically, wires, hooks, and pedicle screws have been used to address the posterior columns in deformity correction operations.[14] In many cases, patients require treatment strategies that address both the anterior and posterior columns. Unlike adolescent spinal curves, adult deformities are usually rigid and require a combined anterior-posterior approach.[5] This approach usually involves multiple anterior releases, followed by a posterior procedure in which the deformity correction is completed.[14] Anterior releases can range from a discectomy to a corpectomy, which aid in extending the spine. Anterior reconstruction with a bone graft or cage maintains distraction between the endplates, provides an area for arthrodesis, corrects kyphosis, and restores lordosis.[35]

Structural anterior column support provides several benefits such as improved stability, decreased stress on posterior instrumentation, improved fusion rates, and better lumbar lordosis.[13,16,25,27,28,38] Anterior column support, by way of interbody graft placement, can be achieved

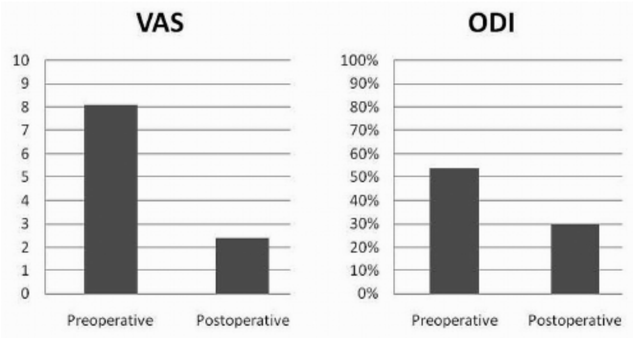

FIG. 3. Bar graphs showing mean preoperative and postoperative values of the VAS (for pain) and ODI.

with an anterior, posterior, or lateral approach. Anterior interbody fusion allows complete visualization of the disc space and placement of a large interbody graft. Reported complications from the anterior approach include retrograde ejaculation, great vessel injury, ureteral trauma, and prolonged ileus.[6,12,24,30,31] The posterior and transforaminal interbody fusions allow incomplete anterior release and smaller cage sizes when compared with the anterior approach. The posterior placement of interbody grafts places the nerve roots at risk for traction injuries.

The minimally invasive, lateral retroperitoneal transpsoas approach provides the surgeon with an alternative option when placing an interbody graft. The goals of minimally invasive surgery are to minimize dissection and trauma of muscle related to the approach, reduce blood loss, shorten hospital stays, mobilize patients early, and hasten recovery.[2,11,36] Similar to the anterior approach, the minimally invasive lateral approach allows for placement of a large interbody graft without need for an access surgeon. When compared with posteriorly placed interbody grafts, laterally placed grafts have a much larger area for potential fusion and are able to restore disc height and lordosis more easily.

When planning to surgically correct adult deformity secondary to degenerative changes of the spine, we must consider the patient population undergoing the operation. Degenerative scoliosis is generally observed in the older population, who tend to suffer from osteoporosis and a higher number of medical comorbidities.[1] Advanced age and medical comorbidities have been reported to cause more complications in deformity surgery.[8,29] In addition, the surgical correction of adult deformity is believed to be more difficult than in adolescent patients and is associated with a higher rate of complications.[5,10,32,33] The pseudarthrosis rate after deformity surgery for adult patients after long fusions has been reported to be 24%, which is significantly higher than in pediatric patients.[17] Despite the increased risk, adult patients with scoliosis who were older than 65 years of age and were treated operatively experienced significantly less pain, a better quality of life, and were more satisfied than patients treated conservatively.[21]

Scoliosis is a 3D deformity of the spine and all 3 planes need to be addressed to maximize patient outcomes. These procedures tend to be lengthy and invasive due to the need to expose and fuse a large portion of the spine. The incidence of complications has been reported to be between 20 and 80%.[1,8,22,39] In his series of patients undergoing posterior fusion and instrumentation for degenerative lumbar scoliosis, Cho et al.[9] reported an overall complication rate of 68% and an early perioperative complication rate of 30%. One of the main risk factors that increased the early perioperative complications in this study was a blood loss of more than 2 liters.[9]

Although the minimally invasive, lateral retroperitoneal transpsoas approach avoids many of the disadvantages of both the anterior and posterior approaches, it does have certain limitations and disadvantages of its own. Secondary to the anatomical constraints of the iliac crest, the L5–S1 disc space is not easily or safely approachable with this technique. This approach relies on indirect decompression of the spinal canal and neural foramen by restoring disc height and lordosis. If supplemental posterior instrumentation or direct decompression is required, a separate posterior incision and approach must be performed.

As with all new techniques and technologies associated with minimally invasive spine surgery, there is a steep learning curve associated with this approach. The use of EMG neural monitoring and intraoperative fluoroscopy is critical to the safe passage within the psoas muscle. Prior reports of lateral retroperitoneal approaches included mobilization of the psoas muscle from the lumbar spine, with a high incidence (30%) of paresthesias in the thigh/groin region.[3,23] Knight et al.[18] reported a 10% incidence of lateral femoral cutaneous nerve deficit and a 3% incidence of L-4 motor deficit using the lateral retroperitoneal transpsoas approach. In our series of patients, we identified 3 patients (12%) with transient postoperative ipsilateral sensory deficits that resolved by the 3-month follow-up visit. There were no patients with postoperative motor deficits.

As stated above, in our series of patients, the incidence of postoperative sensory deficit (12%) using the minimally invasive, lateral retroperitoneal transpsoas approach is consistent with rates in the published literature.[18] The approach-related complications of sensory deficits are not prevented by EMG neuromonitoring, which only helps identify motor nerves. Because most of these deficits are transient, we believe they are stretch or neurapraxic injuries. The origin is most likely secondary to placement of the dilators/retractor system and aggressive dissection of the retroperitoneal space. In an effort to minimize these approach-related complications, we decrease the amount of lateral flexion of the patient and flex the hip during positioning. We believe that this may decrease the amount of tension on the lumbar plexus. Some nerves have mixed motor and sensory fibers, such as the femoral nerve, which carries the fibers of the anterior femoral cutaneous nerve. Neuromonitoring using EMG will not directly assist in detection or localization of sensory nerves; however, locating the femoral nerve will indirectly indicate the location of the sensory fibers of the anterior femoral cutaneous nerve. In addition, we advocate acquiring knowledge of the anatomy of the disc space in relation to the neural structures, gentle dissection, and minimizing expansion of the retractor whenever possible.

In addition to the transient sensory deficits already noted, 1 patient suffered from perioperative rhabdomyolysis. He underwent a 6-level interbody cage placement via the lateral transpsoas approach. This patient required approximately 4 months of hemodialysis prior to return of his renal function. Secondary to the rhabdomyolysis, he did not undergo the second stage of his surgery for placement of posterior pedicle screws.

Conclusions

Degenerative scoliosis of the adult spine is secondary to asymmetrical degeneration of the discs. Surgical decompression and correction of the deformity can be performed from an anterior, posterior, or combined approach. These procedures are often associated with long operative times and a high incidence of complications. Our experience using the minimally invasive, lateral retroperitoneal transpsoas approach for placement of a large interbody graft for anterior column support, restoration of disc height, arthrodesis, and realignment shows that this approach is a feasible alternative to more traditional approaches.

Disclosure

Dr. Uribe has served as a consultant to Nuvasive, and has received clinical or research support for this study from Nuvasive.

Author contributions to the study and manuscript preparation include the following. Acquisition of data: RF Cardona. Drafting the article: E. Dakwar. Study supervision: DA Smith, JS Uribe.

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Minimally invasive surgery for thoracolumbar spinal deformity: initial clinical experience with clinical and radiographic outcomes

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Object. Adult degenerative scoliosis can be a cause of intractable pain, decreased mobility, and reduced quality of life. Surgical correction of this problem frequently leads to substantial clinical improvement, but advanced age, medical comorbidities, osteoporosis, and the rigidity of the spine result in high surgical complication rates. Minimally invasive surgery is being applied to this patient population in an effort to reduce the high complication rates associated with adult deformity surgery.

Methods. A retrospective study of 23 patients was undertaken to assess the clinical and radiographic results with minimally invasive surgery for adult thoracolumbar deformity surgery. All patients underwent a lateral interbody fusion followed by posterior percutaneous screw fixation and possible minimally invasive surgical transforaminal lumbar interbody fusion if fusion near the lumbosacral junction was necessary. A mean of 3.7 intersegmental levels were treated (range 2–7 levels). The mean follow-up was 13.4 months.

Results. The mean preoperative Cobb angle was 31.4°, and it was corrected to 11.5° at follow-up. The mean blood loss was 477 ml, and the operative time was 401 minutes. The mean visual analog scale score improvement for axial pain was 3.96. Clear evidence of fusion was seen on radiographs at 84 of 86 treated levels, with no interbody pseudarthroses. Complications included 2 returns to the operating room, one for CSF leakage and the other for hardware pullout. There were no wound infections, pneumonia, deep venous thrombosis, or new neurological deficits. However, of all patients, 30.4% experienced new thigh numbness, dysesthesias, pain, or weakness, and in one patient these new symptoms were persistent.

Conclusions. The minimally invasive surgical treatment of adult deformities is a promising method for reducing surgical morbidity. Numerous challenges exist, as the surgical technique does not yet allow for all correction maneuvers used in open surgery. However, as the techniques are advanced, the applicability of minimally invasive surgery for this population will likely be expanded and will afford the opportunity for reduced complications.
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Key Words • **deformity** • **scoliosis** • **minimally invasive surgery** • **pedicle screw** • **aging spine** • **interbody fusion**

Due to advances in medical care, the life expectancy of Americans has increased significantly over the past half century. However, with this lengthening of the human lifespan has come an increase in the prevalence of disorders associated with aging, including adult spinal deformity. Adult thoracolumbar scoliosis and kyphosis can be the consequence of numerous etiologies, including progression of a preexisting deformity, delayed posttraumatic sequelae, infection, progressive disc and facet joint degeneration, iatrogenic spinal destabilization, and arthropathies such as rheumatoid arthritis.[9] In most cases these deformities will progress with age as patients experience progressive loss of muscular bulk, bone mass, and joint integrity.[19]

While the treatment of these debilitating disorders can be highly rewarding and meaningful for the patient in terms of pain reduction, improved functional capabilities, and cosmesis, the morbidity associated with surgical correction can be substantial. Given the need for longer-construct multilevel surgery, as well as the need for extensive spinal mobilization and reconstruction, these procedures are typically associated with long anesthesia times and large quantities of blood loss. Thus, in this patient population, which is frequently already medically deconditioned, surgery presents unique hazards.

Traditional open surgery has been associated with a major complication rate as high as 28–86%, even at specialized centers,[1,8,24] and the risks of morbidity have

Abbreviations used in this paper: EMG = electromyography; rhBMP = recombinant human bone morphogenetic protein; VAS = visual analog scale.

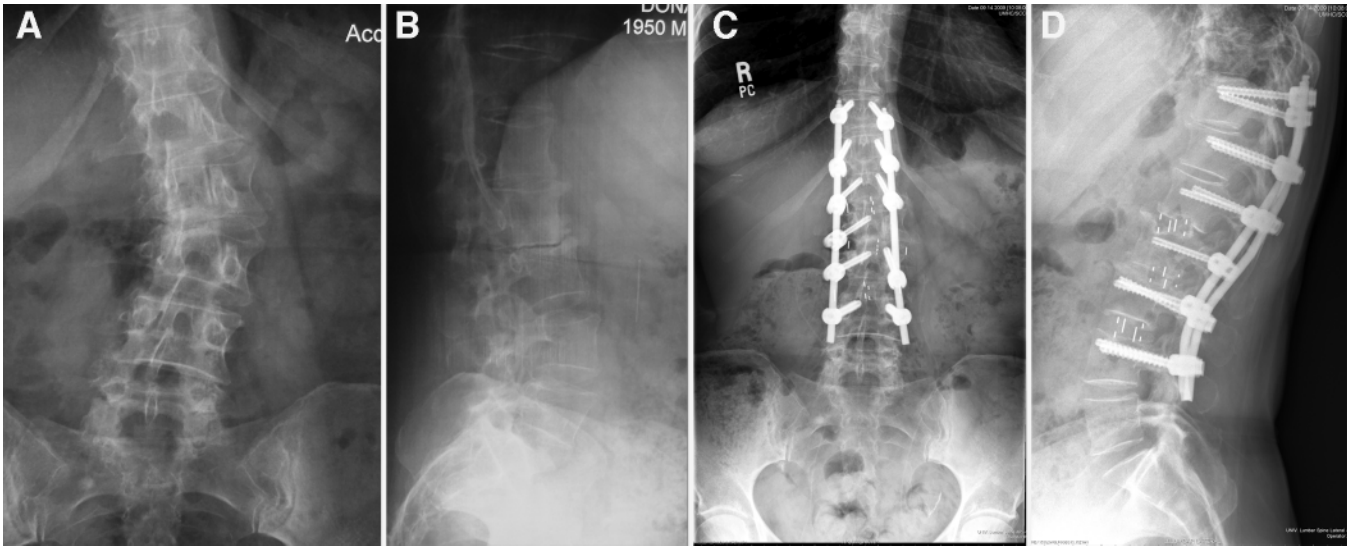

Fig. 1. Case 19. Radiographic examples of lumbar degenerative scoliosis treated via an anterior-posterior minimally invasive approach. **A and B:** Preoperative images demonstrating a 32° Cobb angle. **C and D:** Postoperative images demonstrating curve correction to 5° with maintenance of proper local sagittal balance.

been shown to increase with advancing age.[25] Minimally invasive surgical approaches offer the potential to reduce some of the complications associated with traditional open spinal surgeries.[10–14] Because minimally invasive surgery may reduce soft-tissue trauma, intraoperative blood loss, and surgical site infections, patients may experience reduced postoperative pain and narcotic consumption and more rapid mobilization. While yet unproven, these factors may be especially important in the setting of the medically compromised patient. In the study by Rosen et al.[17] 50 patients older than 75 years with significant medical comorbidities underwent minimally invasive spinal surgery for spinal canal decompression. While the study had no control arm, the authors were able to demonstrate that the procedure could be performed efficiently and safely. More importantly, the authors reduced their average length of stay to 29 hours, an impressive feat in this age group.

Recently, instruments and implants have been developed for longer-segment fixation, fusion, and segmental manipulation—making minimally invasive surgery for deformities a feasible option in select patients.[22] This report describes our initial experience with minimally invasive surgery for adult thoracolumbar spinal deformity.

Methods

Patient Population

A continuous series of 23 patients undergoing minimally invasive primary or supplemental fixation for adult thoracolumbar spinal deformities at 2 academic medical centers was included in this study: University of California at San Francisco (4 patients) and the University of Miami (19 patients). The patient mean age was 64.4 years (range 42–84 years), and 74% were women. The mean follow-up time was 13.4 months (range 6–34 months) (Table 1). Inclusion criteria were the presence of coronal deformity greater than 20° and/or significant sagittal decompensation with loss of global spinal balance. Patients with limited or focal sagittal imbalance, such as those presenting primarily with a spondylolisthesis, were excluded. In addition, patients with severe central canal stenosis that could not be managed with unilateral minimally invasive decompression were excluded from this study.

The patient population was assessed with regard to clinical outcomes, complications, surgical blood loss, and operative times. Separate VAS scores were obtained for leg (radiculopathic) and axial back pain by patient self-report. Radiographic parameters included preoperative and postoperative Cobb angles to assess sagittal and coronal plane deformity correction based on standing 36-inch radiographs. The sagittal alignment was obtained between the T-11 or T-12 and the S-1 endplates. Fusion status was assessed using fine-slice helical CT scans as determined by attending neuroradiologists. All data were collected with institutional review board approval.

Surgical Technique

All patients underwent combined anterior-posterior surgery in a single anesthesia session (Fig. 1). The anterior procedure was performed using a mini-open direct lateral exposure of the intervertebral discs, as described previously.[23] Retraction or spreading of the psoas muscle allowed for disc or vertebral body removal, anterior release, and anterior height restoration. Direct local stimulation as well as continuous live EMG were used in all cases involving a transpsoas approach, and the anterior reconstruction was achieved using femoral ring allograft, polyetheretherketone interbody cages (Medtronic Sofamor Danek or Nuvasive), or expandable cages (Fig. 2) (Globus Medical or Synthes Spine). These interbody devices were filled with rhBMP-2 (InFuse, Medtronic Sofamor Danek). Posterior supplemental fixation was performed with the use of Viper percutaneous pedicle screws and connecting

TABLE 1: Clinical characteristics and demographics for 23 patients*

			Procedure							
Case No.	Age (yrs), Sex	Pathology	Stage 1	Stage 2	No. Levels Fused	Graft Type	EBL (ml)	Op Time (min)	LOS (days)	Dis-charge
1	72, F	LDS	L1–5 lat IF	L1–5 percutaneous screws	4	allograft bone, BMP	220	380	4	home
2	68, M	L3–4 postlaminectomy kyphosis	L2–3, L3–4, & L4–5 TP lat IF	L2–5 percutaneous screws	3	BMP	250	320	4	home
3	66, F	LDS	L2–3 & L3–4 TP lat IF	L2–S1 percutaneous screws, L4–5 & L5–S1 MIS TLIF	4	BMP	450	500	5	home
4	66, F	lumbar postlaminec-tomy kyphoscoliosis	L2–3 & L3–4 TP lat IF	L1 kyphoplasty, L2–5 percutaneous screws	3	BMP, allograft chips	200	310	7	home
5	56, F	LDS	L2–3 & L3–4 TP lat IF	L2–5 percutaneous screws & L4–5 MIS TLIF	3	BMP & facet autograft	200	360	7	home
6	42, F	previous fernstrom ball surgery with spinal deformity	minimal access L-4 partial cor-pectomy & L3–4 & L4–5 IF	L3–5 percutaneous screws	2	BMP, vertebral autograft	300	260	4	home
7	61, M	delayed posttraumatic kyphosis from T-12 & L-1 burst fractures	minimal access T-12 & L-1 partial corpectomies	T10–L3 percutaneous screws	5	BMP, vertebral autograft	300	400	5	home
8	44, F	LDS	L1–2 & L2–3 TPIF	L1–3 percutaneous screws	2	BMP	210	200	3	home
9	72, F	LDS	L2–3 & L3–4 TP lat IF	L2–5 percutaneous screws & L4–5 MIS TLIF	3	BMP, facet autograft	300	405	3	rehab
10	71, F	LDS	L2–3 & L3–4 TP lat IF	L2–5 percutaneous screws & L4–5 MIS TLIF	3	BMP, facet autograft	300	420	6	rehab
11	79, F	LDS	L3–4 & L4–5 TP lat IF	L3–5 percutaneous screws	2	BMP	200	280	5	home
12	76, M	LDS	L2–3, L3–4, & L4–5 TP lat IF	L2–S1 percutaneous screws, L5–S1 TLIF	4	BMP, facet autograft	300	600	6	rehab
13	84, M	LDS	L2–3, L3–4, & L4–5 TP lat IF	L2–S1 percutaneous screws, L5–S1 TLIF	4	BMP, facet autograft	300	450	3	rehab
14	55, F	LDS	L2–3 & L3–4 TP lat IF	L2–5 percutaneous screws & L4–5 MIS TLIF	3	BMP	450	400	7	rehab
15	62, F	LDS	L1–2, L2–3, & L3–4 TP lat IF	T10–L4 percutaneous screws, MIS posterolat fusion T10–L1	6	BMP, rib autograft	250	460	7	home
16	82, F	LDS	L1–2 & L2–3 TP lat IF	T12–L3 percutaneous screws, T12–L1 posterolat fusion	3	BMP, rib autograft	200	230	6	rehab
17	64, F	LDS	L2–3 & L3–4 TP lat IF	L2–5 percutaneous screws & L4–5 MIS TLIF	3	BMP, facet autograft	500	320	4	home
18	66, M	LDS	L1–2, L2–3, & L3–4 TP lat IF	L1–5 percutaneous screws, L4–5 MIS TLIF	4	BMP, facet autograft, rib autograft	450	360	5	home

(continued)

TABLE 1: Clinical characteristics and demographics for 23 patients* *(continued)*

Case No.	Age (yrs), Sex	Pathology	Procedure: Stage 1	Procedure: Stage 2	No. Levels Fused	Graft Type	EBL (ml)	Op Time (min)	LOS (days)	Discharge
19	59, F	LDS	L1–2, L2–3, & L3–4 TP lat IF	T11–L4 percutaneous MIS screws, T11–L1 posterolat fusion	5	BMP, rib autograft	350	360	4	home
20	61, F	LDS	L2–3, L3–4, & L4–5 TP lat IF	T11–S1 percutaneous screws, T11–L1 posterolat fusion, L5–S1 MIS TLIF	7	BMP	400	490	7	rehab
21	54, F	delayed posttraumatic kyphosis from T-12 burst fracture	T-12 corpectomy†	T11–L2 percutaneous screws	3	BMP, vertebral autograft	700	420	20	home
22	61, F	LDS	L1–2, L2–3, & L3–4 TP approach IF	L1–S1 percutaneous screws, L5–S1 MIS TLIF	5	BMP, rib autograft, iliac crest autograft	650	660	10	home
23	61, M	kyphosis from post-vertebroplasty osteomyelitis	L2–3 TP partial corpectomies, L3–4 & L4–5 interbody fusion	L1–S1 percutaneous screws & L5–S1 MIS TLIF, unilat percutaneous iliac screw	5	BMP, vertebral autograft	3500	660	10	home

* EBL = estimated blood loss; IF = interbody fusion; LDS = lumbar degenerative scoliosis; LOS = length of stay; MIS = minimally invasive surgical; rehab = rehabilitation facility; TLIF = transforaminal lumbar IF; TP = transpsoas.

† In this case, the anterior surgery was performed via open approach.

rods (DePuy Spine) introduced through the proximal or distal screw entry site. The screw insertion technique was based on using primarily anteroposterior fluoroscopy, and no image guidance was used. Posterolateral intersegmental fusion was achieved at levels without interbody fusion by exposing the facet joints and transverse processes of interest, decorticating with a high speed bur, and laying in autograft, rhBMP-2, or bone graft substitutes. These are both off-label uses for rhBMP-2.

Results

Operative Statistics

An average of 3.7 intersegmental levels (range 2–7 levels) were fused per patient as seen in Table 1. The mean operative time was 401 minutes (range 200–660 minutes) including the anterior component of the combined surgeries. Surgical blood loss averaged 477 ml (range 200–3500 ml). Seven (30.4%) of the patients were discharged to inpatient rehabilitation, and the remainder were discharged home.

Clinical Outcomes

The VAS scores for leg pain averaged 4.35 preoperatively and improved to 1.57 postoperatively, reflecting a mean improvement of 2.78 (Table 2). Utilizing a single-tailed t-test, this revealed a significant change with $p < 0.01$. The VAS scores for axial back pain averaged 7.30 preoperatively and improved to 3.35 postoperatively, reflecting a mean improvement of 3.96. Using a single-tailed t-test, this revealed a significant change ($p < 0.01$). There were no instances of worsening back pain; however, 3 patients experienced minimal or no improvement in their symptoms.

Radiographic Outcomes

With regard to coronal plane abnormalities, 16 of the patients had preoperative deformities. The mean pre- and postoperative Cobb angles were 31.4 and 11.5°, respectively, reflecting a mean 20.0° improvement in coronal alignment. The degree of sagittal deformity, as measured by the degree of lordosis between the thoracolumbar junction and S-1 endplate, was 37.4°. This increased to 45.5° following surgery and reflected an 8.0° increase in global thoracolumbar lordosis.

Fusion was demonstrated at all interbody levels as assessed on fine-cut CT scanning. Of the 7 cases with a posterolateral (without interbody) fusion at the thoracolumbar junction, 2 (28.6%) did not demonstrate radiographic fusion. In 1 case, this resulted in asymptomatic screw loosening at the 9-month follow-up. All fusion sites and levels involved the use of rhBMP-2 except in Case 21, although the dose was not standardized.

Complications

There were no intraoperative complications identified at the time of the surgical procedures or anesthesia. There were also no intraoperative complications related to the anterior approach (hollow viscus or vascular in-

TABLE 2: Clinical and radiographic outcomes in 23 patients*

	Leg VAS Score		Back VAS Score		Cobb Angle (°)			Sagittal Angle (°)					
Case No.	Preop	Postop	Preop	Postop	Preop	Postop	Change	Preop	Postop	Change	Fusion	FU Time	Complications
1	2	1	10	2	32	8	–24	45	45	0	fused on CT	34	none
2	6	2	8	3	32	11	–21	45	50	5	fused on CT	23	transient thigh numbness & pain
3	2	2	7	2	36	10	–26	42	48	6	fused on CT	21	transient thigh numbness
4	7	1	8	3	29	5	–27	38	48	10	fused on CT	19	T-11 compression fracture 12 mos postop, transient thigh numbness
5	5	2	8	3	27	9	–18	40	52	12	fused on CT	16	transient thigh numbness & pain
6	6	0	10	4	26	3	–23	38	46	8	fused on CT	14	none
7	1	1	7	2	22	6	–16	30	48	18	fused on CT	14	none
8	3	2	9	0	37	12	–25	35	42	7	fused on CT	13	none
9	8	3	7	4	36	14	–22	42	46	4	fused on CT	13	none
10	5	0	8	3	33	7	–26	28	30	2	fused on CT	13	sacroiliac joint pain syndrome
11	10	1	1	1	26	18	–8	37	38	1	fused on CT	13	none
12	5	1	8	3	28	4	–24	51	53	2	fused on CT	12	none
13	8	4	8	8	24	22	–2	43	54	11	L5–S1 not clearly fused on CT	12	transient thigh numbness & pain
14	2	4	8	7	46	22	–24	35	40	5	fused on CT	11	CSF leak, new leg & thigh pain
15	2	2	7	4	67	34	–33	32	43	9	clearly fused	11	none
16	1	0	8	2	52	25	–27	34	46	12	fused on CT	11	none
17	7	1	4	3	28	8	–20	36	35	–1	fused on CT	9	none
18	3	2	7	4	20	6	–14	42	54	12	fused on CT	9	developed atrial fibrillation (asymptomatic) postop Day 3
19	1	0	8	2	32	5	–27	33	47	14	fused on CT	9	none
20	7	7	6	6	49	29	–20	31	40	8	fused on CT	7	S-1 screw pullout postop Day 34; revised w/ open op
21	0	0	6	2	0	0	0	9	32	23	fused on CT	6	pneumothorax
22	9	0	10	7	21	3	–13	45	53	8	fused on CT	9	persistent thigh pain & dysesthesias on side of TP approach
23	0	0	5	2	24	3	–21	50	57	7	pseudarthrosis at L1–2 level (no IF)	9	pseudarthrosis at L1–2

* FU = follow up.

Fig. 2. Case 23. Example of kyphosis treated via a minimally invasive approach. **A and B:** The patient presented with spinal osteomyelitis status after vertebroplasty. **C:** The patient underwent a partial corpectomy with expandable cage reconstruction and posterior percutaneous fixation with cannulated pedicle screws. Mini-open posterolateral fusion was performed at the sites where there was no interbody fusion. **D:** Follow-up CT scanning demonstrated pseudarthrosis and proximal screw loosening, although the patient did not complain of any new symptoms.

jury), except a case of pneumothorax due to exposure at T-12. There were no complications due to pedicle screw placement. In the postoperative period, one patient experienced new-onset atrial fibrillation, which was treated with medical management, and another patient developed a pneumothorax that was not identified intraoperatively. This necessitated chest tube placement and a longer hospitalization (20 days). One patient developed a CSF leak not seen at the time of the initial surgery that resulted in reexploration, which did not reveal any obvious CSF dural tear. Another patient required a return to the operating room to extend the construct to the ilium after an S-1 screw pullout on postoperative Day 34. There were no cases of superficial or deep wound infections. One patient (Case 23) underwent partial corpectomies with a significant blood loss of 3500 ml. This was due to excessive bone bleeding during the partial corpectomies and was unrelated to any vascular injury. This patient required allogeneic blood transfusions.

Thigh numbness, pain, weakness, and dysesthesias, all lateralized on the side of the anterolateral approach, were seen in 7 patients (30.4%) despite the use of continuous EMG neuromonitoring during exposure in all cases. In all but 1 case, these symptoms resolved in the postoperative period. However, this resulted in 2 patients being admitted to inpatient rehabilitation rather than discharged home. The patient in Case 21 experienced sensory and motor changes that were severe and persistent enough to require use of an assistive device for ambulation.

Discussion

The minimally invasive surgical treatment of spinal disorders is increasingly being recognized as safe and effective, with the opportunity for a reduction in pain and postoperative complications. The advantages of minimally invasive surgery have been disputed in the treatment of localized pathologies that are well managed using traditional methods, as evidenced by a recent randomized study of minimally invasive surgery versus open lumbar discectomy by Arts et al.[3] In that study of 328 patients, the authors concluded that there was no advantage of tubular discectomy over traditional open surgery. However, surgeons are increasingly recognizing that as the morbidity of the procedure and/or debility of the patient increases, the advantages of a minimally invasive approach are likely to be increased.

We recently reported our initial results using minimally invasive surgical techniques to treat adult spinal deformities.[22] Other authors have corroborated our experience, demonstrating that adult spinal deformities may be treatable using minimally invasive methods.[2,4,18] This report summarizes our early experiences with percutaneous thoracolumbar spinal fixation for adult degenerative deformities through a combined anterior-posterior technique for deformity correction. It should be noted that these procedures and corrections have been made possible only because of the recent confluence of commercially available devices, advanced surgeon training, and modern intraoperative imaging techniques. Specifically, percutaneous pedicle screws, anterolateral approaches, neuromonitoring, specialized deformity correction instruments, and BMP have been critical in allowing spine surgeons to manage these complex pathologies in a minimally invasive fashion.

In this report, our clinical and radiographic results for these 23 patients demonstrate that an anterolateral minimally invasive surgical approach for release, anterior height restoration, and interbody fusion followed by percutaneous pedicle screw fixation was safe and effective. Overall, the mean correction in the coronal plane was 20° with maintenance or improvement of sagittal plane alignment (mean correction of 8°). Clinical improvement in back pain (as measured by VAS) at this early follow-up averaged 3.96 cm. This is similar to larger cohort studies of open surgery, such as the 317-patient cohort of the Spinal Deformity Study Group, which experienced a mean 3.7-point improvement on the numeric rating scale at 2-year follow-up.[20] There were no cases of wound infection, with the only medical perioperative complications being the new onset of atrial fibrillation and pneumothorax in 1 case each. Ultimately, 2 patients required a return to the operating room, one to repair a CSF leak and another to revise instrumentation for an S-1 screw pullout. Overall, these complication rates compare favorably with those of other open surgical series. In particular, the low incidence of surgical site infections has been a finding in other minimally invasive surgical series.

We have found that the transpsoas approach leads to a high frequency of thigh numbness, pain, weakness, and dysesthesias, which are likely the result of retraction in proximity to the lumbosacral plexus and have been well described in previous anatomical studies.[5] Seven (30.4%) of our patients experienced new thigh symptoms due to exposure through the psoas muscle, despite the use of continuous EMG and direct stimulation testing to localize the lumbosacral plexus in all cases. While the transpsoas approach has been described in numerous previous reports,[6,15,16,23] there has been little mention of this complication, and it is likely underreported in the literature. We have typically avoided using this approach below the L3–4 disc space due to anatomical studies on the location and proximity of the lumbosacral plexus in the low lumbar spine. Nevertheless, despite its drawbacks, the mini-open direct lateral approach is a powerful complement to posterior minimally invasive techniques. An interbody fusion obviates the need for an extensive posterolateral exposure, which may be compromised in the setting of minimally invasive surgery. This was demonstrated in our study, which found no anterior pseudarthroses compared with a 29% pseudarthrosis rate with the posterior mini-open exposure on early follow-up.

One of the major limitations of this study is the lack of longer-term follow-up. These data would be essential in determining whether the progression of adjacent-level disease rates is acceptable, as many of the patients in this series may potentially have undergone longer fusion constructs with an open operation. In addition, while CT scans were obtained to confirm the presence of a bony fusion, it is possible for instrumentation failure or deformity progression to occur due to an occult pseudarthrosis.

It should also be noted that the radiographic outcomes in this series are likely to be inferior as an aggregate when compared with open surgical series in terms of deformity correction. Given current limitations in technology, specific reconstruction techniques, such as spinal osteotomies, remain challenging with minimally invasive surgery due to issues with blood loss, risk of neural injury, exposure, and segmental control. While this is currently an area of active research,[21] it remains a tradeoff when trying to achieve lower complication rates than those associated with open surgery. Similarly, the lack of dorsal bony exposure for a fusion surface will likely result in higher rates of pseudarthrosis at segments where an interbody fusion is not used. The longer-term implications of smaller, residual deformities for curve progression, adjacent-level deterioration, or the persistence of symptoms remain unknown.

In this light, it is important to emphasize that the treatment of this patient population is often primarily focused on the management of symptoms due to spinal column incompetency at specific discs and facet joints or due to neural entrapment. The treatment is thus not necessarily directed at the deformity per se, but rather with deformity as an important subcontext. This is unlike the management of idiopathic adolescent deformities in terms of the indications for intervention, specific techniques used, and natural history of the disease.[7]

Conclusions

This initial clinical series demonstrates that select thoracolumbar deformities can successfully be treated using a combined anterolateral transpsoas interbody fusion followed by a posterior minimally invasive approach using percutaneous transpedicular instrumentation. Ultimately, longer-term follow-up and comparison studies will be needed to demonstrate any advantages over traditional open surgical techniques.

Disclosure

Drs. Wang and Mummaneni are consultants for DePuy Spine. Dr. Wang is also a consultant for Biomet Spine and Aesculap Spine. Dr. Mummaneni is a consultant for and has received grants from Medtronic Sofamor Danek and receives royalties from DePuy Spine.

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Correction of lumbar coronal plane deformity using unilateral cage placement

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The authors describe a surgical technique for the correction of symptomatic degenerative lumbar scoliosis. Using a single, unilateral, interbody cage placed on the concave side of the coronal deformity, combined with a dorsal decompression and instrumented posterolateral fusion, this technique has resulted in excellent curve correction, fusion results, and clinical outcomes in a series of 4 patients. Each of these patients presented with intractable, axial low-back pain and symptomatic unilateral nerve root compression on the concave side of a lumbar scoliotic deformity. The management is described in detail. *(DOI: 10.3171/2009.12.FOCUS09283)*

Key Words • **degenerative lumbar scoliosis** • **interbody cage** • **spinal deformity**

Lumbar scoliosis is increasingly recognized as a cause of debility in the adult population.[3,8,17,20,22,25] In contrast to thoracic scoliosis, in which the deformity itself is often the cause of concern for the patient, in lumbar scoliosis, the most frequent presenting complaint is radicular pain caused by nerve root compression.[22] The causes of lumbar scoliotic deformities can be categorized as idiopathic, degenerative, or iatrogenic due to factors following prior unsuccessful spinal surgery.[1,17] In each of these categories, there is a coronal curvature of the lumbar spine that is frequently associated with an oblique angulation and/or rotation of the involved VBs.[7,11,18,19,22] Degenerative lumbar scoliosis is the result of a progressive, coupled, asymmetrical degeneration of the intervertebral discs and facet joint complexes.[8,20] Additionally, both an asymmetrical collapse of the VBs and lateral listhesis may occur, which further increases the degree of coronal plane deformity.[23] This phenomenon is most commonly observed as a focal deformity, involving only 1 or 2 motion segments, and occurs in the midportion of the lumbar spine.[21] In the lumbar spine, the resulting scoliotic deformity has a concave curve that leads to a relative narrowing of the ipsilateral neural foramen, and a convex curve that opens the corresponding contralateral neural foramen.[8,13] Clinical symptoms of lumbar scoliosis most frequently result from bony compression—by either bone, disc, or both—of the ipsilateral nerve root on the concave side. Additionally, severe disc space collapse, which is frequently observed on the concave side of the deformity, may lead to a bone/nerve root/bone phenomenon at the neural foramen, with resulting intractable radicular pain that is unresponsive to any attempts at nonsurgical therapy. Furthermore, it is not uncommon for a translational deformity to occur where the L-2 or L-3 vertebra is translated laterally with respect to the adjacent vertebrae, further compounding the degree of nerve root compression.[23]

The surgical goals in the treatment of lumbar scoliosis are neural decompression, reduction of the coronal plane deformity, maintenance of sagittal balance, and mechanical stabilization of the spine.[2,3,8,12,16,24,25] In this report, we describe a modification of our usual surgical technique of posterior lumbar interbody fusion,[9] which has been found useful for treating patients with lumbar scoliosis resulting in ipsilateral, symptomatic, nerve root compression.

Methods

Four female patients, age 33–71 years (mean age 55 years), who presented to our institution with complaints of axial low-back pain and intractable unilateral radicular pain, were found to have lumbar scoliotic deformities. All patients harbored a left-convex lumbar scoliosis, with two patients having a double-curve thoracolumbar type of deformity. Coronal plane deformities were measured according to the Cobb method, using the maximally angled end-vertebrae of the coronal curve. The magnitude of the lumbar scoliotic deformity varied from 22–36°

Abbreviations used in this paper: BMD = bone mineral density; DEXA = dual-energy x-ray absorptiometry; VB = vertebral body.

TABLE 1: Summary of demographic data in 4 patients who underwent unilateral interbody cage placement

Factor	Case 1	Case 2	Case 3	Case 4
age (yrs), sex	71, F	61, F	33, F	53, F
T-score	−3.2	+1.5	−2.9	+1.6
smoking status	yes	yes	yes	yes
yrs of follow-up	2	1.75	2.5	2

with a mean of 29.9°. In each case, imaging studies demonstrated significant narrowing of the neural foramen and disc spaces on the concave side of the curve. On the contralateral convex side, the neural foramina were enlarged, and the disc spaces were of normal height. Dynamic lateral bending radiography demonstrated that the lumbar scoliotic curves were rigid in all 4 patients. Flexion and extension radiographs revealed unstable lumbar degenerative spondylolisthesis in 3 patients. Prolonged attempts at conservative therapy had been undertaken in each of these patients without success. All patients were smokers and were referred to smoking-cessation programs during preoperative evaluation. Surgery was performed only after preoperative smoking abstinence was achieved. Details of the patients are presented in Table 1.

In addition to obtaining a detailed history and physical examination, a full medical evaluation was conducted in each case prior to surgical treatment. Furthermore, DEXA scans with a bone densitometer (QDR-2000, Hologic Inc.) were obtained in each patient. We determined T-scores (comparison with normal 30-year-old women) for the lumbar spine in each case (T-score range −3.2 to +1.6 [mean −0.75]).

Surgical Technique

The surgical technique for each case was identical at the level of maximal coronal curvature. At the index coronally deformed segment(s) a dorsal osseous decompression was performed that included removal of the spinous process, bilateral laminae, bilateral pars interarticularii, bilateral inferior zygapophyseal facet joints, and the medial and superior aspects of the subjacent superior facet joints. This degree of bone resection allows for the involved nerve roots to be completely decompressed in addition to a dorsal release of the coronal deformity and passive deformity correction. At this point, pedicle screws are placed above and below the involved segment. In addition, if more levels need to be treated, the pedicle screws are placed at these levels as well.

Once the pedicle screws are in position, and intraoperative fluoroscopy has confirmed their appropriate placement, then the bone graft is harvested. Autologous bone graft is obtained from the iliac crest and combined with the additional local bone graft which was obtained during the dorsal bony decompression. All soft tissue is removed from the bone prior to mixing the local bone with the iliac crest autograft.

An aggressive discectomy is performed at the index level where the coronal correction is to be performed. This is performed bilaterally, using curettes, pituitary rongeurs, and paddle-shaped disc "shavers," which allows virtually all of the disc material to be removed from the disc space. This process alone helps to gain some degree of coronal plane correction. After the discectomy is completed, attention is directed toward the placement of the structural interbody strut graft. We routinely use a lordotic-shaped carbon fiber cage, which is filled with morcelized autologous bone graft. A distractor is placed between the pedicle screws on the concave side of the coronal deformity. With distraction between these screws, the cage is impacted into the disc space. Following impaction to the appropriate depth, the distractors are released, the VBs recoil, and the unilateral cage serves to maintain the coronal curve correction that has been achieved. The contralateral disc space on the convexity is then addressed. Generous amounts of autologous fusion substrate bone are packed into the disc space on the convex side, extending from the anterior annulus fibrosis back to the posterior annular defect. In this manner, a very significant amount of bone graft can be compacted into the intervertebral space.

After the index coronally deformed segment has been treated, the remainder of the procedure is carried out in the usual fashion. Prior to securing the rods to the pedicle screws, a compressive force is applied to the screws, bilaterally, at the index level; however, the force applied is greater on the convex side. This allows for a further degree of coronal curve correction. Importantly, by providing dorsal compression, the posterior column is effectively shortened and lumbar lordosis is maintained. The remainder of the construct is secured and a layered wound closure, over 2 suction drains, is performed.

Postoperatively, plain radiographs are obtained in the recovery room on the day of surgery. A CT scan is obtained on the third postoperative day. Serial neurological examinations are performed throughout the hospital stay. Routine follow-up includes clinical examinations with plain radiographs at 6 weeks, 3 and 6 months, and 1 and 2 years. The degree of deformity correction is initially assessed on the postoperative CT scan and compared with the preoperative imaging studies. The final amount of curve correction is determined from the most recent plain radiographs where Cobb angles are determined for both coronal and sagittal alignment on 36-inch standing anteroposterior and lateral films.

Results

Data regarding preoperative coronal plane deformity, and the levels included in this determination for each patient, are provided in Table 2. The levels treated with unilateral interbody cages for coronal plane deformity reduction, as well as the spinal levels that were treated with an instrumented posterolateral fusion, are summarized in Table 2. In one patient, unilateral interbody cages were placed at 2 adjacent spinal levels. In another patient, bilateral interbody cages were placed at separate spinal levels, in addition to the single unilateral interbody cage. Postoperative values are reported from the most recent plain radiographic measurements. The duration of clinical and

TABLE 2: Summary of pre- and postoperative data*

Factor	Case 1	Case 2	Case 3	Case 4
lumbar coronal curve levels/type	L1–5/lt convex	T12–L5/lt convex	T10–L5/lt convex	T10–L5/lt convex
unilat cage level(s)	rt L2–3	rt L2–3	rt L1–2, L2–3	rt L2–3
bilat cage level(s)	NA	L3–4, L4–5	NA	NA
fusion levels	L2–S1	L2–5	T11–S1	T11–L4
reference levels for Cobb angle	L2–5	L2–3	T12–L4	L1–4
preop coronal curve (Cobb angle in °)	22.3	35	35.9	26.5
postop coronal curve (°)	10.4	2.1	24.7	11.1
coronal curve correction (%)	11.9 (53)	32.9 (94)	11.2 (31)	15.4 (58)
preop global sagittal alignment (cm)	+4.5	+2.5	+2.5	–2
postop global sagittal alignment (cm)	+5	+2	+1.9	–1.8
fusion achieved	yes	yes	yes	yes

* NA = not applied.

radiographic follow-up ranged from 1.75 to 2.5 years. The mean duration of both clinical and radiographic follow-up was 25 months. Representative pre- and postoperative radiographs are shown in Figs. 1 and 2.

A successful radiographic spinal fusion was definitively documented in each case. One patient with a long fusion construct (T10–L5), in whom a pseudarthrosis developed and focal kyphosis occurred at the rostral extreme of the construct (T10–11), required revision surgery and rostral extension of the fusion to the T-5 level. The mean correction of coronal plane deformity achieved with this technique was 17.9° over the involved segments. The magnitude of scoliosis correction varied from 94 to 31%. Importantly, no loss of sagittal plane balance occurred as a result of the coronal curve correction procedure. The global sagittal balance was preserved in all cases. The mean preoperative global sagittal alignment was +1.9 cm, and the mean postoperative global sagittal alignment was +1.8 cm. Based on Odom criteria, we determined that clinical outcomes were excellent in 3 patients and good in 1 patient. All 4 patients responded that they would undergo the same procedure again provided that the same postoperative result was achieved.

Discussion

With an increase in the aging population, there has been an increasing awareness of degenerative spinal deformity as a cause of significant morbidity.[3,4,8,17,20–22,25] In the lumbar spine, scoliotic deformities will often be associated with a degree of VB angulation as well as a rotational deformity. Furthermore, unlike thoracic spinal deformity in which cosmetic concerns are prevalent, in lumbar degenerative scoliotic deformity the presenting complaint leading to treatment is most often a combination of axial and radicular pain.[8,11,13,20,21]

When patients present with lumbar radiculopathy, it is important to perform a detailed clinical and radiographic evaluation. Accordingly, this assessment should routinely include plain radiographs of the lumbar spine to investigate for, and quantify the degree of, any lumbar scoliotic deformity that may be present. Although herniated intervertebral discs and/or spinal stenosis are more frequent causes of lumbar radiculopathy, a careful and

Fig. 1. Case 4. **Left and Right:** Preoperative anterolateral and lateral 36-inch standing radiographs demonstrating a 26° left-convex lumbar scoliotic deformity with a degenerative listhesis of L2–3 and an asymmetrical collapse of the right L-2 and L-3 VBs.

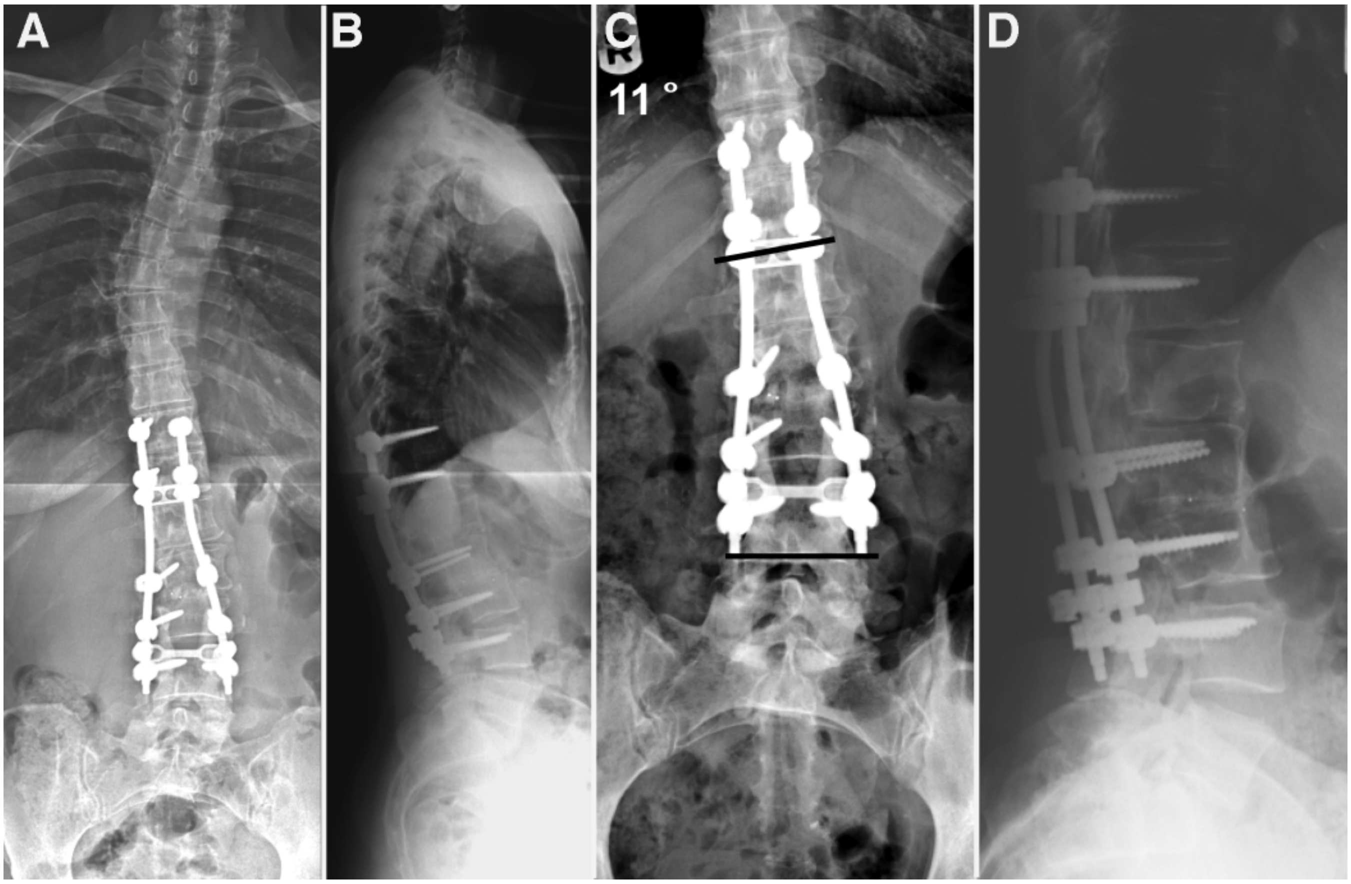

Fig. 2. Case 4. Postoperative 36-inch standing anterolateral and lateral radiographs **(A and B)** and lumbar spine AP and lateral radiographs **(C and D)** following a posterolateral instrumented T11–L4 fusion and placement of a single unilateral interbody cage at the right L2–3 interspace. A coronal plane correction of 15.4° (58%) was achieved with preservation of the global sagittal balance.

systematic review of the radiographic studies will demonstrate that a significant proportion of these patients also harbor a concomitant lumbar spinal deformity. It is important to determine whether radicular symptoms are related to the spinal deformity, spinal stenosis, herniated discs, or a combination thereof, to formulate an effective treatment plan and achieve satisfactory clinical results.

Previously, the technique we had used for patients with lumbar scoliosis requiring spinal fusions was to place bilateral cages into the involved intervertebral disc space. In this manner, the nerve roots were able to be well decompressed and the lumbar lordosis was maintained or improved in most cases; however, the degree of coronal plane deformity did not change appreciably. The modified surgical technique has allowed us to achieve substantial curve corrections while also providing a thorough decompression of the involved nerve roots.

It is important to note that an aggressive bony decompression and disc removal not only provide an excellent decompression of the neural elements, but also serve as a deformity-release maneuver. When combined with proper surgical positioning, with the patient's hips fully extended on a radiolucent operating table, a substantial degree of passive curve correction can be achieved by removing aggressive bony and disc material, and thus less corrective mechanical force needs to be applied to the construct to produce a satisfactory degree of deformity correction. To lessen the incidence of failure of the bone-implant interface or fracture, it is necessary to minimize the corrective mechanical forces on constructs in patients with low BMD. Furthermore, in patients with low BMD, the use of carbon fiber cages, which have a similar modulus of elasticity to that of the adjacent bone, may serve to lessen the incidence of cage subsidence.[5,6,10,14,15]

By placing a single cage on the concave side of the deformed segment and by applying asymmetrical dorsal compressive forces to the stabilizing construct, we have been able to achieve excellent coronal curve correction. The selective application of relatively increased compressive forces on the convex side of the curve allows for an additional coronal plane curve correction and applies a compressive force on the interbody graft material in the disc space proper. At the same time, this technique allows a very generous quantity of bone graft to be packed into the convex side of the intervertebral disc space. The application of bilateral compressive forces also shortens the posterior column, which is pivotal in the maintenance or improvement of lumbar lordosis and global sagittal balance.[12]

All 4 patients in this series were smokers and 2 patients had significantly decreased BMD shown on DEXA evaluation. Despite the presence of these significant risk factors for nonunion, the packing of generous amounts of bone into the intervertebral disc space, in addition to bilateral posterolateral autograft fusions over the transverse processes, has led to successful circumferential arthrodesis of the coronally deformed segments in all 4 cases. In one patient, in whom a pseudarthrosis developed at the rostral-most extreme of the fusion construct, requiring a revision surgery, the pseudarthrosis occurred at spinal segments that were not involved with the coronal plane deformity and were treated with an instrumented posterolateral fusion rather than circumferential stabilization and fusion.

Conclusions

The preliminary results with this minor technical improvement have been gratifying. In all 4 patients we have documented excellent improvements in coronal plane alignment, noted no instance of deterioration in sagittal balance, and observed solid circumferential fusions at the levels of the coronal deformity. In addition, the clinical outcomes have been uniformly positive. In candidates for lumbar spinal fusion surgeries who also possess focal coronal curvatures, consideration and implementation of unilateral intervertebral cage placement has produced excellent overall results in our preliminary experience.

Disclosure

DuPuy Spine and Biomet Spine provide support of non–study-related clinical or research efforts overseen by Dr. Heary. Conception and design: RF Heary. Acquisition of data: both authors. Analysis and interpretation of data: both authors. Drafting the article: both authors. Critically revising the article: both authors. Reviewed final version of the manuscript and approved it for submission: RF Heary.

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Intraoperative computed tomography image–guided navigation for posterior thoracolumbar spinal instrumentation in spinal deformity surgery

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Object. Placement of thoracolumbar pedicle screws in spinal deformity surgery has a reported inaccuracy rate as high as 30%. At present, image-guided navigation systems designed to improve instrumentation accuracy typically use intraoperative fluoroscopy or preoperative CT scans. The authors report the prospective evaluation of the accuracy of posterior thoracolumbar spinal instrumentation using a new intraoperative CT operative suite with an integrated image guidance system. They compare the accuracy of thoracolumbar pedicle screw placement using intraoperative CT image guidance with instrumentation placement utilizing fluoroscopy.

Methods. Between December 2007 and July 2008, 12 patients underwent posterior spinal instrumentation for spinal deformity correction using intraoperative CT-based image guidance. An intraoperative CT scan of the sterile surgical field was obtained after decompression and before instrumentation. Instrumentation was placed, and a postinstrumentation CT scan was obtained before wound closure to assess the accuracy of instrumentation placement and the potential need for revision. The accuracy of pedicle screw placement was later reviewed and recorded by independent observers. A comparison group of 14 patients who underwent thoracolumbar instrumentation utilizing fluoroscopy and postoperative CT scanning during the same time period was evaluated and included in this analysis.

Results. In the intraoperative CT-based image guidance group, a total of 164 thoracolumbar pedicle screws were placed. Two screws were found to have breached the pedicle wall (1.2%). Neither screw was deemed to need revision due to misplacement. In the comparison group, 211 pedicle screws were placed. Postoperative CT scanning revealed that 11 screws (5.2%) had breached the pedicle. One patient in the fluoroscopy group awoke with a radiculopathy attributed to a misplaced screw, which required revision. The difference in accuracy was statistically significant ($p = 0.031$).

Conclusions. Intraoperative CT-based image guidance for placement of thoracolumbar instrumentation has an accuracy that exceeds reported rates with other image guidance systems, such as virtual fluoroscopy and 3D isocentric C-arm-based stereotactic systems. Furthermore, with the use of intraoperative CT scanning, a postinstrumentation CT scan allows the surgeon to evaluate the accuracy of instrumentation before wound closure and revise as appropriate. *(DOI: 10.3171/2010.1.FOCUS09275)*

Key Words • **neuronavigation** • **image guidance** • **spinal deformity** • **spinal instrumentation** • **intraoperative computed tomography**

The development of transpedicular instrumentation has provided the spine surgeon with a multitude of options when planning posterior instrumentation strategies. Although the technique of such instrumentation is becoming commonplace in the everyday practice of spine surgery, it still carries the risks of neural element or vascular injury associated with misplacement.[13] Furthermore, the biomechanical strength of the construct is directly related to the accuracy of instrumentation placement.

The evaluation of the accuracy of transpedicular thoracolumbar instrumentation is a subject of great interest in the spine community as we attempt to limit complications and improve patient outcomes. This has led to numerous published evaluations of the accuracy of pedicle screw placement and the development of innovative techniques to improve the accuracy of instrumentation.[1,3,4,9,16,19,21,22]

Currently, several techniques are used to assist the surgeon with placement of posterior instrumentation. These include free-hand techniques using anatomical landmarks, fluoroscopy, and image-guided navigation systems that typically use intraoperative fluoroscopy or preoperative CT scanning. The use of image-guided navigation systems has been shown to improve accuracy and safety in the placement of posterior instrumentation.[2,8,23]

We present a novel application of image guidance technology combined with intraoperative CT scanning. The technique is performed in a new operative suite equipped with a CT scanner interfaced with the operative table, allowing rapid CT scanning of the sterile surgical

Fig. 1. Left: The intraoperative CT suite at UPMC Presbyterian Hospital with a 64-slice multidetector CT scanner. **Right Upper:** Prior to the intraoperative CT scan, the wound is covered with an adhesive antimicrobial dressing and sterile drape. Following the scan, the additional drapes are removed and the field is block draped with new sterile drape. **Right Lower:** View through the CT gantry from the vantage point of the anesthesiologist. Real-time neuronavigation feedback is provided on the monitors, one of which can be seen in the background.

field. This application increases accuracy and safety of instrumentation while allowing the surgeon an intraoperative assessment of instrumentation placement.

Methods

Patient Population

Between November 2007 and July 2008, 12 patients underwent posterior spinal instrumentation using intraoperative CT-based image-guided navigation for spinal deformity. All screws were placed under the direction of the senior surgeon (D.O.O.). A comparison group of 14 patients who underwent thoracolumbar instrumentation utilizing fluoroscopy during the same time period and who had postoperative CT scans was evaluated and included in this analysis. All patients in the comparison group underwent surgery for correction of scoliosis.

Operative Technique

In the image guidance group, patients underwent intraoperative CT-based image guidance of spinal instrumentation in a newly installed intraoperative suite at UPMC Presbyterian Hospital (Fig. 1). Patients underwent induction of general anesthesia and were then placed prone. Surgical exposure was carried out in routine fashion. If removal of hardware was planned, this was carried out prior to CT scanning. Reference fiducials were then placed in rigid bone landmarks. An intraoperative CT scan of the operative field was then obtained using a 64-slice multidetector CT scanner (GE LightSpeed). Contiguous 0.625- or 1.25-mm images at 120 kVP and 240 mA were obtained. Image acquisition time was < 1 minute in all cases.

Because of the design and movement of the CT scanner table, intraoperative CT scanning of the sterile field is possible. Patients are draped using 4 sterile drapes in a square block-drape fashion. Prior to beginning the scan, the wound is covered with an antimicrobial adhesive dressing. The entire operative field is then covered with another sterile drape, and all operative instruments placed on a sterile table away from the field (Fig. 1). Following CT scanning, the drape is removed and the adhesive dressing is incised to expose the wound. A new adhesive drape and 4 sterile drapes are used to recreate the sterile operative field. Using this method, no patient in this series suffered a wound infection. A 3D volume set of contiguous axial CT images was uploaded to an image guidance workstation (Stryker). Reference fiducials in the surgical field were registered after securing the image guidance tracker to a spinous process. System accuracy ranged between 1.0 and 1.8 mm.

Coronal, axial, sagittal, and trajectory views are available to the surgeon in real time during drilling, tapping, and placement of instrumentation (Fig. 2). Prior to placement of screws, the pedicle tract is palpated using a ball-tipped "feeler" probe. This was performed in both the image guided and fluoroscopy groups. Triggered electromyography was used in the non–image guidance cases to assess for potential pedicle breeches by lumbar pedicle screws. A threshold of 10 mA is used. Any screw with nerve root stimulation at < 10 mA is removed and revised

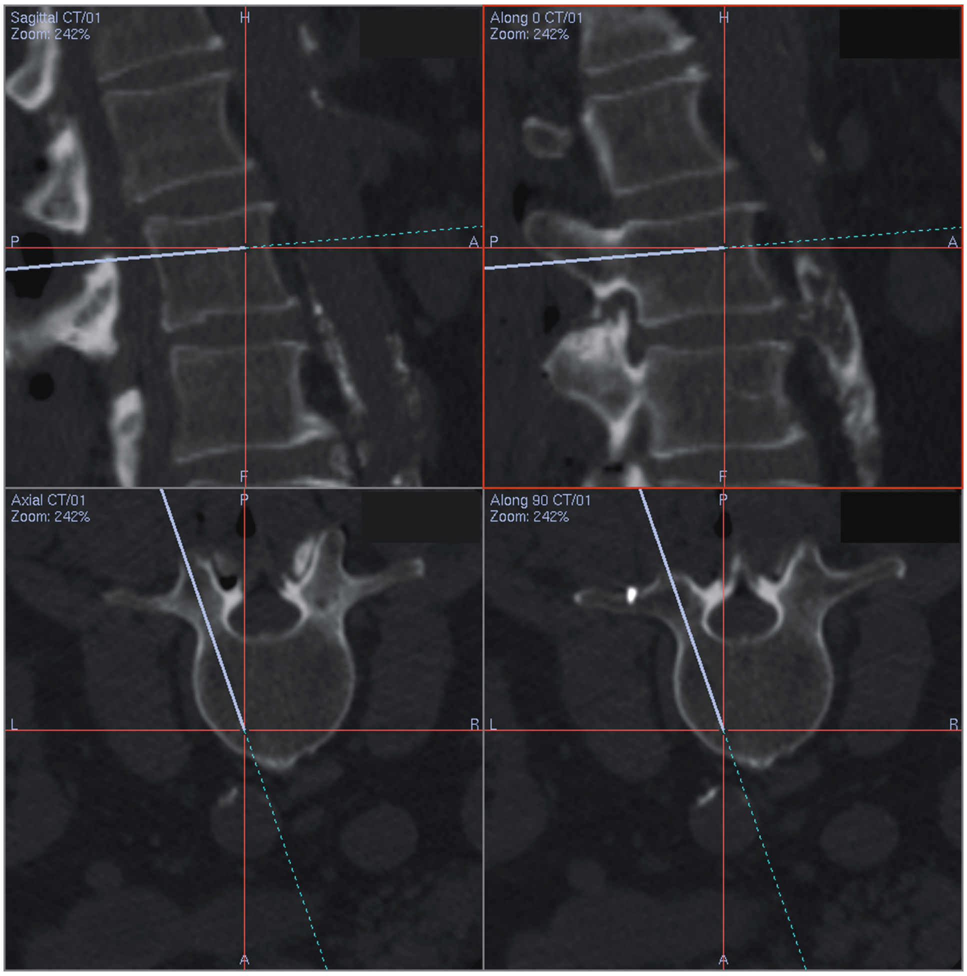

Fig. 2. A screen capture from the image guidance screen during pedicle probing. Coronal, axial, sagittal, and trajectory views are available to the surgeon in real time during drilling, tapping, and placement of instrumentation.

as necessary. Triggered electromyography was used in an early subset of the CT image guidance cases. Rods and set screws were placed on each side to complete the screw-rod construct. A final intraoperative CT scan through the region was obtained to confirm proper placement, trajectory, and length of all screws before wound closure.

Patients in the fluoroscopy group underwent similar procedures for induction, exposure, and decompression. Instrumentation was placed with serial lateral fluoroscopic images. Anatomical landmarks and direct visualization were used to confirm the mediolateral trajectory. Following surgery and extubation, the patients underwent CT scanning to assess accuracy of instrumentation placement, as is our standard postoperative protocol in patients with spinal deformities.

Postoperative Evaluation

The postoperative CT scans were reviewed by 2 independent observers. The main objective was to determine if any screws were malpositioned. Once malpositioned screws were identified, the spinal level, positioning, and the presence of impingement or invasion of adjacent neurovascular structures were recorded. Follow-up radiographs were evaluated for the presence of instrumentation failure and pseudarthrosis.

Results

Image Guidance Group

One-hundred sixty-four pedicle screws were placed in 12 patients via a posterior approach using the aforementioned intraoperative CT guidance protocol. Of these screws, 85 were placed in the thoracic spine and 79 in the lumbosacral spine.

Independent, blinded review of postinstrumentation CT scans revealed that 2 screws (1.2%) breached the pedicle cortex. Both screws were located in the thoracic spine. We reviewed the operative reports of these 2 patients after unblinding the data. In 1 patient, a right-sided T-5 screw broke through the cortex medially. Notation was made to leave the screw in place, as less than half of the screw diameter had penetrated the pedicle wall and there was no impingement on adjacent neural elements. The second patient had a left-sided T-8 screw minimally breach the medial pedicle wall. Again, it was noted that the spinal canal and adjacent structures were not at risk, so the decision was made to leave the screw in its initial position. The overall accuracy for the image guidance group was 98.8%.

No intraoperative instrumentation-related complications (that is, screw breakage, pedicle fracture, or neurovascular injury) were encountered during any of these procedures. Following postinstrumentation intraoperative CT scanning, the surgeons determined that all screws were in a satisfactory position and no screws were revised during the initial procedure. The mean follow-up for patients undergoing CT-based image guidance was 16.8 months (range 14–21 months). During the follow-up period, no patient showed evidence of instrumentation failure or pseudarthrosis. No patient required reoperation for revision of instrumentation.

Fluoroscopy Group

In the comparison group, 211 screws were placed in 14 patients. Ninety-one screws were placed in the thoracic spine, and 120 were placed in the lumbar spine. Eleven screws were found to breach the pedicle wall. The overall accuracy for the fluoroscopy group was 94.8%. The difference in accuracy between the 2 systems was found to be statistically significant ($p = 0.031$).

Postoperatively, 1 patient awoke with a radiculopathy attributable to a medially misplaced screw. This patient returned to the operating room for revision of this screw. Two patients in the comparison group had postoperative wound infections that required operative debridement.

Discussion

Intraoperative CT-based spinal navigation is an effective and accurate means of achieving complex instrumentation of the thoracolumbar spine. Its use improves the accuracy of instrumentation placement and decreases the risk to adjacent neurovascular structures. Furthermore, with intraoperative CT-based image guidance, the operating room staff is spared the radiation exposure of traditional procedures that use fluoroscopy.

The accuracy of intraoperative CT-based image guidance is maximized because the images off of which the guidance is performed are obtained with the patient in the same position as that during placement of the instrumentation. Fiducial reference markers are placed after exposure and within millimeters of the intended starting points for the instrumentation, further enhancing accuracy of the image guidance.

The use of intraoperative CT-based spinal navigation allows real time feedback to the surgeon of instrumentation placement in the coronal, sagittal, and axial planes. Any errors in starting point, trajectory, screw size, or anatomical relationships may be corrected through adjustment of the drill. Final instrumentation placement is assessed by a second intraoperative CT scan such that any suboptimal screw may be replaced at the surgeon's discretion if necessary.

A major concern of spine surgeons when placing instrumentation is the accuracy with which the instrumentation has been placed. A recent meta-analysis on pedicle screw placement accuracy found a median accuracy for thoracolumbar instrumentation without navigation to be 86.6% (range 27–100%) when compared with a navigation-assisted median accuracy of 93.7% (range 72–100%).[9] In our series, all lumbar/lumbosacral instrumentation was accurately placed within the pedicle 100% of the time. An analysis of our thoracic instrumentation showed 2.4% of our thoracic pedicle screws (1.2% of all screws placed) were outside of the pedicle. However, neither screw had more than half of its diameter outside of the pedicle. No neurovascular structures were impinged on, and no significant change in spinal canal diameter resulted. In our series, image guidance was superior to fluoroscopy. Three patients in the fluoroscopy group required a second surgery, including a patient who required instrumentation revision for neurological impingement.

The use of 3D image guidance software also allows not only for placement of instrumentation within the boundaries of the pedicles but also with the desired axial and sagittal angles required to maximize construct strength. Surgical correction of spinal deformity requires that implants withstand the force necessary to achieve the correction. Increasing biomechanical stiffness will lead to higher arthrodesis rates.[7,15] Maximizing bone-implant interface assists in resisting pullout. In the thoracic and lumbar spine, triangulation of pedicle screws has been shown to significantly increase pullout strength in in vitro studies.[10,18,24] The surgeon may maximize convergence, as well as screw size, via surgical planning on the axial images provided by the navigational software. Further strength may be added to the construct by choosing an optimal sagittal trajectory. A biomechanical study by Lehman et al.[11] showed an increase in pullout strength if transpedicular instrumentation was placed parallel to the endplate rather than down the axis of the pedicle. The sagittal reconstructions afforded by intraoperative image guidance allow the surgeon to capitalize on real-time imaging to place instrumentation parallel to the endplate and maximize pullout strength.

Current image guidance systems can be classified by the imaging they use and include standard fluoroscopy and 3D C-arm fluoroscopy systems. A weakness of a standard C-arm image guidance system is the lack of coronal and sagittal reconstructions that allow the surgeon a real-time visual feedback regarding the trajectory of instrumentation.

Three-dimensional C-arm fluoroscopy is able to account for many of the limitations of fluoroscopy-based systems. The systems rely on an isocentric C-arm fluoroscope combined with a navigational computer. The images can be reconstructed in 3D to provide axial, coronal, and sagittal reconstructions. In addition, intraoperative and postinstrumentation imaging can be obtained to assess accuracy. Application of this technology to spinal instrumentation has provided encouraging results,[5,12,17] and it is readily available. While image quality of 3D C-arm fluoroscopy is an improvement, it is not on par with thin-slice CT scanning. In the face of complex deformity, image quality allows for improved accuracy during utilization of image-guided navigation systems. The new intraoperative CT scanner at our institution provides for improved image quality, and the accuracy of instrumentation reported herein confirms that.

The introduction of intraoperative CT in the 1980s enabled surgeons to adapt their operative plans with up-to-date high-resolution imaging.[14] While the use of intraoperative CT scanning in spinal surgery is not new,[6,20] we believe we are the first to report its marriage to image guidance for instrumentation placement in complex spinal deformity. Our use of intraoperative CT scanning with spinal neuronavigation eliminates the disadvantages of other navigational systems. The image-guidance CT scan is obtained with the patient in the operative position and takes into account operative decompression or surgical landmark manipulation. The images obtained are thin-slice CT images of the same quality as those obtained using diagnostic CT scanners. This resolution is absolutely necessary when attempting to maximize screw length, diameter, and trajectory in the vicinity of neurovascular structures.

A criticism of this technology is the cost required to install and use an intraoperative CT suite. The debate rests between the cost of installation of this system and the cost of reoperation in patients with misplaced screws. Our current investigation is not able to address a cost-benefit analysis as sample size and length of follow-up are insufficient to power such a study. As our experience grows, we hope to make this a focus of future analyses.

An important issue is whether intraoperative imaging may lead to unnecessary replacement of radiographically suboptimal screws that are otherwise not clinically significant. Unnecessary repositioning of screws places the patient at an increased risk for complications related to screw placement and runs the risk of biomechanically weakening the construct. Of the 164 screws placed in the image guidance group, none were revised following the second intraoperative scan. This includes the 2 screws that were deemed suboptimal. The surgeon must judge whether the risks of replacing a screw outweigh the potential clinical implications of its misplacement. For each of the 2 misplaced screws in the CT image–guided group, the surgeon made a conscious decision not to revise the screws as neither vascular nor neural elements were at risk.

Conclusions

Intraoperative CT-based spinal navigation for the placement of thoracolumbar pedicle screw instrumentation improved accuracy to 98.22%. It also allowed for revision of misplaced instrumentation before closure. When compared with standard fluoroscopy, intraoperative CT-based spinal navigation significantly improves the accuracy of instrumentation placement.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: DO Okonkwo, PA Gardner, RM Spiro. Acquisition of data: DO Okonkwo, MJ Tormenti, PA Gardner, AS Kanter, RM Spiro. Analysis and interpretation of data: DO Okonkwo, MJ Tormenti, DB Kostov. Drafting the article: DO Okonkwo, MJ Tormenti, DB Kostov. Critically revising the article: DO Okonkwo, MJ Tormenti, AS Kanter, RM Spiro. Reviewed final version of the manuscript and approved it for submission: DO Okonkwo, MJ Tormenti, DB Kostov, AS Kanter.

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Variable positions of the sacral auricular surface: classification and importance

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Object. Although the area at the auricular surface defines the magnitude of weight transmission to the hip bones, this study proposes that the position of the auricular surfaces may also significantly influence load bearing patterns at the sacrum. This study attempts to investigate and classify variable positions of the auricular surfaces that may cause vertical shifts in weight-bearing patterns between the L-5 and S-1 segments, altering weight distribution at the lumbosacral and sacroiliac regions.

Methods. Three hundred human sacra were studied to determine the position and extent of their auricular surfaces in relation to the sacral segments. Specimens were grouped as "normal," "high-up," and "low-down" auricular surface-bearing sacra. All bones were also scrutinized for the presence of accessory articulating facets on the ala of the sacrum and sacralization of the L-5 segment or lumbarization of the S-1 segment. Seven dimensions and 5 articular areas were measured in all sacra. Nine indices were calculated to show proportional representation of dimensions and areas in the bones. Obtained data were analyzed for differences in groups of sacra bearing different auricular surface positions.

Results. Thirty-nine of the sacra (13%) showed auricular surfaces that occupied a high-up position (from upper S-1 to low S-2 segments). Forty-four of the sacra (15%) exhibited a low-down auricular surface (from the low S-1 to low S-3 sacral segments). The remaining bones demonstrated a normal position of the surface (from the S-1 to the middle of the S-3 segments). Twenty of the high-up sacra demonstrated unilateral or bilateral accessory articulating facets on the alae that articulated with extended transverse processes of the L-5 vertebrae. The low-down sacra transmitted load predominantly via lower (S2–3) segments and exhibited stouter, broader, and efficient weight-bearing lower sacral elements, and a prominent gap between the S-1 segment and the rest of the sacrum. The high-up sacra: 1) were shorter and broader in comparison with the normal sacra; 2) at times presented accessory articular facets on their alae; 3) had a smaller body span and a wider ala; 4) were found to have the plane of the facet joints nearer to the posterior aspect of the S-1 body; and 5) had the smallest of the facet areas. The low-down sacra were longer than they were broad, had a substantially broad body span at S-1, possessed the smallest interauricular distance, and showed considerable depth of the plane of the facet joints.

Conclusions. The position of the auricular surface varies in human sacra. These variations are associated with differential load bearing at the sacral joints. Only the high-up sacra demonstrated the presence of accessory articulating facets between L-5 and S-1. The position of the auricular surface can explain or possibly predict low-back pain situations. *(DOI: 10.3171/2009.12.FOCUS09265)*

Key Words • **auricular surface** • **sacral segment** • **facet joint** • **low-back pain**

The sacrum acts as the interface between the axial and the appendicular skeleton. The word sacrum means "sacred (bone)."[17] The entire load received at the upper end of the sacrum is transmitted bilaterally to the ilium through the strong sacroiliac articulations.[5,18] The associated ligaments and muscles around the joint actively assist in the transmission of load toward the hip joint. The sacral component of the sacroiliac joint is formed by a pair of inverted, L-shaped, extensive articular surfaces, called the auricular surface, due to its resemblance to the pinna of the external ear. A "normal" auricular surface is located on the outer surface of the lateral mass of the sacrum and extends from the S-1 to the middle of the S-3 sacral segments.[25] As studied by Pal et al.,[18] the auricular surfaces measured in 44 human sacra showed that the normally located auricular surfaces (extending from the S-1 to the middle of the S-3 sacral segments) transmitted weight predominantly through the S-1, S-2, and upper half of the S-3 components to the sacroiliac joint.[18]

The upper 3 segments bear strong transverse bars (costal elements) that connect the bodies of the S-1, S-2, and superior half of the S-3 segments to the lateral mass of the sacrum, bearing the auricular surface. As a consequence, the lower segments of the sacrum beyond and below the auricular surface appear to be grossly diminished in size and become narrow.[5,18,25] Unlike the ilium, the position and orientation of the sacrum does not undergo

TABLE 1: Comparison of the mean linear parameters in the 3 groups*

Linear Dimensions (mm)	Normal Group I (217 cases)	High-Up Group II (39 cases)	Low-Down Group III (44 cases)
interfacet distance	52.12 (4.34)	47.88 (5.07)	47.90 (6.10)
facet depth	15.24 (2.90)	13.98 (2.70)	15.88 (3.62)
interauricular distance	102.79 (10.09)	102.04 (6.3)	100.86 (10.25)
body width	46.34 (6.62)	42.90 (5.90)	46.97 (5.63)
mean auricular height	61.15 (8.16)	60.04 (6.36)	61.97 (5.01)
lt auricular height	61.49 (8.44)	60.60 (5.54)	62.12 (5.46)
rt auricular height	60.82 (8.51)	60.32 (5.41)	61.81 (5.64)
sacral height	105.05 (10.24)	94.82 (7.81)	108.40 (14.72)

* All data presented as mean (SD).

drastic changes as a result of a transition from the quadrupedal to bipedal mode of locomotion.[21] Nevertheless, the sacra are the first of the bones to undergo changes in shape across hominoid evolution.[13,14] The changes observed in human sacrum are a more vertical orientation of the bone and the "stockpiling" of its segments, implying its weight-bearing nature. The changes in the sacrum are accompanied by certain morphological adjustments such as an increase in width in comparison with the other primates.[13,14,17,21] In contrast to other primates, the human sacrum exhibits a more compact body consisting of 5 fused segments, comparatively more vertical orientation, and marked load-bearing features across its upper elements, with features of vertical "stacking" of its individual segments[2] and development of the lumbosacral angle.[1,13,24]

Much scientific literature is available related to the size, shape, and dimensions of the sacroiliac joint in both healthy and diseased states.[8,9,11] There is no available literature pertaining to the variation of position of the auricular surface on the lateral mass of the sacrum, except for a superficial comment about the relative change of position of the surface in the Australopithecus fossil remains of *A. africanus* (the skeletal remains Sts 14 [female *A. africanus*] and A.L. 288-1 [female *A. afarensis*, or "Lucy"]) bearing a "high" auricular surface in comparison with the *A. afarensis* (Stw 431 [*A. africanus*]) that has a "low" surface.[17] Several other important skeletal factors, especially the orientation of the pelvis, the curves of the spine, the alignment of the center of gravity, and the fanning of the iliac blades act as deciding variables for developing a complete bipedal mode of locomotion.[16] The position of the auricular surfaces in the context of their orientation with the iliac bone is vital in maintaining an upright posture, because any shift of the auricular surface can alter the dynamics of load transmission within the sacrum (between the sacral segments) at the lumbosacral and sacroiliac articulations. Conversely, specific auricular morphology of the sacrum may be associated with unique load transmission patterns associated with the upright spine observed in humans or perhaps be linked to certain pathological conditions at articulations of the sacrum. The aims of this study were to: 1) detect any gross alteration in the position of the auricular surfaces in human sacra in relation to the sacral segments; 2) attempt to classify sacra according to variations in the relative position of the auricular surfaces; 3) correlate variations in the positions of auricular surfaces with other observable morphological changes in the sacrum; and 4) provide a detailed morphometry of the proposed functional varieties of sacra.

Methods

Three hundred human sacra were used for the study. All the sacra were from the adult age group (18–65 years of age) and included both the sexes. Each of the sacra was measured for the following parameters: 1) the distance between the 2 articular facets; 2) the distance between the posterior limit of the S-1 segment and the coronal plane of the 2 zygapophyseal joints; 3) the width of the body of the S-1 segment; 4) the height of the auricular surface; 5) the height of the sacra; and 6) the maximum distance between the 2 auricular surfaces. The auricular surfaces, area of the zygapophyseal facets, and areas of the upper surface of the body of the sacrum were determined. All linear measurements were obtained using digital sliding vernier calipers with a sensitivity of 0.01 mm. The sur-

TABLE 2: Comparison of the different surface areas in the 3 groups*

Surface Areas (cm^2)	Normal Group I	High-Up Group II	Low-Down Group III
auricular			
mean	10.36 (1.86)	10.98 (1.78)	10.06 (1.58)
rt	10.47 (1.92)	11.08 (2.01)	10.13 (1.78)
lt	10.24 (2.00)	10.88 (1.95)	9.97 (1.63)
facet			
mean	1.71 (0.51)	1.52 (0.48)	1.77 (0.48)
lt	1.68 (0.58)	1.53 (0.51)	1.74 (0.52)
rt	1.73 (0.52)	1.52 (0.57)	1.80 (0.52)
body	10.02 (2.35)	9.85 (2.30)	9.89 (2.82)
accessory facet areas on high-up sacra		2.13 (1.06)	

* All data presented as mean (SD).

TABLE 3: Comparison of the indices in the 3 groups*

Indices (mm)	Normal Group I	High-Up Group II	Low-Down Group III
tripod index (IFD/FD)	3.53 (0.70)	3.54 (0.75)	3.16 (0.80)
transverse index (IAD/BW)	2.24 (0.34)	2.66 (0.67)	2.14 (0.23)
auricular index (SH/AH)	1.74 (0.22)	1.55 (0.28)	1.87 (0.24)
articular index (IAD/IFD)	1.94 (0.21)	2.14 (0.21)	2.12 (0.26)
sacroauricular index (IAD/SH)	1.02 (0.08)	0.93 (0.89)	0.94 (0.13)
auriculofacet depth index (IAD/FD)	6.92 (1.25)	7.56 (1.48)	6.63 (1.53)
Index I (ASA/BSA)	1.01 (0.24)	1.14 (0.27)	1.05 (0.21)
Index II (ASA/FSA)	6.27 (2.24)	7.97 (3.13)	6.43 (3.86)
Index III (BSA/FSA)	6.17 (1.91)	6.99 (2.76)	6.24 (3.62)

* All data presented as mean (SD). Abbreviations: AH = auricular surface height; ASA = auricular surface area; BSA = upper surface of the body of the sacra; BW = body width; FD = facet depth; FSA = area of the zygapophyseal facets; IAD = interauricular distance; IFD = interfacet distance; SH = sacral height.

face areas were traced on tracing paper and measured with a digital planimeter. All sacra were inspected to detect the position and extent of the auricular surfaces, the presence of any accessory articulating facet on the alae of the sacrum, and the presence of any lumbosacral vertebral fusion. The sacra were identified as 1 of 3 types according to the position of their auricular surface. The sacra showing an auricular surface extending from the S-1 to the middle of the S-3 sacral segments were designated as Group I (normal). Auricular surfaces beginning superiorly above the upper level of the S-1 segment and extending inferiorly up to the upper S-3 segment were categorized as Group II sacra ("high-up;" Fig. 1). Bones with auricular surfaces beginning at the lower half of the S-1 segment and extending up to the inferior aspect of the S-3 segment were categorized as Group III ("low-down;" Fig. 2). Several indices were calculated, based on the observed values. Differences in the absolute values of the data among the groups were analyzed and interpreted. Seven sacra exhibited complete sacralization of the L-5 vertebra; these sacra exhibited low-down auricular surfaces and were included in Group III (Fig. 2 right).

Results

Table 1 shows the mean values of all linear parameters in each of the 3 groups of sacra. Analysis of the dimensions revealed that the mean height of the high-up sacra (Fig. 1) was smaller than the height in the normal and low-down groups. The mean body width of the S-1 segments was considerably smaller in the Group II specimens, and the interfacet distance was smaller, but the mean interauricular distance in this group was comparable to that in the normal group. The plane of the facet joints in Group II appeared to be nearer to the S-1 vertebral body, given that the mean facet depth was found to be lower in Group II than in the other 2 groups. The heights of the auricular surfaces were similar in all 3 groups. The sacra in Group III (low-down) demonstrated a greater length, wider S-1 body, and closer auricular surfaces (smaller interauricular distances).

Table 2 compares the mean superior surface areas of the S-1 segment body in the 3 groups. The mean facet surface areas were found to be smaller in Group II in comparison with the other groups. No significant differences were observed among the groups for the auricular

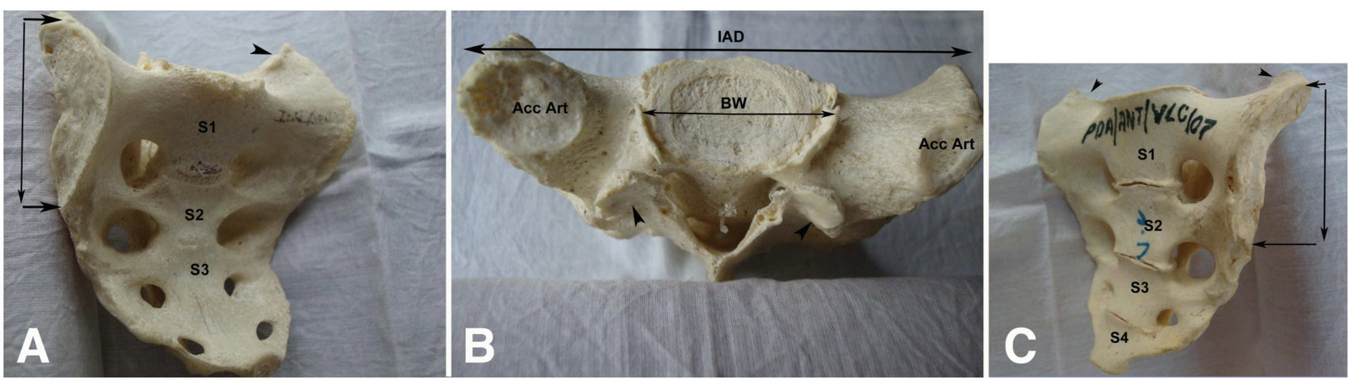

Fig. 1. Representative sacra from Group II (high-up). **A:** In this image, note that the auricular surface is limited to the upper 2 sacral segments (S-1 and S-2) and begins above the level of the S-1 segment. The *arrowhead* indicates the accessory articulation on the left sacral ala. **B:** Upper view demonstrates the small body area, the smaller facets *(arrowheads)*, and the accessory articulating areas (Acc Art). BW = body width; IAD = interauricular distance. **C:** Example showing 4 segments (lumbarization) and 2 accessory facets *(arrowheads)* on the alae.

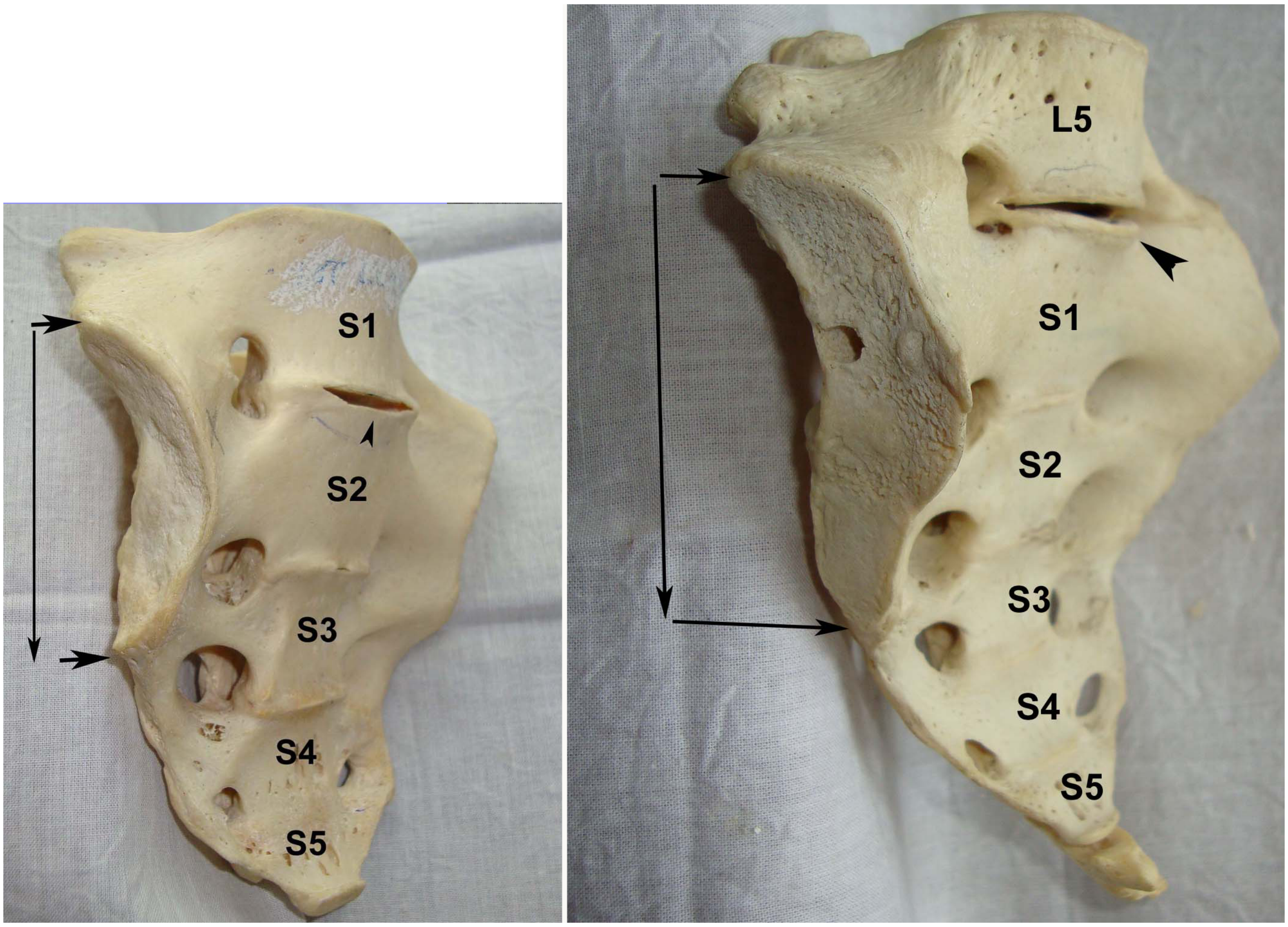

Fig. 2. Representative sacra from Group III (low-down). **Left:** Note the relatively low position of the auricular surface in the sacrum. The surface occupies the lower half of S-1 and extends well into the S-3 component. Note the increased space between the upper 2 sacral components. **Right:** Example showing complete sacralization of L-5. The *arrowheads* in both figures show the gap between the upper 2 components.

surface areas. Among the indices shown in Table 3, the following are noteworthy. Index I (auricular surface area/body surface area) showed a higher value for Group II, indicating a larger auricular surface area in comparison with the small body area at S-1. A high Index II (auricular surface area/facet surface area) value in Group II indicated a lower percentage of weight shared by the smaller facet joints at the sacrum. All absolute values as well as the indices indicate no appreciable variations in the dimensions of the auricular surfaces. Group I auricular surfaces extend from the upper S-1 segment to the middle S-3 segments. The Group II auricular surface sacra show well developed S-1 and S-2 sacral components; the upper limits of the auricular surfaces jut beyond the superior surface of the S-1 segment in this group.

Of the 39 high-up sacra detected in the study (13%), 20 demonstrated the presence of unilateral or bilateral accessory articulating facets (mean area 2.13 ± 1.06 cm^2) on their alar surface that articulated with a well-defined reciprocal area on the tip of an extended transverse process of L-5. The rest of the high-up sacra demonstrated evidence of stronger attachments of the sacroiliac ligaments than usually encountered. The sacral segments below the S-2 element exhibited narrow bodies that ended abruptly with approximating lateral borders. No accessory articulating facets were visualized in Group I or Group III sacra. The 44 low-down auricular surfaces (14.6%) stretched between the middle S-1 up to the lower S-3 levels (Fig. 2). In all groups, the auricular surface area occupied approximately 2.5 sacral segments. Three sacra exhibited unilateral fusion of the L5–S1 transverse processes (Fig. 3). The unfused sides demonstrated a high-up auricular surface whereas the fused (opposite) sides presented a low-down surface, probably due to incorporation of the L-5 transverse elements into the auricular surface (with the body of L-5 now representing the top of the sacra). Seven sacra showed complete sacralization of the L-5 vertebrae. These bones presented bilateral low-down auricular surfaces (Fig. 2 right).

Two of the high-up sacra presented only 4 sacral segments (Fig. 1C). Both of their alae bore bilateral accessory articulations. In fact, these spines revealed that the S-1 components of their sacral columns were incompletely lumbarized and now presented as the sixth lumbar ver-

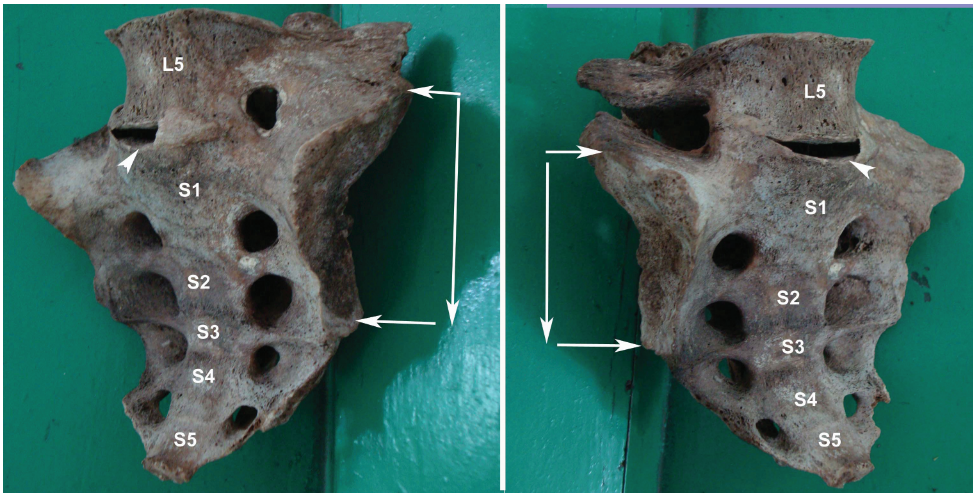

Fig. 3. A representative sample of a partially sacralized L-5 vertebra. The sacralized side exhibits a low-down auricular surface **(left)**, whereas the unfused side bears a high-up surface **(right)**. The *arrowhead* indicates the gap between the L-5 and S-1 segments.

tebra. The L-6 vertebrae connected to the sacral alae by bilateral accessory articulations. The majority of the low-down sacra presented wider gaps between the S-1 and the S-2 components of the sacral corpus (Fig. 3).

Discussion

Human sacra are structurally adjusted to a bipedal mode of locomotion and therefore assume specific spatial orientation and angulation.[1,2,21] The sacrum bears weight and is transformed into a compact triangular bone. The sacrum receives weight from the upper vertebral column via the upper surface of the body of the S-1 segment and also through the articular facets that constitute the lumbosacral zygapophyseal joints. The magnitude of the forces received is proportional to the articulating surface areas[19] and is also dependent on the sacral articulation angle.[1] The load is transferred bilaterally to the ilium through the auricular surfaces via the sacroiliac joints. The less-weight-bearing sacrum in the quadrapeds is longer and is composed of a fewer number of segments.[2,14,17,21] The fusion of sacral segments imparts stability as well as efficiency in load transmission in a vertically oriented vertebral column.[18] In fact, the fusion results from the need to stabilize the sacral column at the expense of its mobility, for a complete and proficient transmission of load. In addition to fusion of the sacral bodies, the transverse processes of the sacral segments coalesce to represent the massive lateral masses of the sacrum.

As observed in Group I (normal sacra), load is primarily routed through the first 2.5 segments at the auricular surfaces that are located exactly at the level of the S-1, S-2, and upper S-3 segments. These sacral segments show robust costal elements and a prominent trabecular pattern[18] at these levels. These sacra also exhibit attenuation of their sacral segment sizes below with a quick narrowing of the lateral borders. The sacrum assumes its characteristic anteroposterior curve only below these stable and vertical components.

The Group III (low-down) auricular surfaces indicate increased stability and strength at the lower (S-2 and S-3) sacral segments. The occasional presence of exaggerated gaps (increased intervertebral spaces) between the S-1 and S-2 segments in low-down sacra indicates that more weight is transmitted through the lower segments of these vertebrae, which obviates the need for complete fusion of the S-1 segment. This situation can be viewed as a condition of incomplete incorporation of the S-1 segment in the sacral "stockpiling" due to already stable and efficient lower segments.

The Group II sacra demonstrated stable upper segments (S-1 and S-2) with strong features of load transmission at their costal and transverse elements and sacral bodies. Weight transfer in these sacra occurs chiefly at the upper vertebral levels due to the superior position of the auricular surfaces. This weight is transferred laterally to the 2 sacroiliac joints. This transverse direction of load shift in Group II high-up sacra is more acute when compared with Group I or III sacra, because the auricular surfaces in Group II sacra are situated higher up. The observation that the alar slopes of the S-1 segment are similar in Group I and Group III,[26] and that they are steeper in Group II, demonstrates that the transmitted load in the high-up category possesses a more horizontal trajectory and influences the load-bearing pattern at this region. In fact, a good number of these sacra with high-up auricular surfaces present with unilateral or bilateral accessory articulations between the ala of the sacrum and extended transverse processes of the L-5 vertebra. This may indicate a partial "recruitment" of an additional upper component (transverse process of the L-5 vertebrae) into the sacral stockpiling to increase its load-bearing capability. Observation of successive lumbar vertebrae from above downward reveals that the plane of the facet joints gradually moves away from the vertebral body and act as a tripod to support weight.[10] The continuation of this phenomenon can be encountered in Group III, Group I, and Group II specimens in decreasing order of the relative distances of the plane of the facet joints from the vertebral body. The role of the sacral anatomical orientation angle in this recruitment of additional segments to facilitate load bearing is a matter of further research.

Observation of the sacra with unilateral sacralization of L-5 demonstrates 2 types of auricular surfaces on the 2 sides of the bone (Fig. 3). On the side of fusion of the L-5 transverse process, the auricular surface appears to represent a low-down variety. It appears so because of the inclusion of the body of the L-5 vertebra on top of the corpus of the sacrum. This characteristic also imparts a greater height to the bone. A part of the transverse process also contributes to increase the area of the auricular surface on that side. The point to be noted is that this side of the sacrum now exhibits an added area to the overall auricular surface but presents a decreased area at the superior facet articular surface of the bone (because the L-5 superior articular facet surface is smaller than the normal S-1 superior facet surface). The lower limit of the auricular surface never extends below the level of the S-2 segment at these fused sides (or in the specimen showing completely sacralized L-5 vertebrae). The opposite half of the sacrum exhibits a high-up auricular surface with an extended transverse process of the L-5 vertebra above it. This process abutted near the sacral ala but failed to articulate with the ala (Fig. 3 right). It may be asked whether a high-up auricular surface necessitates a gradual extension of the transverse process of the L-5 vertebrae to either form an accessory articulation with the ala of the sacrum or fuse with the ala (sacralize), due to functional reasons of load bearing. The evidence of stronger dorsal sacroiliac ligaments in the high-up sacra also indicates the requirement of stronger ligamentous function at these bones. Auricular surfaces in bilaterally and completely sacralized L-5–bearing sacra can be visualized as high-up surfaces in the Group 3 sacra that now appear to be lower in position after the union of L-5 atop the S-1 segment.

Classification of sacrum according to sex has been well documented in the literature. The attempt to classify sacrum according to the dynamics of load sharing has not been attempted before. The present study is an attempt to establish that: 1) the position of the auricular surfaces varies in the context of the sacral segments; 2) variations can be grouped under 3 broad categories; and 3) variations signify different patterns of load bearing within the sacra. The high-up sacra demonstrate considerable association with accessory unilateral or bilateral articulations for functional requirements. These accessory joints present increased levels of stress and activity, indicating active load sharing at the regions.[6,20] It could be of immense value for clinicians to assess and understand the gross morphology of sacra in light of the positions of their auricular surfaces. Load-sharing, shear, and strain patterns involved with a particular group of sacra can be better understood and transitional states at the lower back[3] can be better explained when the relative positions of the auricular surfaces are taken into account. Biomechanical classification of sacrum may help identify potential low-back pain situations.[7,12,15,22] No accessory articulations (transitional states) were observed in sacra other than those in Group II. In light of the argument put forth in this study, it could be further investigated as to whether the accessory articulations observed in the high-up variety of sacra possibly induce structural changes that would lead to a transitional state at the lumbosacral junction, supplementing genetic determinants implicated in the development of transitional states at the lumbosacral junction.[4,23] From the observations obtained from this study, it may also be asked whether a complete lumbarization of the S-1 component of a sacrum would lead to the formation of a high-up auricular surface in the remainder of the sacrum. In contrast, it may also be asked whether a complete sacralization of the L-5 vertebrae could result in a low-down auricular surface in the resulting sacral mass, in the trail of its formation. It can be a matter of further investigation as to whether the dynamics of load bearing at the lumbosacral junction directs a fusion (sacralization) of the L-5 vertebrae or determines a separation (lumbarization) of the S-1 sacral component, or arrests events at a transitional state. In any of these circumstances, the vital position of the auricular surfaces determines the load-bearing pattern in the sacrum, including the specific sacral segments that are involved in transmission of load towards the hip bone.

Disclosure

The author reports no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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An S-2 alar iliac pelvic fixation

Technical note

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Multiple techniques of pelvic fixation exist. Distal fixation to the pelvis is crucial for spinal deformity surgery. Fixation techniques such as transiliac bars, iliac bolts, and iliosacral screws are commonly used, but these techniques may require separate incisions for placement, leading to potential wound complications and increased dissection. Additionally, the use of transverse connector bars is almost always necessary with these techniques, as their placement is not in line with the S-1 pedicle screw and cephalad instrumentation. The S-2 alar iliac pelvic fixation is a newer technique that has been developed to address some of these issues. It is an in-line technique that can be placed during an open procedure or percutaneously. *(DOI: 10.3171/2010.1.FOCUS09268)*

Key Words • **sacropelvic fixation** • **iliac fixation** • **percutaneous approach**

Distal fixation in thoracolumbar spinal deformity surgery is crucial when arthrodesis to the sacrum is indicated.[10] Multiple studies have shown that long instrumentation and fusion to the sacrum without supplemental pelvic fixation predisposes to fixation failure and reoperation.[3,4,12] Kim and colleagues[6] have shown that the L5–S1 junction is the single level with the highest incidence of pseudarthrosis in adult scoliosis surgery, with a rate of 24%. Pseudarthrosis in adult thoracolumbar spinal deformity surgery is associated with adverse clinical outcomes.[4] Multiple techniques exist for spinal fixation distal to S-1 pedicle screws. Techniques for pelvic fixation include transiliac bars, iliac bolts, and iliosacral screws. These techniques frequently require separate incisions for placement or the use of offset connectors, adding to surgical time and morbidity.[1,5,7,11] The S2–AI technique is an alternative, low-profile, in-line technique that can provide distal fixation in spinal deformity surgery.

Case Report

We describe the case of a 73-year-old woman who underwent laminectomy 10 years prior to presentation. At presentation she complained of significant low-back pain, which had worsened over the last few years, and, at present time, she had pain at rest as well. Her activity level had declined significantly due to her pain. Nonoperative management, including 8 epidural injections and 2 courses of physical therapy, had failed to resolve her pain. At the time of presentation, she was taking high-dose oral narcotics on a daily basis without durable pain relief. The patient was neurologically intact with respect to leg sensation and motor function.

Imaging studies showed a postlaminectomy degenerative scoliosis with severe hypertrophy of facet joints. The worst areas were L2–3 and L4–5, with moderate degeneration of L3–4. Radiographs demonstrated a 35° dextroscoliotic degenerative lumbar curve from T-11 to L-5. Lateral listhesis of 5 mm was noted at L3–4. After a discussion of the risks and benefits of surgery, the patient agreed to undergo corrective spinal surgery to address her postlaminectomy spinal deformity.

Operative Technique

The patient underwent a 2-stage posterior–anterior lumbar fusion and stabilization with instrumentation. The first operation was a revision posterior decompression and fusion with instrumentation placed from T-10 to the pelvis, including S2–AI screws.

The patient was given general anesthesia and placed prone on a Jackson frame to enhance lumbar lordosis. Prophylactic antibiotics were administered and the patient's back was prepared and draped in a sterile fashion. The previous incision was used and extended proximally to the T-9 level. Dissection was carried out through the subcutaneous tissue to the fascial layer. Using a Cobb

Abbreviation used in this paper: S2–AI = S-2 alar iliac.

Fig. 1. Standing 3-ft radiographs of S2–AI pelvic fixation in a patient treated for thoracolumbar spinal deformity.

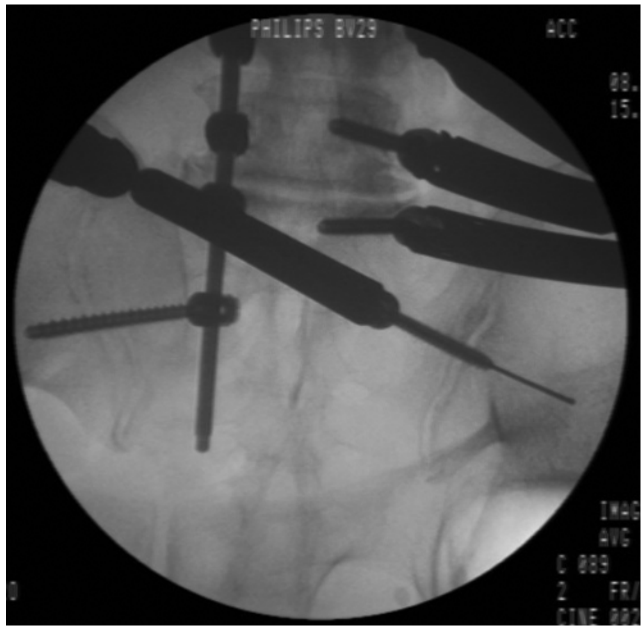

Fig. 2. Percutaneous placement in a cadaveric specimen: the screws have been placed in full on the left side and the rod advanced. This image illustrates the S2–AI screw in line with the cephalad instrumentation.

elevator and electrocautery for dissection, the spinous processes of L-1 and L-2, remnant laminae of L-2, L-3, L-4, L-5, S-1, along with S-2, were exposed. A localizing radiograph was acquired to confirm the levels. Dissection was carried out over the facet joints to the transverse processes. The sacrum was exposed to the level of the S-1 foramen. Next, revision decompression of the neural elements was undertaken from L-1 to S-1 by mobilizing the scar-bone interface and performing complete bilateral facetectomy. Then, pedicle screws were placed using internal and external landmarks from T-10 to S-1, with the exception of the right pedicle of T-12, which was skipped due to medial wall perforation.

Following this step, using fluoroscopic guidance, S2–AI screws were placed bilaterally. The starting point is 1 mm inferior and 1 mm lateral to the S-1 dorsal foramen, which was directly visualized. Angulation was directed toward the greater trochanter and approximately 30° anterior from the floor. A 3.5-mm pelvic drill (extended length) was used to "tap" drill through the sacroiliac articulation. On average, it will be at 35–40 mm before the ilium is reached. The anteroposterior radiograph is used to ensure placement cephalad to the sciatic notch. The pelvic inlet radiograph is then used to ensure extrapelvic placement, as judged by viewing the anterior sacroiliac joint (see Fig. 4). Once the drill was in the ilium, a ball-tipped probe was placed into the ilium and manually advanced through the cancellous bed until a cortex is reached. The length was measured and the tract was then tapped past the sacroiliac articulation. A 7 × 80–mm screw was inserted. Again, radiography was used to evaluate placement.

Final steps during this operation included the placement of posterior interbody cages at L2–3 and L3–4, as well as prophylactic vertebroplasty at T-9 to prevent proximal junctional kyphosis due to fracture. Appropriate-length rods were contoured and the spine was reduced to the coronally straight rods. Segmental compression was applied to the construct and the end caps were torqued down. Copious irrigation of the wound and arthrodesis followed. Local bone, cancellous chips, demineralized bone matrix, and iliac crest were placed onto the decorticated surfaces. The wound was closed in layers. The patient tolerated this procedure well and recovered in the hospital until transfer to a rehabilitation center on postoperative Day 10.

The second-stage anterior discectomy and fusion of L5–S1 was performed 1 month after the first operation. A right retroperitoneal exposure was done by a fellowship-trained vascular surgeon. The L5–S1 disc space was exposed and the great vessels protected. A discectomy was performed, the endplates prepared, and a femoral ring allograft filled with demineralized bone matrix was placed at L5–S1. An anterior plate was used with 2 locking screws in both L-5 and S-1. The surgical wound was irrigated and closed by the approach surgeon without complication. The patient again recovered in the hospital and was discharged to home on postoperative Day 3. Standing radiographs showed adequate alignment and hardware placement at 1 year postoperatively (Fig. 1).

At 1-year follow-up, the patient was off all narcotic medications and had returned to independent activities. Her Oswestry Disability Index score improved from 50 preoperatively to 20 at 1 year postoperatively.

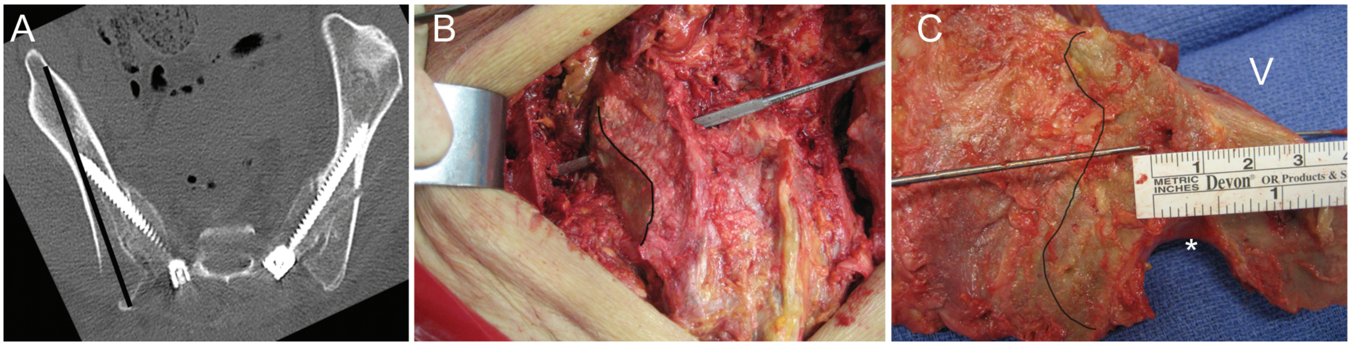

Fig. 3. **A:** Axial CT scan cut through the ilia demonstrating the trajectory of the S2–AI screws. The *black line* on the patient's right illustrates the trajectory of a traditional iliac screw. **B:** Open cadaveric specimen with a probe illustrating the trajectory of the S2–AI screw. The *line* demarcates the articular and nonarticular portion of the sacroiliac joint. The medial ilium has been excised for better visualization. **C:** Removed left ilium of a cadaveric specimen after S2–AI screw placement. *Asterisk* marks the greater sciatic notch. The *line* demarcates the articular and nonarticular portion of the sacroiliac joint. V = ventral.

Discussion

An S2–AI sacropelvic fixation is a new technique described contemporaneously by Dr. Sponseller[10] and Dr. Kebaish for use in the pediatric and adult population, respectively. O'Brien et al.[9] adapted it for use in minimally invasive applications (Fig. 2). The S2–AI technique for pelvic fixation is a modification of an S-2 alar screw driven through the sacroiliac articulation into the iliac wing. This technique is preferable because the screws have a lower profile[2,10] and are in line with cephalad instrumentation. On average, the S2–AI screw was 2 cm deeper than the starting point for a traditional iliac screw.[10] The relatively deeper location and smaller dissection to place the S2–AI screw is crucial in cases where wound breakdown can be an issue—such as in neuromuscular scoliosis.[10] Furthermore, with 4 years of clinical experience, the authors have found no need for the use of offset connectors to link long constructs to the S2–AI screws, even with the presence of dual-bilateral S2–AI screw placement.

Fig. 4. The pelvic inlet view is used to ensure that placement is extrapelvic. The anterior sacroiliac joint is a key reference.

Concerns have been raised regarding the penetration of the sacroiliac articulation by the S2–AI screw. It is important to review the sacroiliac joint articulation to address these concerns. Anatomical studies have demonstrated that the projection of the lateral sacral mass on the ilium is larger than the projection of the sacroiliac articular cartilage.[13] The posterior aspect of the sacroiliac joint corresponds to a nonarticular area.[13] In a cadaveric study, O'Brien et al.[9] found that approximately 60% of S2–AI screws did violate the articular cartilage of the sacroiliac joint (Fig. 3). Though a concern, the clinical significance of this penetration is unknown. It is important to note that traditional iliac screws do bridge the sacroiliac joint with fixation on either side of it. At 5–10 years postoperatively, Tsuchiya et al.[11] found no increase in sacroiliac degeneration with traditional iliac fixation. Two-year prospective clinical data have been presented on the S2–AI technique at the 2009 Annual Meetings of the Scoliosis Research Society and North American Spine Society (Sponseller PD et al., presented at the Scoliosis Research Society Annual Meeting, 2009; and Kebaish K et al., presented at the North American Spine Society Annual Meeting, 2009). The authors have found no increase in sacroiliac degeneration or pain at 2-year follow-up in either adult or pediatric populations. More long-term data are needed, but the S2–AI technique exhibits promise as a good alternative to iliac fixation at this time.

The S2–AI screw can be placed by either open or percutaneous approaches, a detail that currently limits the application of traditional iliac fixation. Wang et al.[12] used minimally invasive technique to place iliac screws; however, these constructs did not include S1 pedicle screws. No reports currently exist that have placed minimally invasive iliac screws with S1 pedicle screws. Recently, O'Brien and colleagues[8] found that percutaneous S2–AI placement was feasible, reproducible, and safe in a cadaveric feasibility study. As centers move toward expanding the application of minimally invasive spine surgery, it is crucial to have a minimally invasive pelvic fixation option.

Conclusions

The S2–AI fixation is a potential option in open and minimally invasive spinal surgery. The screws are in-line with cephalad instrumentation, are approximately 2 cm deeper compared with iliac screws, cross-connectors are not needed, and lengths of 80–100 mm are attainable. Limitations of the technique include direct penetration of the sacroiliac joint, and pending biomechanical evaluation.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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DOI: 10.3171/2009.3.FOCUS09268a

Erratum

An S-2 alar iliac pelvic fixation. Technical note

To The Readership: An error should have been corrected during the publication process in the article "An S-2 alar iliac pelvic fixation. Technical note" (*Neurosurg Focus 28 (3):*E13, 2010; *DOI: 10.3171/2010.1.FOCUS09268*) but was missed.

The first sentence of the *Discussion* section was originally published as "An S2–AI sacropelvic fixation is a new technique, described contemporaneously by Sponseller[10] in the pediatric population and adapted by Kebaish for use in the adult population." This sentence has been corrected to the following:

> An S2–AI sacropelvic fixation is a new technique described contemporaneously by Dr. Sponseller[10] and Dr. Kebaish for use in the pediatric and adult population, respectively.

We apologize for this error. The error has been corrected online as of March 4, 2010.

Gillian Shasby
Director of Publications–Operations
Charlottesville, Virginia

Please include this information when citing this paper: published online March 4, 2010; *DOI: 10.3171/2010.3.FOCUS09268a*.

Outcomes after surgery for cervical spine deformity: review of the literature

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Object. Symptomatic cervical kyphosis can result from a variety of causes. Symptoms can include pain, neurological deficits, and functional limitation due to loss of horizontal gaze.

Methods. The authors review the long-term functional and radiographic outcomes following surgery for symptomatic cervical kyphosis by performing a PubMed database literature search.

Results. Fourteen retrospective studies involving a total of 399 patients were identified. Surgical intervention included ventral, dorsal, or circumferential approaches. Analysis of the degree of deformity correction and functional parameters demonstrated significant postsurgical improvement. Overall, patient satisfaction appeared high. Five studies reported mortality with rates ranging from 3.1 to 6.7%. Major medical complications after surgery were reported in 5 studies with rates ranging from 3.1 to 44.4%. The overall neurological complication rate was 13.5%.

Conclusions. Although complications are not insignificant, surgery appears to be an effective option when conservative measures fail to provide relief. *(DOI: 10.3171/2010.1.FOCUS09278)*

Key Words • **cervical kyphosis** • **deformity** • **spine surgery** • **outcomes** • **review**

Cervical spine deformity is an uncommon but potentially debilitating condition with multiple causes, including but not limited to spondylosis, inflammatory arthropathy, trauma, infection, iatrogenic, neoplastic, congenital, and neuromuscular processes. Sagittal plane deformities result in kyphosis, whereas coronal plane deformities lead to a scoliotic configuration. The most common cause of cervical kyphotic deformity is prior surgical destabilization.[2,4] Scoliotic deformities are mostly encountered in congenital and neuromuscular conditions.

Progressive cervical kyphosis can cause neurological symptoms, such as myelopathy.[8] Moreover, severe kyphotic deformities, as seen in spondylitic arthropathies, can lead to a chin-on-chest deformity with significant compromise of horizontal gaze, swallowing, and breathing.[3,16] Even in the absence of neurological symptoms, the pain associated with deformity contributes to functional disability.

Surgical intervention remains an option for patients with progressive symptomatic cervical kyphosis in whom conservative treatment has failed. Surgery can be accomplished through multiple approaches. Correction can be ventral,[4,6,12,29] dorsal,[1,5] or through a combined ventral-dorsal approach.[1,11,15,22] The overall surgical objectives entail correction of deformity and decompression of neural elements.

The increased potential for neurological morbidity associated with deformity correction greatly underscores the utility of functional outcome data. A recent review of outcomes in patients who underwent corrective surgery for cervicothoracic kyphosis due to a specific cause, ankylosing spondylitis, supported the effectiveness of surgery.[7] However, the long-term outcome for individuals undergoing surgery for symptomatic cervical kyphosis caused by other factors has not been systematically studied. Hence, we systematically reviewed the literature to assess functional and radiographic outcomes in all patients, regardless of cause, who underwent kyphotic deformity correction in the subaxial cervical spine.

Methods

A comprehensive literature search was performed using the PubMed database for all journal articles published until October 2009. Key words used in the search included "cervical deformity," "cervical kyphosis," "correction," "surgery," and "fusion;" terms were searched individually or in combination. The appropriate articles

Abbreviations used in this paper: CBV = chin-brow vertical; JOA = Japanese Orthopaedic Association.

TABLE 1: Demographic data from patients undergoing cervical kyphotic deformity correction*

Authors & Year	No. of Patients	Mean Age (Yrs)	Male/Female	Mean Follow-Up (mos)	Study Type
Zdeblick & Bohlman, 1989	14	46	11/3	31	retrospective
Herman & Sonntag, 1994	20	58	14/6	28	retrospective
McMaster, 1997	15	48	13/2	18	retrospective
Abumi et al., 1999	30	47	17/13	42	retrospective
Steinmetz et al., 2003	10	40	7/3	9	retrospective
Ferch et al., 2004	28	57	17/11	25	retrospective
Belanger et al., 2005	26	NA	NA	54	retrospective
Simmons et al., 2006	131	50	112/19	103	retrospective
Langeloo et al., 2006	16	51	14/2	min 12 mos	retrospective
Tokala et al., 2007	13	54	6/2	24	retrospective
O'Shaughnessy et al., 2008	16	52	9/7	54	retrospective
Mummaneni et al., 2008	30	56	16/14	31	retrospective
Gerling and Bohlman, 2008	9	67	5/4	72	retrospective
Nottmeier et al., 2009	41	61	20/21	19	retrospective

* NA = not available.

for our study were subsequently selected using several criteria. Only studies that specifically addressed surgical correction of cervical kyphosis were selected. In addition, outcome data with respect to the degree of kyphosis correction as well as functional outcome had to be included in the study. We excluded case reports, case series with fewer than 5 patients, as well as series that did not incorporate outcome parameters. Using the above criteria, we identified 14 retrospective clinical studies that described postsurgical outcomes following deformity correction for cervical kyphosis.

Results

Patient Demographics

We identified 14 clinical studies that described a total of 399 patients who underwent surgical correction for symptomatic cervical kyphotic deformity. The demographic data are illustrated in Table 1. The mean age at the time of surgery was 52.6 years based on data from 13 of the 14 studies. There was a male predominance of 261 patients (71%) based on 13 studies that included information on sex.[1,8,9,12,14,16–18,21,23,26,28,29]

Preoperative Assessment

Patients were preoperatively evaluated clinically as well as radiographically. Surgery was generally reserved for patients who were symptomatic from their kyphosis or, in some instances, for patients who demonstrated progression of deformity. Axial neck pain and neurological symptoms of myeloradiculopathy were indications for surgical intervention. Multiple studies used cervical myelopathy as the predominant indicator for correction.[8,17,18,21,26] In patients with severe fixed cervicothoracic kyphosis, the significant compromise of horizontal gaze served as the basis for surgical intervention.[3,14,16,23,28]

Radiographic assessments were used to ascertain the extent of deformity, possible stenosis, and the degree of correction necessary. These studies usually entailed MR imaging, CT scanning, and static and dynamic plain radiographs of the cervical spine.

Surgical Technique

Techniques for correction of cervical spine deformity were quite varied and depended on pathology. In patients with ventral compressive pathologies or compromised integrity of the ventral column, a ventral approach was considered in conjunction with dorsal fusion. If dynamic radiographs suggested a flexible deformity or if the deformity was reducible by traction, correction could be accomplished via a dorsal approach alone. With fixed kyphotic deformities, a ventral approach was usually considered for correction.

Ventral correction with or without fixation was the main surgical modality in 4 clinical studies.[8,12,26,29] Zdeblick and Bohlman[29] used ventral corpectomies with strut-grafting to treat 14 patients with cervical kyphosis and myelopathy. In a subsequent study, ventral reduction with interbody fusion and ventral plating was used by Herman and Sonntag[12] to treat 20 patients who had postlaminectomy kyphosis. Using a ventral strategy, Ferch et al.[8] treated 28 patients with progressive myelopathy and cervical kyphosis, mostly due to degenerative spondylosis. Nine patients who had focal canal compression at the disc interspace were treated with discectomies and grafting. The remaining patients who had diffuse canal stenosis underwent corpectomies. Similarly, Steinmetz et al.[26] used a ventral approach in their series of 10 patients with progressive kyphosis, presumably caused by prior dorsal and ventral cervical operations. Canal decompression was typically attained either through multiple discectomies or corpectomies. Grafts were secured using either rigid or dynamic constructs.

In situations in which the predominant presentation was kyphosis at the cervicothoracic interface with facet ankylosing,[3,14,16,23,28] correction was mainly accom-

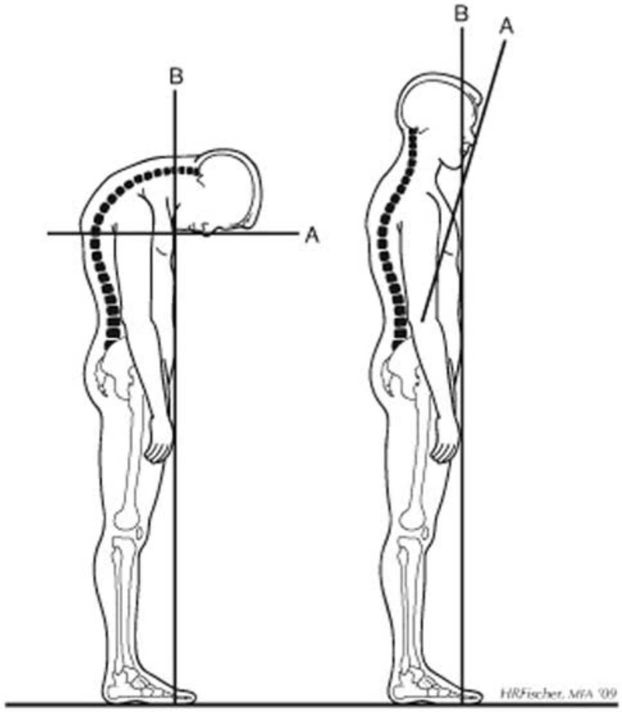

Fig. 1. Diagram illustrating CBV angle, which is the angle between lines A and B. In the figure with the flexion deformity **(left)** the angle is approximately 90°, while in the figure with near-normal alignment **(right)** the angle is closer to 0°.

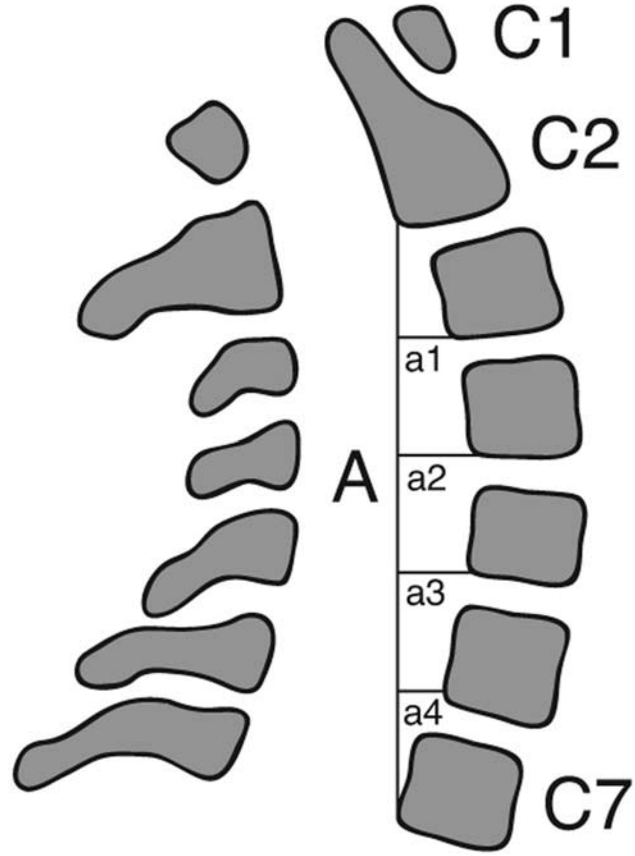

Fig. 2. Diagram showing Ishihara curvature index. On a lateral radiograph, a vertical line (A) is drawn between the dorso-inferior edges of C-2 and C-7. For a1–a4, perpendicular lines are drawn from line A to the dorsoinferior edge of C-3 to C-6. The lines are measured in millimeters. The Ishihara index = (a1+a2+a3+a4)/A × 100.

plished through a C7–T1 dorsal osteotomy, as reported by Simmons.[24,25] This entailed complete laminectomy of C-7, partial laminectomies of C-6 and T-1, partial pedicle osteotomy, osteoclasis of the ventral vertebral body, and finally correction of the deformity. Reduction was then maintained by either external halo-casting[16,23] or internal fixation.[3,14,16,28] In instances in which patients exhibited flexible kyphosis, they were treated via a dorsal approach without ventral release.[1,9]

Combined ventral and dorsal approaches were used in several clinical studies.[1,9,17,18,21] In these studies, patients underwent discectomies or corpectomies based on the extent of canal compression. Some patients required ventral osteotomies for correction in the setting of ankylosis. Posterior osteotomies were carried out as needed for decompression and reduction. Instrumented fixation was used ventrally and dorsally.

Intraoperative monitoring was documented in multiple studies.[9,12,17,21] This typically entailed somatosensory evoked potential, electromyography, and transcranial motor evoked potential monitoring.

Kyphosis Correction Outcomes

Kyphosis correction outcomes were assessed using several parameters, as illustrated in Table 2. Several studies used the CBV angle as an index of horizontal gaze.[14,23,28] The CBV angle, which is ascertained from photographs, measures the angle between the vertical axis of an upright patient and a line drawn from the chin to the brow. In very severe cases, this angle can approach 90° (Fig. 1). Hence, increases in the CBV angle correspond to increased compromise of horizontal gaze. All 3 studies reported significant improvement in CBV angle following surgical intervention (Table 2).[14,23,28]

Another radiographic outcome measure is the Ishihara index, which assesses cervical curvatures on the basis of lordosis and kyphosis (Fig. 2).[10,13,27] Mummaneni et al.[17] reported significant improvement in the mean Ishihara indices from a preoperative kyphotic index of −17.7 to a postoperative lordotic index of +11.4. Some authors reported degrees of kyphotic correction based on comparisons of preoperative and postoperative values.[1,3,8,9,16,18,21,26,28,29] Overall, as illustrated in Tables 2 and 3, significant deformity correction was achieved in most cases. However, a subset of patients subsequently lost some degree of correction noted at subsequent follow-up.[3,9,16,26]

Functional Outcome

Functional outcome measures varied between studies, as illustrated in Table 4. In studies in which loss of horizontal gaze was the main surgical indicator, all patients reportedly achieved restoration of horizontal gaze.[3,14,16,23,28] Patients were generally satisfied with their surgical outcomes.[23,28]

TABLE 2: Postsurgical outcome data for patients undergoing cervical kyphotic deformity correction*

Authors & Year	Main Correction Approach	Results
Zdeblick & Bohlman, 1989	ventral	mean preop kyphosis of 45° corrected to 13° for a mean correction of 32°; most patients experienced residual kyphosis
Herman & Sonntag, 1994	ventral	mean preop kyphosis of 38° corrected; most patients experienced an average residual kyphosis of 13°
McMaster, 1997	dorsal	mean preop kyphosis of 23° corrected to 31° for mean correction of 54°; mean loss of correction at FU of 6°
Abumi et al., 1999	dorsal/combined	mean preop kyphosis of 29.4° corrected to 2.3°; dorsal correction improved kyphosis from 28.4 to 5.1° in 17 patients; combined dorsal/ventral correction in 13 patients improved kyphosis from 30.8 to 0.5° at FU
Steinmetz et al., 2003	ventral	mean correction 20° w/ mean loss of 2.2° at FU; w/ exception of 1 patient, lordotic curvature was attained in all
Ferch et al., 2004	ventral	26/30 patinets improved toward lordosis w/ a mean local sagittal angle correction of 14° & mean regional sagittal angle correction of 11°; 4 patients had persistent kyphosis
Belanger et al., 2005	dorsal	mean correction 38° w/ a mean loss of 3° at FU
Simmons et al., 2006	dorsal	CBV angle improved from 56 to 4° in 114 patients treated w/ smaller osteotomy; CBV angle improved from 49 to 12° in 17 treated w/ a wider osteotomy
Langeloo et al., 2006	dorsal	CBV angle improved from 42 to 5°
Tokala et al., 2007	dorsal	CBV angle improved from 41 to 6°
O'Shaughnessy et al., 2008	combined	based on Cobb angles, kyphosis improved from a preoperative mean of 38° corrected to −10° for mean correction of 48°
Mummaneni et al., 2008	combined	based on Ishihara indices, kyphosis improved from preop mean of −17.7° to postop mean of +11.4°
Gerling and Bohlman, 2008	dorsal/combined	overall preop kyphosis was 69.6° w/ a mean correction of 57.1° postop & 41.4° at FU for all 9 patients; in 3 patients w/ dorsal wire constructs, kyphotic correction was lost from 37° postop to 18° at FU; loss of correction was intermediate in 4 patients w/ wire/rod constructs from 69 to 49°; 2 patients w/ rod/screw constructs retained their correction from 64 to 63°; mean correction for dorsal approach was 53.8° & for combined was 61.3°
Nottmeier et al., 2009	combined	mean correction of sagittal angle was 24°

* FU = follow-up.

The Nurick score,[19,20] which ranges from 0 to 5 with 5 being considered wheelchair-bound, was the outcome assessment used in several studies.[17,21,29] There was a tendency toward improvement of mean Nurick scores following deformity correction. The modified JOA provides an assessment of sensory and motor function in the extremities as well as urinary function. Mummaneni et al.[17] noted improvement in modified JOA scores from 10 to 15 at follow-up. When modified JOA scores were assessed by Ferch and colleagues[8] in 28 patients with cervical myelopathy, there was improvement in 41% of patients, while 56% remained stable. When patients were assessed for cervical neck pain outcome in the same study, there was no significant difference between preoperative and postoperative neck pain. The authors stressed that neck pain was a secondary indication for surgery, and myelopathy was the main indication. There was also significant improvement in mean Odom outcome grades, suggesting symptomatic improvement.[9,21] Gerling and Bohlman[9] reported high patient satisfaction rates and improved pain scores. Abumi et al.[1] used the Frankel grading system to assess outcomes in 24 patients. Three patients experienced a 2-grade improvement, while 11 patients improved by a single grade. The remaining 10 patients were reportedly stable.

Not every author used a validated functional assessment tool. Steinmetz et al.[26] reported improvement in preoperative symptoms in all patients, with a small subset of patients experiencing complete resolution of symptoms. Similarly, Nottmeier et al.[18] reported improved preoperative symptoms of neck pain, myelopathy, and radiculopathy in 39 of 41 patients. One patient remained stable while another patient experienced clinical deterioration. When Zdeblick and Bohlman[29] corrected cervical kyphosis in 14 patients, there was complete or partial recovery of neural function in 13 patients. In addition, 3 of 4 patients

TABLE 3: Summary of radiographic outcomes for patients undergoing cervical kyphotic deformity correction

Approach	Mean Correction on Radiography
ventral	11 to 32° (Cobb angle)
dorsal	23.3 to 54° (Cobb angle) 35 to 52° (CBV angle)
combined	24 to 61.3° (Cobb angle)*

* Ishihara index was used in only 1 study and, as a result, was not included in the summary table.

TABLE 4: Postsurgical functional outcome data for patients undergoing cervical kyphotic deformity correction*

Authors & Year	Main Correction Approach	Results	Standardized Outcome Measure
Zdeblick & Bohlman, 1989	ventral	Nurick scores improved from preop mean of 3.6 to a postoperative mean of 1.3; 3/4 previously nonambulatory patients were ambulatory at FU	no
Herman & Sonntag, 1994	ventral	2/20 patients experienced complete resolution of sx, 11 experienced substantial improvement in sx, 6 improved w/ respect to pain but not neurologically, & 1 patient who previously improved experienced progressive sx	no
McMaster, 1997	dorsal	horizontal gaze was restored in all patients; of 15 patients unable to work at time of op, 4 were able to return to work	no
Abumi et al., 1999	dorsal/combined	some patients showed improvement in Frankel score; 3/24 myelopathic patients obtained a 2-grade improvement, 11 obtained a 1-grade improvement, & 10 remained stable	no
Steinmetz et al., 2003	ventral	all patients experienced significant improvement in neck pain & myeloradiculopathy sx; 3 patients experienced complete resolution of sx	no
Ferch et al., 2004	ventral	mJOA scores improved in 11 patients, remained stable in 15, & deteriorated in 1; cervical neck pain scores remained unchanged following the op	yes
Belanger et al., 2005	dorsal	horizontal gaze was restored in all patients; dysphagia sx improved in 18/19 patients	no
Simmons et al., 2006	dorsal	horizontal gaze restored in all patients; all patients expressed satisfaction w/ op	no
Langeloo et al., 2006	dorsal	horizontal gaze restored in all patients	no
Tokala et al., 2007	dorsal	horizontal gaze restored in all patients; of 3/8 patients treated, 3 expressed excellent satisfaction w/ op & 5 reported good satisfaction	no
O'Shaughnessy et al., 2008	combined	mean Nurick scores improved from 2.4 to 1.5 in all 16 patients; similarly, there was improvement in Odom classification w/ 6 patients rated excellent, 8 good, 1 fair, & 1 poor; 9 patients denied dysphagia, 6 reported minor swallowing problems, & 1 major swallowing problems	no
Mummaneni et al., 2008	combined	mean Nurick scores improved from 3.2 to 1.2, & mJOA scores improved from 10 to 15 in statistically significant manner	yes
Gerling and Bohlman, 2008	dorsal/combined	based on Odom scale, 5 patients had excellent outcome, 2 had good, & 2 had fair; patient satisfaction was reported as excellent by 7 patients & fair by 2 patients	no
Nottmeier et al., 2009	combined	in 41 patients, preoperative sx were improved in 39, stable in 1, & worse in 1 patient	no

* mJOA = modified Japanese Orthopaedic Association scale.

who were previously nonambulatory became ambulatory following surgery. Herman and Sonntag[12] reported outcomes in patients with predominantly degenerative kyphosis who were treated by a ventral approach. Of the 20 patients, 2 experienced complete symptomatic resolution, 11 had significant improvement in pain and neurological symptoms, and 7 had improvement in pain but not neurological symptoms.

Complications

A total of 9 surgery-related deaths were reported in 5 of the 14 studies (Table 5).[3,8,14,17,23] In these 5 studies, the mortality rate ranged from 3.1 to 6.7%. With these 9 reported cases, the overall surgery-related mortality encompassing all 399 patients from the 14 clinical studies was 2.3% (Table 6). Two studies noted 3 additional deaths that were not related to surgery. In the study by Zdeblick and Bohlman,[29] 1 patient died of a carcinoma 10 months after surgery, while the other died of a myocardial infarction 6 months after surgery. Ferch et al.[8] had a patient who died of pneumonia 3 months after surgery. Major medical complications, such as pulmonary embolism, pneumonia, symptomatic pneumothorax, seizure, and deep venous thrombosis, were noted in 5 of the 14 studies, affecting 13 total patients with rates ranging from 3.1 to 44.4% (Table 5).[3,9,12,14,23] Based on 13 cases, the incidence of major medical complication within the series of 399 patients from all 14 studies was 3.3%. A total of 53 neurological complications (13.5%) were reported. The most significant number of neurological complications was seen in patients treated by dorsal osteotomy at the cervicothoracic interface.[3,14,16,23,28] In these 5 studies comprising a total of 196 patients, 46 (23.5%) had postoperative neurological deficits. Surgical wound infections were noted in 13 patients for an incidence of 3.3%. This does not take into account the high incidence of halo pin-

TABLE 5: Complications in patients undergoing cervical kyphotic deformity correction

Authors & Year	No. of Patients	Results (no. of patients)
Zdeblick & Bohlman, 1989	14	graft dislodgment & pseudarthrosis (3)
Herman & Sonntag, 1994	20	vocal cord paresis (3); pneumonia (2); wound dehiscence/infection (1); hardware failure (1); deep venous thrombosis (1)
McMaster, 1997	15	quadriparesis (1); C-8 weakness (2); C-8 radiculopathy (4); transient dysphagia (3); wound infection (1); pseudarthrosis (2)
Abumi et al., 1999	30	radiculopathy (2); durotomy (1); wound infection (1)
Steinmetz et al., 2003	10	dysphagia (1); hoarseness (2)
Ferch et al., 2004	28	death (1); wound infection (1); dysphagia (2); residual spinal canal stenosis (1)
Belanger et al., 2005	26	death (1); radiculopathy (5); seizure (1); pseudarthrosis (1)
Simmons et al., 2006	131	death (4); paraplegia (2); hemiparesis (1); transient C-8 radiculopathy (18); halo-site infection (15); pulmonary embolism (4); pseudarthrosis (6)
Langeloo et al., 2006	16	death (1); C-6 spinal cord injury (1); transient C-8 paresthesia (9); wound infection (2); viral meningitis (1)
Tokala et al., 2007	13	transient C-8 radiculopathy (3); wound infection (2)
O'Shaughnessy et al., 2008	16	quadriplegia (1); C-5 palsy (3); adjacent segment kyphosis not requiring revision (1); durotomy (2); gastrostomy tube (4); tracheostomy (3)
Mummaneni et al., 2008	30	death (2); wound infection (2); durotomy (1); dysphagia (1); pseudarthrosis (1); dysphonia (1); hardware failure (1); gastrostomy tube/tracheostomy (4)
Gerling & Bohlman, 2008	9	pulmonary edema & hypotension (1); pneumonia (1); pneumonia & pneumothorax (1); implant failure & dysphagia (1); dysphagia, gastrostomy tube, & pneumonia (1); periincisional ulcer (1); pseudarthrosis (1)
Nottmeier et al., 2009	41	quadriparesis (1); C-8 radiculopathy (1); pseudarthrosis (1); dysphagia (1); wound dehiscence/infection (3); hardware failure requiring revision (2); adjacent segment kyphosis not requiring revision (3)

site infections reported in the series by Simmons et al.[23] Ventral graft dislodgments were seen in 3 of 14 patients in the study by Zdeblick and Bohlman.[29] Pseudarthrosis rates ranged from 0 to 13.3% in the McMaster series.[16] There were a total of 15 reported cases of pseudarthrosis, accounting for an overall incidence of 3.8%.

Discussion

Cervical kyphosis can be a progressive, debilitating condition caused by multiple factors. Symptomatic patients can experience axial neck pain, myelopathy, and/or radiculopathy resulting in significant functional limitations. Patients can also experience loss of horizontal gaze, making mundane activities such as swallowing, breathing, or eating a challenging task. When patients remain symptomatic or exhibit disease progression despite conservative therapies, surgical correction is typically considered a high-risk but viable option.

In the preoperative evaluation of patients, all studies reviewed were similar in terms of the general indications for surgery. Surgery was mainly recommended to patients who had pain, significant neurological symptoms, compromise of horizontal gaze, and/or progression of deformity. In the articles in which the predominant etiology was ankylosing spondylitis, the loss of horizontal gaze was the primary indication for surgery.[3,14,16,23,28]

Surgical management was attained through various approach strategies dictated mostly by anatomical as well as pathological considerations. In several articles in which patients had fixed cervicothoracic kyphosis from ankylosing spondylitis, C7–T1 dorsal wedge osteotomy was the main surgical intervention.[3,14,16,23,28] It was reasoned that at this location there was a lower risk to vertebral artery injury. In addition, the nerve root that was most at risk with closure of the osteotomy was the C-8 nerve root, which was less critical for hand function than for other nerve roots. The dorsal approach alone was also most useful in situations in which the kyphosis was reducible without significant residual compression of the spinal canal, as was the case with some patients in the series by Abumi et al.[1]

In general, ventral-only approaches resulted in mild to moderate deformity correction with mean correction ranging from 11 to 32° (Table 2). Dorsal approaches with osteotomy or circumferential approaches resulted in greater correction. The mean correction ranged from 23.3 to 53.8° and 35 to 52° based on Cobb and CBV angles, respectively, for dorsal approaches. For combined approaches, the mean correction ranged from 24 to 61.3°. In chin-on-chest deformities, often occurring due to ankylosing spondylitis, the dorsal approach with osteotomy was most frequently used with significant correction.

Ventral strategies for correcting kyphosis have evolved. Initial attempts to correct cervical kyphosis through a strictly ventral approach proved to be very challenging. Zdeblick and Bohlman[29] reported one of the earlier series of ventral correction by using corpectomies without ventral cervical plating. As a result, there was a higher incidence of graft dislodgment, and most patients

TABLE 6: Summary of complications for patients undergoing cervical kyphotic deformity correction

Complication	No. of Patients (% of cohort)
mortality	9 (2.3)
major medical complication	13 (3.3)
neurological	54 (13.5)
durotomy	4 (1.0)
dysphagia	10 (2.5)*
vocal cord paresis/hoarseness	6 (3.4)†
pseudarthrosis	15 (3.8)
infection	13 (3.3)
tracheostomy	7 (1.8)
gastrostomy tube	9 (2.3)

* Of these 10 patients, 7 underwent a ventral-only or combined procedure. The percentage is based on 176 of the 399 patients who underwent ventral-only or combined approach (4.0%).
† All 6 patients underwent ventral-only or combined approach. The percentage reported is based on 176 patients who underwent ventral or combined approach.

were left with residual kyphosis following correction. Herman and Sonntag[12] subsequently incorporated ventral cervical plating. Using a combination of rigid and dynamic ventral instrumentation with multiple points of fixation, Steinmetz et al.[26] subsequently demonstrated the feasibility of achieving cervical lordosis in kyphotic patients from a ventral approach. Most recently, there has been an increase in combined ventral and dorsal approaches, which appears to be most useful in patients with fixed kyphosis from ankylosed facets. An attractive feature of this procedure is the combination of ventral lengthening and dorsal shortening to attain correction. The feasibility of attaining significant correction with this approach was best demonstrated by Abumi et al.[1] In his cohort of 30 patients, 17 were corrected dorsally while the remaining 13 underwent a circumferential approach. While he noted an improvement in kyphosis from 28.4 to 5.1° within the group that had dorsal correction, correction in the combined group was even more impressive, with a preoperative kyphosis of 30.8 to 0.5° at follow-up. The sequence of surgery in combined approaches is also a factor considered in clinical decision-making. In general, the ventral approach was initially undertaken except in situations in which an initial dorsal osteotomy was deemed necessary to enhance correction.

The means of assessing the degree of deformity correction varied among studies, although significant improvement was noted in all studies. However, several studies noted subsequent loss of some degree of correction at follow-up examination.[3,9,16,26] McMaster[16] reported a mean loss of 6° from a previously corrected mean of 54°, while Belanger et al.[3] reported a mean loss of 3° from a corrected mean of 38°. These patients had been treated with dorsal cervicothoracic osteotomies with internal fixation or halo-casting. Gerling and Bohlman[9] reported on 9 patients who had an average preoperative kyphotic angle of 69.6° and who underwent correction using dorsal wiring, wire and rod constructs, or rod and screw constructs. The most significant loss of correction was seen in patients with wire constructs, whereas patients who had the rod and screw constructs maintained their correction. Steinmetz et al.[26] reported a mean loss of 2.2° from a mean correction of 20° using ventral instrumentation. Nonetheless, the lordotic curvature was not significantly compromised.

Functional outcomes were significantly improved for patients who underwent correction for kyphosis. Horizontal gaze was uniformly restored in all patients with cervicothoracic kyphosis from ankylosing spondylitis.[3,14,16,23,28] Where documented, patients expressed great satisfaction with surgical outcome for compromised horizontal gaze.[9,23,28] There was improvement in symptoms and myelopathy as documented by Nurick score outcomes,[17,21,29] modified JOA scores,[8,17] Odom outcome grading,[9,21] and Frankel grade.[1] Even when patients were not formally assessed with a standardized assessment tool, surgery was reported to improve symptoms in most patients.[18,26] Of note, patients in the series by Herman and Sonntag[12] were more likely to report improvement in pain symptoms than improvement in myelopathy.

The overall surgery-related mortality rate was 2.3%. The incidence of major medical complications was 3.3%. Of note, only 5 of the 14 reviewed articles reported major medical complications. It is unclear whether an evaluation for a major medical complication was performed in the remaining studies, and thus, the overall incidence of 3.3% should be interpreted accordingly. Some surgery-related complications were approach-dependent. Dysphagia[8,9,16–18,26] and hoarseness[12,26] were almost exclusively seen in strategies that incorporated a ventral approach. These symptoms were mostly transient. The most common neurological complications in patients treated by dorsal osteotomies through a modified Simmons technique were C-8 radiculopathy and spinal cord injury.[3,14,16,23,28] During closure of the dorsal wedge osteotomy, the C-8 nerve root is vulnerable. In addition, durotomies appeared to be more common in dorsal approaches.[1,17,21] All durotomies were successfully managed without residual CSF fistulas. Surgical wound infections had an overall incidence of 3.3%. Hardware failures were more common with ventral approaches, consisting most commonly of graft dislodgment.

Conclusions

The best clinical evidence for outcomes in patients treated for cervical spine deformity comes from retrospective clinical studies. Overall, a dorsal approach with osteotomy or circumferential approach appeared to result in greater deformity correction than a ventral-only approach. Although complications were not insignificant, the majority of patients had improvement in neurological and functional symptoms.

Disclosure

Dr. La Marca is a consultant for Medtronic, Depuy Spine, and Biomet.

Author contributions to the study and manuscript preparation include the following. Conception and design: P Park, F La Marca. Acquisition of data: AB Etame, AC Wang, KD Than. Analysis and interpretation of data: AB Etame, AC Wang, KD Than. Drafting the article: AB Etame, AC Wang, KD Than. Critically revising the article: P Park. Reviewed final version of the manuscript and approved it for submission: P Park, F La Marca. Statistical analysis: AB Etame, AC Wang, KD Than. Study supervision: P Park, F La Marca.

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Comparison between anterior and posterior decompression with instrumentation for cervical spondylotic myelopathy: sagittal alignment and clinical outcome

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Object. A variety of anterior, posterior, and combined approaches exist to decompress the spinal cord, restore sagittal alignment, and avoid kyphosis, but the optimal surgical strategy remains controversial. The authors compared the anterior and posterior approach used to treat multilevel cervical spondylotic myelopathy (CSM), focusing on sagittal alignment and clinical outcome.

Methods. The authors studied 48 patients with CSM who underwent multilevel decompressive surgery using an anterior or posterior approach with instrumentation (24 patients in each group), depending on preoperative sagittal alignment and direction of spinal cord compression. In the anterior group, a 1–2-level corpectomy was followed by placement of an expandable titanium cage. In the posterior group, a multilevel laminectomy and posterior instrumentation using lateral mass screws was performed. Postoperative radiography and clinical examinations were performed after 1 week, 12 months, and at last follow-up (range 15–112 months, mean 33 months). The radiological outcome was evaluated using measurement of the cervical and segmental lordosis.

Results. Both the posterior multilevel laminectomy (with instrumentation) and the anterior cervical corpectomy (with instrumentation) improved clinical outcome. The anterior group had a significantly lower preoperative cervical and segmental lordosis than the posterior group. The cervical and segmental lordosis improved in the anterior group by 8.8 and 6.2°, respectively, and declined in the posterior group by 6.5 and 3.8°, respectively. The loss of correction was higher in the anterior than in the posterior group (–2.0 vs –0.7°, respectively) at last follow-up.

Conclusions. These results demonstrate that both anterior and posterior decompression (with instrumentation) are effective procedures to improve the neurological outcome of patients with CSM. However, sagittal alignment may be better restored using the anterior approach, but harbors a higher rate of loss of correction. In cases involving a preexisting cervical kyphosis, an anterior or combined approach might be necessary to restore the lordotic cervical alignment. *(DOI: 10.3171/2010.1.FOCUS09253)*

Key Words • **instrumentation** • **decompression** • **kyphosis** • **lordosis** • **cervical spondylotic myelopathy** • **alignment**

Cervical spondylotic myelopathy is a common cause of neurological morbidity.[8,41] Although decompression is an accepted procedure for CSM,[12] the optimal surgical strategy for this condition remains controversial. Patients with cervical deformities and kyphosis are associated with a higher risk of developing neurological deficits or pain.[2,24,26,35,37] Therefore, the loss of lordosis and postoperative development of kyphosis should be prevented if possible. Thus, a variety of anterior,[5,7,13,14,21,47] posterior,[6] and combined approaches,[1,20,29,30,34] with and without instrumentation, have been advocated to achieve an adequate decompression of the spinal cord, restore or maintain sagittal alignment, and avoid kyphosis.

Although isolated anterior pathologies can be treated adequately using an anterior approach,[13,48] the extension of the pathology over many vertebral levels can require a posterior approach.[26,37] The development of postlaminectomy kyphotic deformities[36] lead to different modifications of posterior decompressive techniques, such as laminoplasty or laminectomy in combination with posterior screw-rod fixation. Extensive anterior decompression and instrumentation includes the danger of pseudarthrosis, stress to adjacent levels, induction of an accelerated degeneration, development of swallowing difficulty, and construct failure.[4,10,14,17,19,33,43] Therefore, many surgeons restrict anterior approaches to diseases that involve only 1 or 2 vertebral body levels[4,9,12] and advocate posterior approaches in these other cases.[15,19,26,27,30] However, precise data concerning changes of the cervical alignment before and after these operations are rare.[42] The aim of the present study was to compare the efficacy of multi-

Abbreviations used in this paper: CSM = cervical spondylotic myelopathy; mJOA = modified Japanese Orthopaedic Association; VAS = visual analog scale.

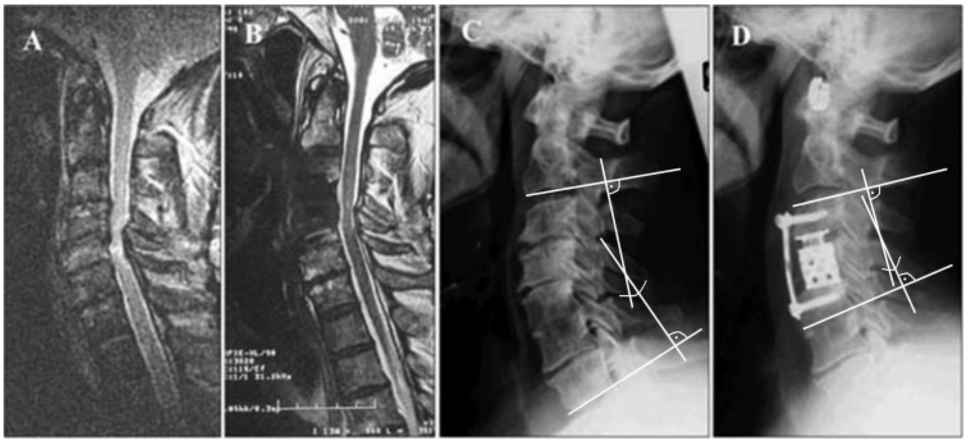

Fig. 1. Sagittal preoperative **(A and C)** and postoperative **(B and D)** images of a patient with progressive myelopathy resulting from cervical spinal canal stenosis **(A)**. A corpectomy and reconstruction of the anterior column was performed using an anterior distraction device with a plate **(D)**. Postoperative MR imaging demonstrated sufficient decompression **(B)**. A postoperative radiograph shows good cervical balance **(D)**. The methods of measurement for the cervical and segmental lordosis are shown in panels **C** and **D**, respectively.

level anterior or posterior decompressive surgery of the cervical spine with instrumentation, focusing especially on sagittal alignment.

Methods

Between 1998 and 2008, 67 patients underwent multilevel decompressive surgery for CSM. Thirty-nine patients underwent a corpectomy followed by placement of an expandable titanium cage to reconstruct the anterior column, and 28 patients underwent a laminectomy followed by posterior instrumentation with lateral mass screws. Based on our past experience, patients who underwent a corpectomy with implantation of an "all-in-one" device (AddPlus, Ulrich GmbH & Co. KG) were excluded from this study due to a higher loss of lordotic correction.[6] For a more accurate comparison with the anterior group, patients who underwent a laminectomy greater than 4 levels were excluded from the posterior group.

Thus, 48 patients were included in the study: 24 in the anterior group, and 24 in the posterior group. These patients suffered from degenerative cervical spinal canal stenosis, and underwent decompressive surgery of the cervical spine sometime between 1998 and 2008. The primary symptom in all patients was myelopathy (CSM). In total, there were 29 men (12 anterior group, 17 posterior group) and 19 women (12 anterior group, 7 posterior group) who underwent operations. The patients' ages at operation ranged from 45 to 84 years old, with a mean of 64 years. The posterior group (66.2 ± 8.8 years) was significantly older than the anterior group (60.4 ± 9.9 years; $p = 0.045$).

The reasons for using the anterior approach were spondylosis in 14 patients, ossification of the posterior longitudinal ligament in 6, degenerative kyphosis in 2, and spondylolisthesis in 2. The reasons for using the posterior approach were spondylosis in 17 patients, and os-

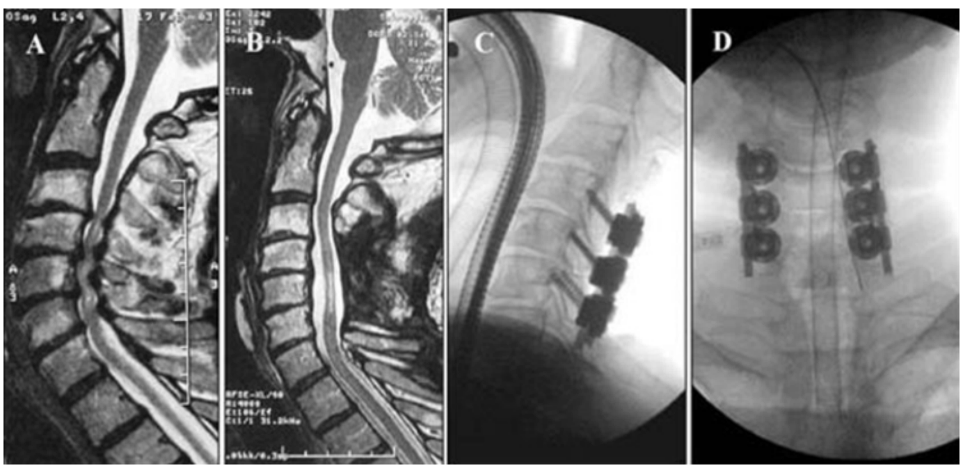

Fig. 2. Preoperative **(A)** and postoperative **(B–D)** MR images of a patient with progressive myelopathy resulting from cervical spinal canal stenosis. A laminectomy and posterior instrumentation were performed. Sagittal postoperative imaging demonstrates sufficient decompression, but immediate loss of lordosis **(B)** due to intraoperative fixation **(C)**. For the posterior instrumentation, lateral mass screws were used **(C and D)**. The size of the screw heads might be a further handicap to achieving adequate lordosis, because big screw heads tend to touch each other even in a straight position.

TABLE 1: Clinical outcomes in both groups according to the VAS, mJOA scale, and Odom criteria*

Assessment	Anterior Group	Posterior Group	p Value
VAS score†			
preop	4.8 ± 1.2	4.4 ± 1.1	0.6
12 mos	3.3 ± 1.0	3.5 ± 1.0	
last FU	3.3 ± 1.1	3.6 ± 0.9	0.56
p value preop/last FU	<0.001	<0.001	
mJOA scale score†			
preop	12.5 ± 2.1	11.7 ± 3.2	0.522
12 mos	15.2 ± 2.1	14.3 ± 2.8	
last FU	15.8 ± 2.8	14.9 ± 3.2	0.537
p value preop/last FU	<0.001	<0.001	
Odom criteria‡			
excellent	11 ± 45.8	13 ± 54.2	
good	8 ± 33.3	7 ± 29.2	
fair	4 ± 16.7	4 ± 16.7	
poor	1 ± 4.2	0	

* FU = follow-up.
† Values given as mean ± SD.
‡ Values given as number of patients (%).

sification of the posterior longitudinal ligament in 7. All patients were refractory to conservative treatment. The decision to use the chosen procedure depended on 2 main factors: direction of spinal cord compression, and preoperative cervical alignment.

Radiological examinations included plain radiography, MR imaging, CT, myelography, and lateral tomography. Radiological outcome was evaluated using measurement of cervical lordosis as an angle between C-2 and C-7, according to Cobb. An angle between the adjacent vertebral bodies to the affected or removed vertebral body was measured to evaluate segmental lordosis (Fig. 1).

Stability was assessed in the anterior and posterior groups. Solid arthrodesis was evaluated using flexion-extension radiographs and defined as the absence of motion between the spinous processes in the anterior group and between the vertebral bodies of the posterior group. Additionally, in the anterior group, the operated segment was considered solid in the absence of a radiolucent gap between the cage and the endplate. Because titanium cages were used, trabeculation between the adjacent segments could not be assessed correctly in all patients; therefore, CT scans were additionally performed in some of these cases. However, the absence of motion was the main criterion used to determine solid arthrodesis, which had also been used in other analyses involving cervical fusion cages.[11,18,46]

The 24 patients in the anterior group were treated using a corpectomy followed by placement of an expandable titanium cage to reconstruct the anterior column (Add, Ulrich GmbH & Co. KG). A cervical plate was added in all cases (17 cases with an ABC plate [Aesculap]; 7 cases with an Alpha semiconstrained plate [Stryker]). Autograft bone from the corpectomy was placed around or into the cages.

In the posterior group, a 2- to 4-level laminectomy followed by posterior instrumentation with lateral mass screws was performed in 10 cases with the Spine System Evolution cervical system (Aesculap), in 13 cases with the S[4] cervical system (B Braun Melsungen AG), and in 1 case with the Oasys system (Stryker). Local bone autograft from the laminectomy was packed beneath and around the instrumentation.

Postoperative radiographs were obtained after 1 week and after 12 months in all cases, and at last follow-up after 15–112 months (mean 33 months). Clinical outcome was assessed before and after surgery using the VAS score of neck pain and the mJOA scale score, and using the Odom criteria.[31]

The chi-square test, nonparametric Mann-Whitney U-test, and t-test were used for statistical analysis of data. Results were considered significant at a p value < 0.05. The analyses were performed using SPSS statistical software, version 17 (SPSS Inc.).

Results

In the anterior group, corpectomies were performed in 5 cases at the C-4 level, in 4 cases at C-5, in 4 cases

TABLE 2: Radiological outcomes of both groups according to cervical and segmental lordosis*

Lordosis (°)	Preop	1 wk	1 yr	Last FU	p Value‡
cervical					
anterior group	5.3 ± 26.2	16.1 ± 10.7	13.8 ± 11.5	14.1 ± 12	0.006
posterior group	12.4 ± 12.9	6.6 ± 13.3	6.1 ± 13.8	5.9 ± 12.6	0.004
p value†	0.039			0.027	
segmental					
anterior group	−2.5 ± 18.0	4.5 ± 12.0	3.6 ± 13.8	3.7 ± 13.1	0.004
posterior group	6.1 ± 10.5	3.0 ± 10.3	2.4 ± 10.0	2.3 ± 8.9	0.004
p value†	0.030			0.870	

* All values given as mean ± SD.
† Between groups.
‡ Preop/last FU in same group.

at C-6, in 2 cases at C-7, and in 9 cases at multiple levels (C4–5 in 5 cases and C5–6 in 4 cases). The follow-up period in this group ranged from 15 to 112 months (mean 35 months). The implantation of the expandable cages was performed without complications and the adjustment of the height could be performed in situ.

In the posterior group, all laminectomies and instrumentation were performed at multiple levels, involving 2 levels in 1 case (C3–4), 3 levels in 11 cases (C3–5 in 4 cases, and C4–6 in 7 cases), and 4 levels in 12 cases (C3–6 in 9 cases, C4–7 in 2 cases, and C1–4 in 1 case). The follow-up period in this group ranged from 15 to 67 months (mean 28 months).

In all patients undergoing operations, an adequate decompression was achieved, as demonstrated on postoperative MR images or myelograms that were compared with preoperative images (Figs. 1 and 2). Clinical evaluation revealed significant improvement of both groups following spinal cord decompression according to scores on the mJOA scale and VAS ($p < 0.0001$). The comparison between the anterior and posterior groups did not show any significant differences before or after the operations according to the VAS score, mJOA scale score, and Odom criteria (Table 1). All patients stated that they would have undergone the operation again, even the patient with a poor outcome. The flexion-extension radiographs did not show any motion of the operated segment in any cases in either group.

Cervical lordosis improved in the anterior group by 8.8° ($p = 0.006$) and declined in the posterior group by 6.5° ($p = 0.004$) at last follow-up (Table 2). Despite a significantly higher preoperative cervical and segmental kyphotic angle in the anterior group ($p = 0.039$), the surgical change of segmental lordosis immediately improved the overall cervical lordosis in the anterior group (7°), whereas an immediate loss of segmental lordosis was observed in the posterior group (3.1°; $p = 0.004$). However, the loss of correction of the overall cervical lordosis was higher in the anterior group compared with the posterior group at last follow-up (–2.0 ± 1.1° vs –0.7 ± 0.7°, respectively; $p = 0.041$).

Complications were noted in 7 cases, 5 requiring revision surgeries. In the anterior group, in which semiconstrained plates were used, follow-up imaging revealed 1 screw break and 1 screw loosening without the necessity of a revision operation. One case in the anterior group required additional dorsal fixation due to adjacent segment disease 1 year after surgery.

In the posterior group, epidural bleeding occurred in 1 case involving 2-level decompression and in 1 case involving 3-level decompression, requiring immediate surgical revision. A wound infection and a CSF fistula required surgery in another 2 cases.

Discussion

The optimal approach in the treatment of CSM remains a controversy in spine surgery. However, the aim of the present study was to compare the exact achievement of sagittal alignment and the possibility of sagittal maintenance and correction, rather than to test the clinical superiority of the presented operative techniques. Data of exact pre- and postoperative sagittal changes are rare in the literature.[42]

We presented 48 patients who underwent multilevel cervical decompression for CSM. Twenty-four patients were treated with a 1–2 level corpectomy followed by placement of an expandable titanium cage (anterior group), and 24 patients underwent a multilevel laminectomy followed by posterior instrumentation with lateral mass screws (posterior group). The clinical outcome did not differ between groups; however, radiological analysis revealed a better restoration of sagittal alignment in the anterior group, but better maintenance of this alignment in the posterior group.

Decompressive Surgery of the Cervical Spine

There are different approaches to decompressive surgery of the cervical spine, including multilevel discectomy, corpectomy, laminoplasty, and laminectomy. An adequate decompression of the spinal cord to improve clinical outcome can be achieved using both approaches,[12,26,28] which is also reflected in the present study. Anterior pathologies that involve only 1 or 2 vertebral body levels usually proceed using an anterior approach,[9,12] while in cases of more than 2 levels the posterior approach appears to be more suitable due to swallowing difficulty and construct failure.[4,9,10,12,14,17,19,26,33,43] However, in cases involving multilevel disease with kyphosis, where the spinal cord is stretched over anterior osteophytes, a combined approach using anterior release and reconstruction of lordosis as well as posterior decompression with instrumentation may be suitable.[30]

Sagittal Alignment

Effective decompression can be achieved by laminoplasty when lordosis of the cervical spine is preserved. However, the long-term success of laminoplasty depends on the preoperative and postoperative preservation of cervical spinal lordosis.[25,38–40,45] The loss of physiological lordosis and the development of kyphosis following cervical surgery should be avoided to prevent further degeneration and late clinical deterioration.[2,24,26,35,37] Therefore, prevention of the late development of kyphosis—which can be observed following anterior[16] and posterior approaches—and the achievement of an optimal alignment is a major goal of spine surgery.

Our clinical and radiological data support the results of the existing literature,[12,26] showing an improvement of cervical alignment in the anterior group and a significant loss of lordosis in the posterior group. The preparation and consecutive denervation of deep extensor muscles is a common cause for loss of lordosis following laminoplasty.[22,23,44] Correction of kyphosis is more difficult or even impossible using only a posterior approach, due to anterior fixation caused by osteochondrosis and spondylosis that cannot be resolved from the posterior side and may prevent distraction and reposition.[30] Both approaches can improve cervical lordosis, whereas anterior approaches demonstrate a better overall correction due to a higher possibility of achieving release and distraction.[3,26,42] Furthermore, patients show better radiological results when undergoing combined procedures than when using posterior or anterior instrumentation alone.[1] Nevertheless, patients undergoing extended posterior decompression and instrumentation maintain sagittal correction for a significant period,[26,28] which is also reflected in our results.

The postoperative loss of lordosis in our posterior group could be partly attributed to a straightening of the cervical spine during positioning that was fixed by dorsal instrumentation (Fig. 2C). Thus, the operative procedure was modified and posterior fixation with a curved rod was performed only after intraoperative optimization of sagittal alignment. Big screw heads can come in close contact during lordotic positioning (Fig. 2); thus, smaller screw heads improve lordotic positioning further. Another possibility for avoiding close contact of the screw heads, which might hinder adequate sagittal correction, is instrumentation of only every second vertebra.[28]

In the posterior group, the instrumentation involved only the vertebral bodies affected by the laminectomy, even in cases of C-7 laminectomy. We did not observe any indication to extend the instrumentation in these 2 cases, although laminectomies and instrumentation that are discontinued at C-7 rather than at T-1 might harbor the risk of cervicothoracic kyphosis.

The higher loss of correction in our anterior group can be explained by subsidence of the cages before a successful fusion was achieved to support the integrity of the construction. The high modulus of elasticity with titanium could be an important factor in cage subsidence. Materials with a lower modulus of elasticity that approach normal bone, such as polyetheretherketone cages, carbon fiber cages, and autograft iliac crest or allograft fibula, show a lower rate of long-term subsidence.[30] The small values of 2.0° and 0.7°, representing loss of correction in the anterior and posterior groups, respectively, lie within measurement errors, but the differences between both groups resemble similar findings in the literature.[3,26,28,42] The screw breakage and screw loosening in the anterior group might be explained by a less effective load sharing of constrained plates compared with dynamic plates.[32]

Conclusions

The aims of treatment for cervical spinal canal stenosis are decompression of the spinal cord and restoration/maintenance of the sagittal alignment. Our results demonstrate better restoration of the sagittal alignment in the anterior group, but less loss of correction in the posterior group. Anterior spondylotic osteophytosis may prevent adequate restoration of the sagittal alignment using only a posterior approach. In these cases, an anterior or combined approach may be necessary to achieve an adequate release and restore lordotic alignment.

Disclosure

Dr. Woiciechowsky has served as a consultant to Ulrich GmbH & Co. and Aesculap. Dr. Kroppenstedt has also served as a consultant to Aesculap.

Author contributions to the study and manuscript preparation include the following. Conception and design: C Woiciechowsky, M Cabraja, S Kroppenstedt. Acquisition of data: C Woiciechowsky, M Cabraja, A Abbushi, D Koeppen, S Kroppenstedt. Analysis and interpretation of data: C Woiciechowsky, M Cabraja, S Kroppenstedt. Drafting the article: C Woiciechowsky, M Cabraja. Critically revising the article: C Woiciechowsky. Reviewed final version of the manuscript and approved it for submission: C Woiciechowsky. Statistical analysis: M Cabraja, D Koeppen. Study supervision: C Woiciechowsky.

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Spondylolisthesis following a pedicle subtraction osteotomy

Case report

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Pedicle subtraction osteotomy (PSO) is a powerful technique for correcting a fixed sagittal plane deformity. The authors report the case of a 51-year-old man with a history of multiple prior lumbar operations, flat-back syndrome, thoracic kyphosis, and radiculopathy, who underwent deformity correction surgery with T3–S1 pedicle screw fixation and L-3 PSO. Progressive spondylolisthesis of the PSO segment associated with rod fracture then developed. The patient subsequently underwent anterior and posterior revision surgery. This case is a rare instance of spondylolisthesis following PSO. *(DOI: 10.3171/2009.12.FOCUS09285)*

Key Words • **pedicle subtraction osteotomy** • **spondylolisthesis** • **deformity**

Pedicle subtraction osteotomy is a powerful technique for the correction of a fixed sagittal plane deformity. This type of osteotomy has been associated with significant perioperative morbidity,[1,2,4–6] which we have described as > 50% in patients undergoing PSO in a revision setting. We here report a rare case of pseudarthrosis at the level of a PSO due to spondylolisthesis of the PSO segment.

Case Report

History and Examination. This 50-year-old man who had undergone 4 prior thoracolumbar operations over the past decade presented with flat-back syndrome, thoracic kyphosis, and right leg radiculopathy (Fig. 1). His preoperative VAS back pain score was 8 out of 10, and his preoperative VAS leg pain score was 6 out of 10. His preoperative SF-36 scores were 28.6 for the PCS and 29.1 for the MCS. He was unable to ambulate a block without stopping.

Operation. We performed a deformity correction with T3–S1 pedicle screw fixation (Expedium 5.5 Ti System, DePuy Spine) and T6–8 Ponte (facet) osteotomies as well as an L-3 PSO (Fig. 2). We did not visualize the ALL. Posterolateral arthrodesis was performed with iliac autograft, local autograft from the spine, and demineralized bone matrix as a graft extender.

Postoperative Course. There were no immediate postoperative complications, and the patient was discharged home in good condition.

Six months later he was noted to have pseudarthrosis at L3–4 associated with rod fractures. He had a significant amount of back pain. Furthermore, radiographic studies showed that progressive spondylolisthesis of the PSO segment was developing (Fig. 3). We suspected that the ALL was torn. He subsequently underwent a T12–S1 revised posterior spinal fixation (Expedium 6.35 Ti system, DePuy Spine) and revised posterolateral fusion from T12–L5 bilaterally utilizing rHBMP-2 (Infuse, Medtronic). To halt the spondylolisthesis of the PSO segment, we performed a second-stage anterior spinal fusion surgery a few weeks later: L2–3 and L3–4 anterior lumbar interbody fusion with titanium cages (Devex, DePuy Spine) filled with rib autograft and rhBMP-2 and supplemented with an anterior screw rod fixation (Expedium Anterior, DePuy Spine).

At the 2-year follow-up from the index deformity surgery, the patient had achieved a solid fusion (Fig. 4). His latest VAS leg pain score was 3 out of 10, and his back pain score was 3 out of 10. His latest SF-36 scores were 32.1 for PCS and 25.5 for MCS. He is now able to ambulate more than a mile.

Abbreviations used in this paper: ALL = anterior longitudinal ligament; MCS = mental component summary; PCS = physical component summary; PSO = pedicle subtraction osteotomy; rHBMP-2 = recombinant bone morphogenetic protein; SF-36 = 36-Item Short Form Health Survey; VAS = visual analog scale.

Fig. 1. Supine lateral lumbar radiograph **(left)** and standing 36-inch lateral radiograph **(right)** demonstrating flat-back syndrome and thoracic kyphosis.

Discussion

The early morbidity of PSO has been well documented in the literature.[1–6] We present a rare, delayed complication of spondylolisthesis of a PSO segment associated with pseudarthrosis (at L3–4) resulting in bilateral rod fracture. Because of the progressive spondylolisthesis of the PSO segment, revision surgery required not only a revised posterior fusion but also an anterior interbody fusion to secure the PSO segment to the adjacent vertebrae.

During a PSO procedure, surgeons pivot the osteotomy closure on the junction of the vertebral body with the ALL. Such pivoting may result in compromise of the ALL. It is important to note that in a PSO, spine surgeons remove all the posterior ligamentous structures and posterior bony elements. Only the ALL and adjacent intervertebral discs remain to prevent a spondylolisthesis of the PSO segment. If the ALL is torn, the PSO segment may be predisposed to spondylolisthesis. Circumferential fusion of the spine or the use of more rigid instrumentation of the spine may be considered in patients with a mobile anterior column.

Fig. 2. Postoperative sagittal reconstruction CT **(left)** and lateral lumbar radiograph **(right)** 1 month postoperatively demonstrating the PSO and deformity correction. Note the early spondylolisthesis of the PSO segment.

Fig. 3. Sagittal reconstruction CT **(left)** and radiograph **(right)** demonstrating pseudarthrosis at L3–4 and bilateral rod failure. Note the progression of the spondylolisthesis of the PSO level because of an incompetent ALL.

Patients should be closely monitored for evidence of ALL failure and spondylolisthesis of a PSO segment. In cases in which the integrity of the ALL is suspected of being compromised and in which spondylolisthesis of the PSO segment begins, the situation may be salvaged early on with an anterior interbody fusion to secure the PSO segment to the surrounding vertebrae prior to posterior rod fracture.

Conclusions

Compromise of the ALL can occur during closure of a PSO. The ALL is the main structure that prevents spondylolisthesis of the PSO segment. If the ALL is compromised, spondylolisthesis of the PSO can occur and result in pseudarthrosis and rod fracture. To prevent this problem, surgeons should watch for signs of progressive spondylolisthesis of the PSO segment and salvage this problem with an early anterior interbody fusion to secure the PSO segment to the surrounding vertebrae.

Disclosure

Dr. Mummaneni is a consultant for Medtronic and Depuy and receives a grant from Medtronic and a royalty from Depuy.

Dr. Berven receives honoraria from Osteotech, Medtronic, Depuy, and US Spine; grants from Medtronic and Depuy; and a royalty from Scient'x.

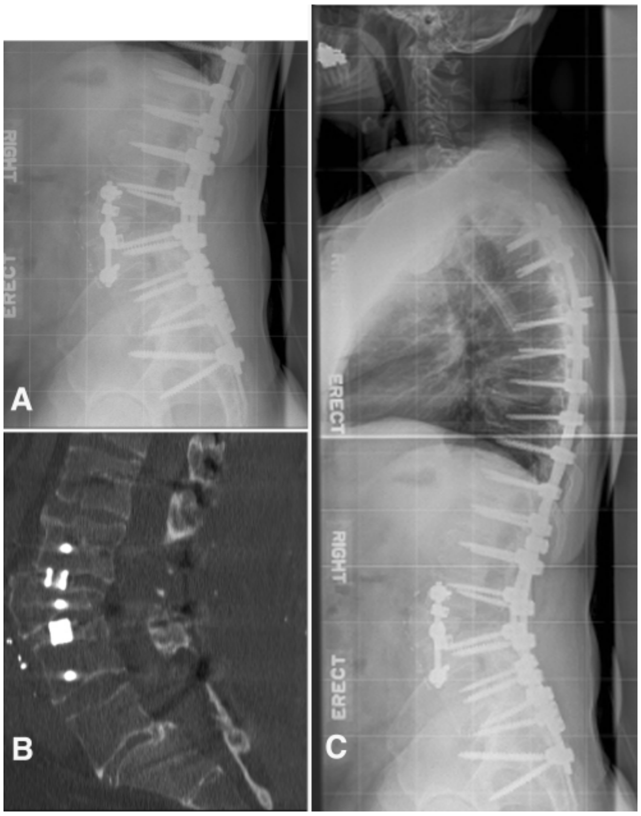

Fig. 4. Postoperative lateral radiograph **(A)**, sagittal reconstruction CT **(B)**, and lateral 36-inch scoliosis radiograph **(C)** after anterior/posterior revision.

Author contributions to the study and manuscript preparation include the following. Conception and design: PV Mummaneni. Acquisition of data: PV Mummaneni, SH Berven. Analysis and interpretation of data: PV Mummaneni, SH Berven. Drafting the article: CD Upadhyaya. Critically revising the article: PV Mummaneni, SH Berven. Reviewed final version of the manuscript and approved it for submission: PV Mummaneni. Study supervision: PV Mummaneni.

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Massive Charcot spinal disease deformity in a patient presenting with increasing abdominal girth and discomfort

Case report

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Charcot spinal disease is a destructive degenerative process involving the vertebrae and surrounding discs, resulting from repetitive microtrauma in patients who have decreased joint protective mechanisms due to loss of deep pain and proprioceptive sensation. The typical presentation of the disease is back pain and progressive spinal instability and deformity. The authors report an unusual case of massive Charcot spinal disease deformity in a patient presenting with increasing abdominal girth and discomfort. *(DOI: 10.3171/2009.12.FOCUS09277)*

Key Words • **Charcot spinal disease** • **vertebral destruction** • **spinal neuropathic arthropathy** • **spinal neurogenic arthropathy**

Charcot disease of the spine, also known as spinal neuropathic or neurogenic arthropathy, is a destructive degenerative process involving the vertebral bodies and surrounding discs. This condition results from repetitive microtrauma in patients who have decreased joint protective mechanisms from loss of deep pain and proprioceptive sensation, typically because of spinal cord injury or sensory neuropathies. The patient typically presents with back pain and progressive spinal instability and deformity. We report a unique case of massive Charcot spinal disease and deformity in a patient presenting with increasing abdominal girth and discomfort.

Case Report

History and Examination. This 33-year-old man suffered a complete spinal cord injury after a 25-foot fall from a parking garage. He was unable to move or feel his legs at the scene, and upon arrival to the emergency department was found to have a complete spinal cord injury with loss of sensation at the T-10 level. A CT scan of the thoracic spine demonstrated a severe T-11 fracture dislocation with complete obliteration of the spinal canal and a moderate local kyphotic deformity (Fig. 1A). Multiple mild compression and burst fractures from T-4 to T-7, in addition to multiple transverse process fractures, were also noted.

Initial Operation. On hospital Day 2, the patient underwent a T8–12 posterior spinal fusion, with pedicle screw instrumentation at T-9, T-10, T-12, and L-1, and posterolateral onlay fusion. This surgery was followed by a second-stage procedure on hospital Day 9 for anterior column reconstruction. A T-11 corpectomy via a left-sided thoracotomy was performed, with insertion of a Synex expandable titanium cage (Synthes, Inc.) and bone allograft (Fig. 1B). A chest tube was placed during the operation, which was removed on postoperative Day 2. The patient recovered appropriately from these procedures and was discharged to inpatient rehabilitation on hospital Day 12. Unfortunately, the patient did not recover any neurological function and remained completely paraplegic. The patient was monitored for 2 years using serial radiographs, which demonstrated mild scoliosis without evidence of hardware failure (Fig. 1C). He was asymptomatic and elected to continue with conservative treatment.

Charcot Spinal Disease. Five years after undergoing reconstruction and fusion, the patient presented with increasing abdominal girth and discomfort. He had no other significant complaints, including no symptoms of back pain. A CT scan of his abdomen demonstrated a large, abdominal, cystic paraspinous mass with hyperemia of the surrounding soft tissue and musculature (Fig. 2D). Thoracolumbar CT scans further demonstrated osseous

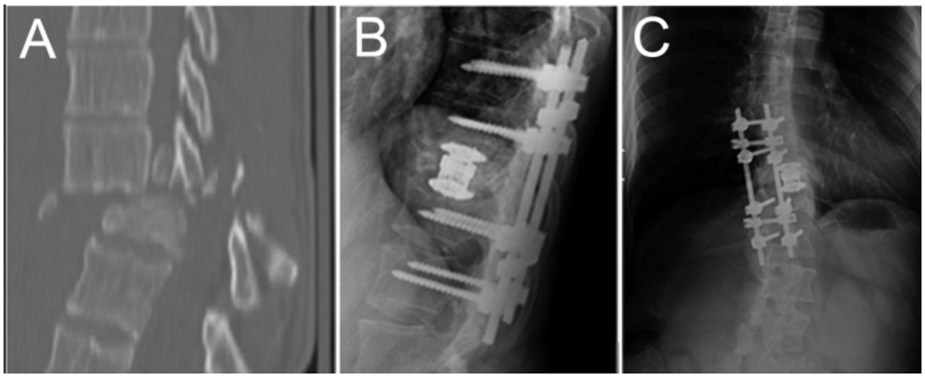

Fig. 1. Preoperative **(A)** and postoperative **(B and C)** images of the patient. **A:** Sagittal thoracic CT scan showing severe T-11 fracture dislocation with local kyphosis and obliteration of the spinal canal. **B:** Sagittal thoracolumbar radiograph demonstrating the fusion construct after T-11 corpectomy, titanium interbody cage implant placement, and T8–12 posterior spinal fusion. **C:** Two-year follow-up anteroposterior radiograph showing mild scoliosis without evidence of hardware failure.

destruction and complete destabilization of the spine below the level of fusion from T-12 to L-3, consistent with Charcot spinal disease (Fig. 2A–C). Infection was considered in the differential diagnosis but was believed to be unlikely because of the patient's near-normal inflammatory markers (white blood cell count $10.5 \times 10^3/mm^3$, erythrocyte sedimentation rate 9 mm/hour, C-reactive protein 1.1 mg/dl).

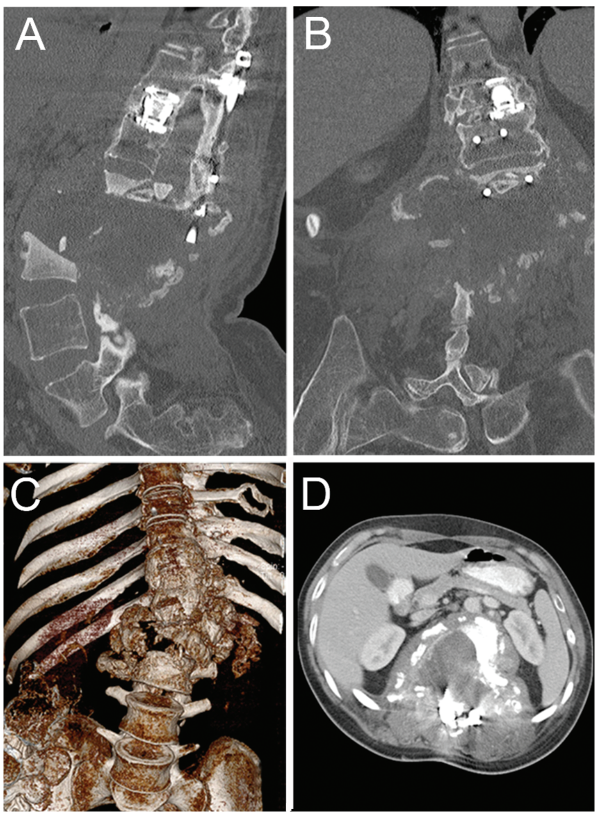

Fig. 2. Images of the patient obtained 5 years after undergoing reconstruction and fusion. **A–C:** Sagittal **(A)**, coronal **(B)**, and 3D reconstructed **(C)** CT scans of the lumbar spine showing severe spinal breakdown with cyst formation below the previous fusion from T12–L3, consistent with Charcot disease of the spine. **D:** Abdominal CT scan demonstrating intraabdominal compression from the large degenerative retroperitoneal cyst.

Second Operation. A 3-stage procedure was planned for decompression and resection, realignment, and circumferential stabilization and reconstruction. The first surgery involved a posterior approach for open debridement and exploration. Free-floating bone fragments were identified and removed, and the visible cyst was aspirated. Laboratory studies on the cyst fluid were negative for infection. Severe spinal instability was apparent at the levels involved with spinal arthropathy. The second procedure was performed on postoperative Day 5 and involved a posterolateral spinal fusion from T-3 to the ileum, with pedicle screw fixation (Fig. 3A). The L1–3 levels showed severe osseous destruction and were omitted from the fusion construct. After recovering for 11 days, the patient underwent the third staged procedure, which involved a retroperitoneal approach for L1–3 corpectomies, anterior reconstruction using a Synex II expandable titanium cage (Synthes, Inc.), and anterolateral instrumentation using an MACS TL plate and vertebral body screws (Aesculap; Fig. 3B).

Postoperative Course. The patient experienced resolution of his abdominal symptoms postoperatively. Bone union was successfully achieved as demonstrated on follow-up radiographs. Although the Synex II cage has been recalled since it was implanted in this patient, the fusion construct and cage have remained solid. At his 1-year follow-up appointment, the patient demonstrated continued spinal stability and appropriate alignment without progressive deformity or pseudarthrosis.

Discussion

Charcot joint disease was initially described in the 19th century in patients inflicted with tabes dorsalis from tertiary syphilis[2,4] and is a progressive destructive disease of the peripheral joints and the spine. Also known as neuropathic or neurogenic arthropathy, this condition is observed in patients with decreased joint protective mechanisms due to loss of deep pain and proprioceptive sensation from various causes including spinal cord injury (secondary to trauma, tumor, or infection), diabetic and other peripheral neuropathies, myelomeningocele, syrin-

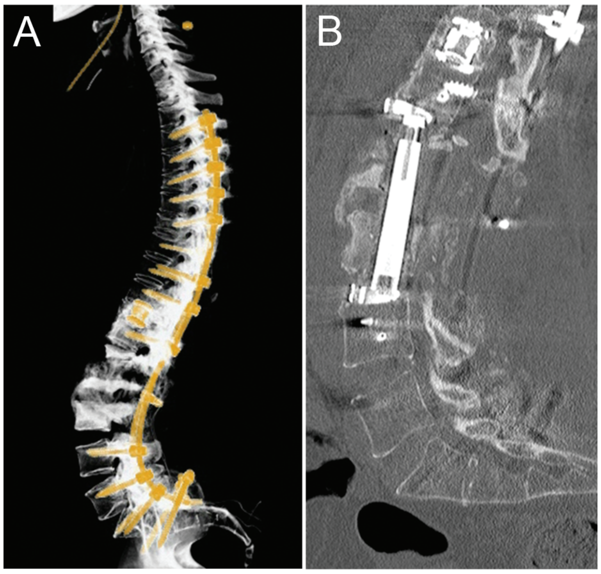

Fig. 3. Images obtained in the patient after the 3-stage procedure. A: Sagittal 3D reconstructed CT scan of the spine with hardware windowing after posterolateral spinal fusion from T-3 to the ileum. B: Sagittal thoracolumbar CT scan of the final construct after retroperitoneal L1–3 corpectomies and anterior column reconstruction with interbody expandable cage, anterolateral plate, and vertebral body screw instrumentation.

gomyelia, severe degenerative spinal disorders, infection (such as syphilis and anesthetic leprosy), and others.[1,5,6,8,11] The loss of sensation, in particular deep pain sensation, impairs the normal protective sensory mechanisms that cause withdrawal when undue increases in stress are placed on the bones and joints. The lack of protective withdrawal responses allows repeated microtrauma from external forces, which over time induce progressive joint dislocations and degenerative osseous and ligamentous destruction.[1,10]

In the spine, Charcot disease most commonly presents at the thoracolumbar junction,[5,11] variably involving the vertebral bodies and intervertebral discs. The transition zone between the thoracic and lumbar spines is prone to increased stress and experiences constant movement to stay in a balanced upright or sitting position. Involvement of the cervical, thoracic, and sacral spines is rare.[11] Increased stress to adjacent lower levels after long-segment posterior spinal fusions, and iatrogenic instability from extensive laminectomies and resection of posterior stabilizing structures, have also been implicated as potential contributing factors.[3,8]

Charcot spinal disease can be mistaken for pyogenic vertebral osteomyelitis and osseous spinal tumors. The distinguishing features of Charcot spinal disease include the "exploded" appearance of the lesion on imaging, associated with severe osseous destruction from concomitant bone resorption and unorganized formation.[9] Paraspinous and vertebral fluid collections (which can be large) and soft-tissue inflammatory changes are often noted on imaging studies, but are nonspecific.[5] The history of an insensate patient is of particular importance, because this disease does not occur in patients with preserved sensation.

The patient with this disease typically presents with symptoms of worsening back pain and audible noises during postural changes. Other presentations include sitting imbalance from progressive spinal instability and deformity, a decrease in lower-limb spasticity or sensation, cutaneous fistulas to paraspinous cysts, development of autonomic dysreflexia, and even deep vein thrombosis from prevertebral compression.[5,7,11] This patient presented with unique complaints of abdominal discomfort and increasing girth from massive bone destruction and cyst formation in the retroperitoneal space, causing compression of the abdominal organs, without other typical presenting complaints. The patient experienced resolution of his abdominal symptoms after surgical decompression of the cyst, resection of disorganized bone, correction of the deformity, and reconstruction and stabilization, which is the current treatment for Charcot spinal disease.[9,11]

Disclosure

Dr. Schmidt has served as a consultant for Aesculap.

Author contributions to the study and manuscript preparation include the following. Conception and design: FS Bishop. Drafting the article: FS Bishop. Critically revising the article: FS Bishop, AT Dailey, MH Schmidt. Reviewed final version of the manuscript and approved it for submission: MH Schmidt.

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