Pedicle Subtraction Osteotomy for the Treatment of Fixed Sagittal Imbalance

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Background: Fixed sagittal imbalance (a syndrome in which the patient is only able to stand with the weight-bearing line in front of the sacrum) has many etiologies. The most commonly reported technique for correction is the Smith-Petersen osteotomy. Few reports on pedicle subtraction procedures (resection of the posterior elements, pedicles, and vertebral body through a posterior approach) are available in the peer-reviewed literature. We are aware of no report involving a substantial number of patients with coexistent scoliosis who underwent pedicle/vertebral body subtraction for the treatment of fixed sagittal imbalance.

Methods: Twenty-seven consecutive patients in whom sagittal imbalance was treated with lumbar pedicle subtraction osteotomy at one institution were analyzed. Radiographic analysis included assessment of thoracic kyphosis, lumbar lordosis, lordosis through the pedicle subtraction osteotomy site, and the C7 sagittal plumb line. Outcomes analysis was performed with use of a before-and-after pain scale, items from the Oswestry questionnaire, and the Scoliosis Research Society (SRS) questionnaire after a minimum duration of follow-up of two years. Complications and radiographic findings were also analyzed for the entire group.

Results: Overall, the average increase in lordosis was 34.1° and the average improvement in the sagittal plumb line was 13.5 cm. One patient had development of a lumbar pseudarthrosis through the area of pedicle subtraction osteotomy, and six patients had development of a thoracic pseudarthrosis. Two patients had development of increased kyphosis at L5/S1, caudad to the fusion, resulting in some loss of sagittal correction. There were significant improvements in the overall Oswestry score ($p < 0.0001$) and the pain-scale score ($p = 0.0002$). Most patients reported improvement in terms of pain and self-image as well as overall satisfaction with the procedure.

Conclusions: Pedicle subtraction osteotomy is a useful procedure for patients with fixed sagittal imbalance. A worse clinical result is associated with increasing patient comorbidities, pseudarthrosis in the thoracic spine, and subsequent breakdown caudad to the fusion.

Level of Evidence: Therapeutic study, Level IV (case series [no, or historical, control group]). See Instructions to Authors for a complete description of levels of evidence.

Symptomatic fixed sagittal deformity is prevalent in adult patients presenting to spine surgeons[1]. Fixed sagittal imbalance can be defined as a syndrome in which the patient is unable to stand erect without flexing the knees and hips. On a long-cassette lateral radiograph, this abnormality is usually observed as a plumb line from C7 that falls well in front of the L5-S1 disc. Therefore, the goals of surgery are (1) to restore sagittal balance so that the patient can stand erect without having to flex the hips or knees and (2) to reduce pain. Because of the sagittal imbalance, simply repairing pseudarthroses will not improve the patient's posture or relieve pain. Patients complain of an inability to stand erect and often complain of pain in the lumbar spine. The lumbar pain is related in part to fatigue of the spinal extensor muscles and to coexistent pseudarthroses. Patients with lumbar scoliosis who have had a previous arthrodesis with Harrington instrumentation, resulting in a long hypolordotic fusion to L4 or L5, are at particular risk for sagittal imbalance. With time, the caudad lumbar levels degenerate and lose their ability to hyperextend to compensate for the cephalad kyphosis produced by the posterior distraction instrumentation, resulting in a progressive loss of sagittal balance[2]. Fixed sagittal deformity also occurs following fixation of thoracolumbar fractures, following distal lumbar arthrodesis, following multilevel laminectomy, and following segmental fixation for the correction of scoliosis as well as in patients with ankylosing spondylitis[1-3]. The two common methods currently used to correct the fixed sagittal imbalance include the Smith-Petersen osteotomy[2,4-6] (Fig. 1) and

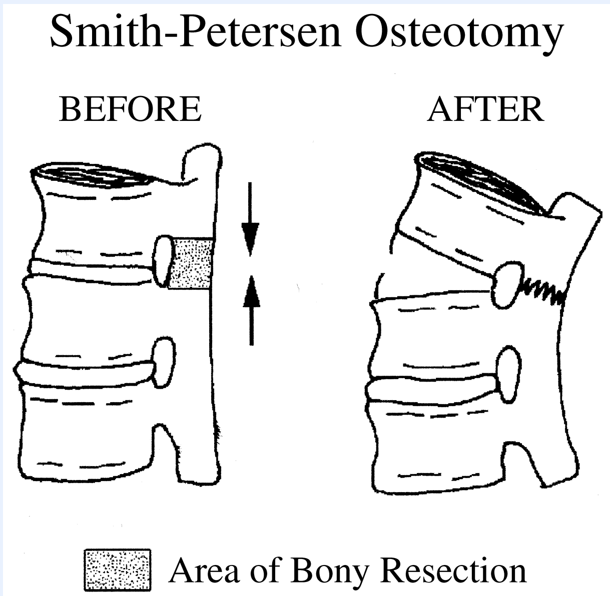


Fig. 1
Smith-Petersen osteotomy: The osteotomy closes the posterior column, hinges on the middle column, and opens the anterior column.

pedicle subtraction osteotomy (Fig. 2)[3,7-15]. To achieve lordosis with the Smith-Petersen osteotomy, the posterior column is shortened and the anterior column is lengthened. With pedicle subtraction osteotomy, the posterior column is shortened without lengthening of the anterior column[7,8].

There have been numerous reports on, and modifications of, spinal osteotomy for the correction of sagittal imbalance[2,4,16-29]. These modifications have included manually fracturing the spine with the patient awake following posterior decompression[27], supplementing the osteotomy site with instrumentation[23,26,27,29,30], removing cancellous bone from the posterior part of the vertebral body with preservation of the pedicles[24], and performing a combined anterior and posterior osteotomy[5].

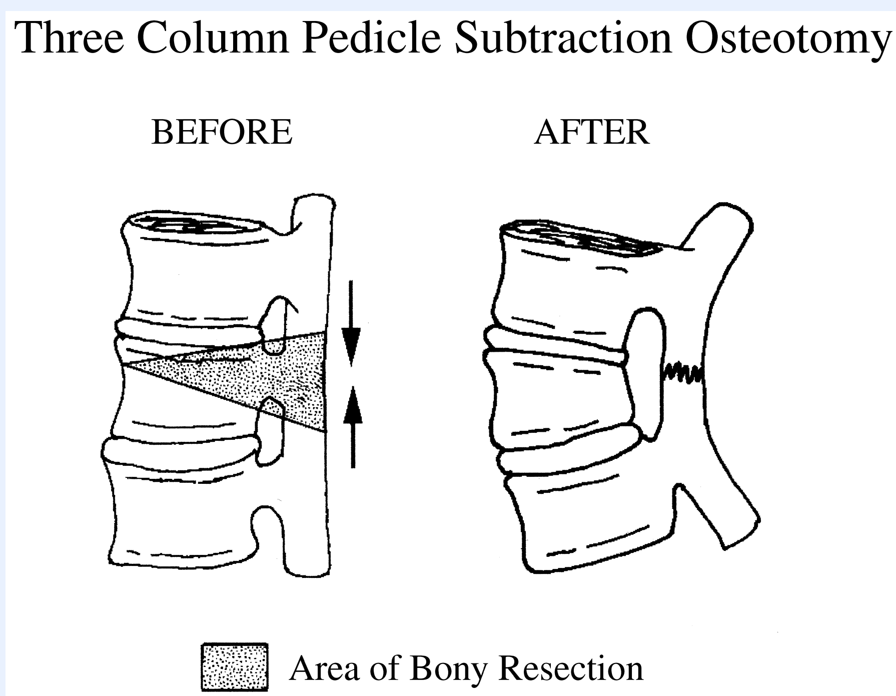
The pedicle subtraction osteotomy or transpedicular wedge resection procedure has the advantage of obtaining correction through all three columns from a posterior approach without lengthening the anterior column, thereby maximizing the healing potential while avoiding stretch on the major vessels and viscera anterior to the spine.

Little has been published about the use of pedicle subtraction osteotomy in patients with coronal, axial, and sagittal deformities or about the feasibility of performing the osteotomy through levels that have had previous decompression. The purpose of the present study was to assess the early and late complications as well as the radiographic and functional outcome of pedicle subtraction osteotomy in patients with fixed sagittal imbalance. We also wanted to assess the feasibility of performing osteotomies through rotated scoliotic segments and through regions previously treated with laminectomy.

Materials and Methods

Following institutional review board approval, the radiographs and clinical course of twenty-seven consecutive patients undergoing pedicle subtraction osteotomy for fixed

Fig. 2
Pedicle subtraction (three-column) osteotomy: The osteotomy closes the posterior and middle columns while hinging on the anterior column.



sagittal imbalance were studied. All patients were managed by two surgeons at one institution between 1995 and 1999. Complications and demographic data were recorded, and patient questionnaires were administered prospectively. The radiographs were made prospectively and then were reviewed retrospectively. All patients were followed for at least two years (range, two to five years) and answered directed questionnaires.

Demographic Data

The patients included twenty-three women and four men who had a mean age of 52.4 years (range, thirty-two to seventy years). The diagnosis was idiopathic scoliosis in fourteen patients (with one patient also having an L5/S1 spondylolisthesis), degenerative sagittal imbalance in eight (with all patients having had previous surgery for spinal stenosis or degenerative disc disease without any coexistent scoliosis or traumatic kyphosis), posttraumatic kyphosis in three (with one patient also having an L5/S1 spondylolisthesis), and ankylosing spondylitis in two. The patients had undergone a mean of 2.1 operative procedures (range, zero to seven procedures) prior to the osteotomy. The previous procedures had involved a mean of 6.6 levels (range, zero to fifteen levels).

Clinical Data

Preoperatively, patients responded to a questionnaire that included items regarding the location and quality of pain, medical and surgical history, and the severity of pain (as rated on a scale from 1 to 9, with 1 indicating no pain and 9 indicating maximum pain) as well as items from the Oswestry questionnaire[31-33]. Patient height was recorded during each visit. Intraoperative data included the operative time, the estimated blood loss, and the amount of blood transfused during the operative and postoperative periods. All twenty-seven patients rated the severity of pain with use of the pain scale preoperatively and at the time of the most recent follow-up. Three patients did not answer the items from the Oswestry questionnaire preoperatively. In addition, twenty-six of the twenty-seven patients completed the Scoliosis Research Society (SRS) twenty-four-item questionnaire at the time of the most recent follow-up[34,35]. The questionnaire data for patients with more than two years of follow-up were recorded. Complications were also recorded for all twenty-seven patients. All data were collected prospectively.

Operative Procedure

The operative procedure consisted of an arthrodesis with posterior instrumentation combined with a posteriorly based closing-wedge osteotomy. After the establishment of fixation points cephalad and caudad to the osteotomy site, the posterior extent of the osteotomy was outlined on the posterior elements/fusion mass. The epidural space was entered, and the appropriate nerve roots were identified. The pedicles were surrounded bilaterally and were separated from all osseous attachments other than the vertebral body. Through the pedicle, a curette was placed in the vertebral body and cancellous bone was removed from the body in the region desired. Care was taken to preserve the anterior and posterior margins of the vertebral body. The pedicle was preserved at this stage to prevent inadvertent injury to the dura and the epidural vessels. The posterior wall of the vertebral body was thinned from within the body. The pedicles were then resected, with special attention being paid to the exiting nerve roots running along the medial and inferior surfaces of the pedicle. The posterior cortex of the body was then fractured in a greenstick manner medial to the pedicles with a Woodson elevator or a reverse-angled curette, with an anteriorly directed force pushing the posterior cortex of the bone into the vertebral body cavity. A Penfield elevator was then placed subperiosteally along the lateral margin of the vertebral body. A Leksell rongeur was used to resect the appropriate amount of bone from the lateral part of the body bilaterally. The anterior cortex of the body was preserved to act as a hinge and to avoid translation during closure of the osteotomy site. The hips and knees were hyperextended to facilitate closure of the osteotomy site. When performing the osteotomy through a previous fusion mass, we initially preferred to achieve complete bone apposition centrally and laterally upon closure of the osteotomy site. However, subsequent to our twentieth case, we now always enlarge the canal centrally and rely on closure of the osteotomy site to produce direct bone-on-bone contact only laterally. The spine was then reconstructed by securing rods to the established fixation points. Cantilever and compression forces were used to close the osteotomy site. The pedicle subtraction osteotomy was performed at L1 in one patient, at L2 in eight patients, and at L3 in eighteen patients. Twelve patients underwent concomitant anterior arthrodeses to supplement newly arthrodesed levels or levels presenting with pseudarthrosis. The osteotomy was performed through the site of a previous laminectomy in ten patients and through a rotated scoliotic vertebra (classified as grade-2 or greater according to criteria of Nash and Moe[36]) in twelve.

Surgical Decision-Making

The posterior procedure was performed in two stages for fourteen patients undergoing revision surgery because it was believed that removal and placement of instrumentation would result in substantial operative time and blood loss. The first stage consisted of removal of existing instrumentation and establishment of new fixation points. The second stage, performed five to seven days later, consisted of performing the osteotomy, harvesting the bone graft, and completing the definitive instrumentation. The arthrodesis was stopped at L5 in six patients in whom the L5-S1 disc appeared well preserved or was completely collapsed and stable. The arthrodesis was extended to S1 in the remaining patients. Iliac screws[37] were used for all arthrodeses to the sacrum, with the exception of those performed in two patients who had ankylosing spondylitis.

The level of the osteotomy was chosen on the basis of a number of factors. We preferred to perform the osteotomy caudad to the conus medullaris and in sites of previously fused segments. Our surgical goals were to restore the sagittal balance to normal (that is, with the C7 sagittal plumb line falling within the L5-S1 disc or slightly behind it). All of the older patients with degenerative sagittal imbalance were managed with a postoperative thoracolumbosacral orthosis for at least six months postoperatively. Most of the younger patients with idiopathic scoliosis in whom a previous fusion had been subsequently extended to the sacrum were not treated with a brace postoperatively.

Radiographic Analysis

Long-cassette standing anteroposterior and lateral radiographs were made preoperatively, two months postoperatively, and at the most recent postoperative visit for all twenty-seven patients. The radiographs were analyzed to determine the preoperative and postoperative levels of fusion; the level of the osteotomy; the C7 sagittal plumb line[38] (measured from the center of the C7 body to the posterosuperior corner of the S1 body); the coronal plumb line (measured from the center of the C7 body to the center of the S1 body); and the sagittal Cobb angle between T5 and T12 (thoracic kyphosis), between T12 and S1 (lumbar lordosis), and between the levels cephalad to and caudad to the osteotomy site (the osteotomy angle). Since the posterosuperior aspect of the S1 body was used as the reference point for the C7 sagittal plumb line, the normal neutral range for sagittal alignment was considered to be within 0 to 4 cm from this point (the plumb line running through the L5-S1 disc).

Statistical Analysis

For most variables for which data were collected preoperatively and postoperatively, paired t tests were used to determine whether there was a significant change between time-points; however, for one variable for which the required conditions were not satisfied, the Wilcoxon signed rank test was used as a nonparametric alternative. Longitudinal analyses for variables that were measured at more than two time-points were carried out with use of mixed-model repeated measures analysis of variance. When assessing change over time, the primary focus of these analyses was on the significance of the time effect, which tested the equality of the measurements over time. When the time effect was significant, the appropriate statistical contrasts were used to test the hypothesis that there was no change in the measurement between two specific time-points. When comparing change over time between groups, the primary focus was on significance of the interaction between group and time, interactions that tested hypotheses about the equality of changes over time in the two groups. When interactions were significant, the appropriate statistical contrasts

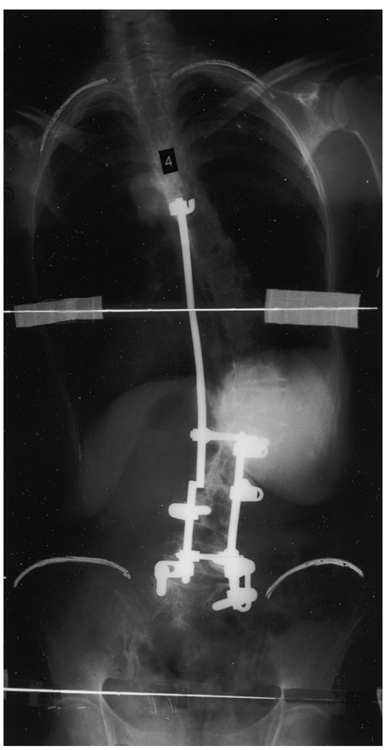


Fig. 3-A

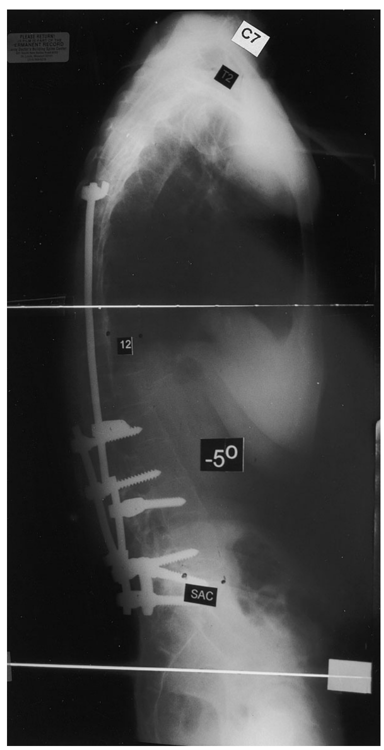


Fig. 3-B

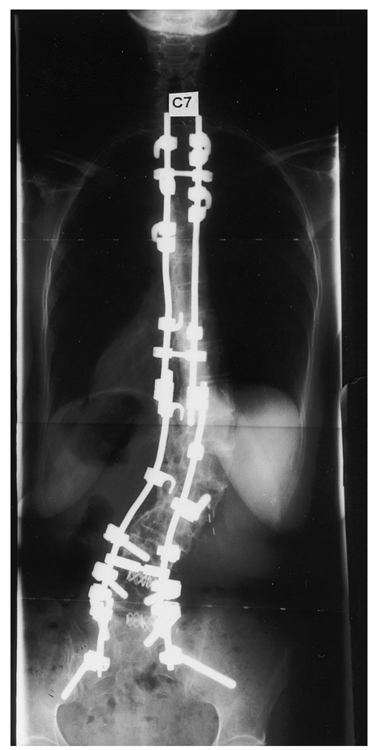


Fig. 3-C

Figs. 3-A through 3-F A forty-seven-year-old woman was managed with pedicle subtraction osteotomy because of fixed sagittal imbalance and multiple pseudarthroses. **Fig. 3-A** Long-cassette standing coronal radiograph made at the time of presentation. Note the coronal plane decompensation and the broken implant. The patient had had a previous posterior instrumentation and fusion to the sacrum. Multiple pseudarthroses are present. **Fig. 3-B** Preoperative sagittal radiograph showing the loss of lumbar lordosis. The C7 plumb is not far in front of the lumbosacral disc because the patient is bending the knees to maintain balance. **Fig. 3-C** Long-cassette standing coronal radiograph made three years postoperatively, showing improvement in the coronal balance.

were used to test the hypothesis that changes between two specific time-points in one group were equal to corresponding changes in the other group. The results are reported as the mean and the standard deviation. The Statistical Analysis System (version 8.2, 1999; SAS Institute, Cary, North Carolina) was used to analyze the data.

Results

Operative Procedure

The patients underwent a mean of 1.6 (one or two) posterior procedures and 0.4 (zero or one) anterior procedures. The mean estimated blood loss per patient for all procedures was 2396 mL (range, 500 to 6650 mL). The mean operative time for all stages of the procedure (posterior and anterior) was 12.4 hours (range, 6.8 to 18.8 hours). The mean perioperative transfusion per patient was 658 mL (range, zero to 2625 mL) of cell-saver blood, 1.4 units (range, zero to four units) of autologous blood, and 3.5 units (range, zero to sixteen units) of allogenic blood. Five patients did not receive any allogenic transfusion.

Complications

Early Complications

Major perioperative complications occurred in several patients (Table I). Two patients required reintubation in the postanesthesia-care unit. One patient had a postoperative myocardial infarction and underwent coronary artery bypass grafting. Aggressive fluid resuscitation (following a 5100-mL operative blood loss) led to massive fluid overload in one patient who required a laparotomy to relieve an abdominal compartment syndrome on the day after the procedure. There was no visceral injury at the time of exploration, and the patient went on to have a complete recovery. Two patients had a postoperative deep-vein thrombosis. Pulmonary embolism was not documented in any patient. One patient required fasciotomies because of an intraoperative compartment syndrome in the hand due to intravenous fluid extravasation in the upper extremity. One patient had a unilateral visual field defect that persisted at the time of the most recent follow-up. This complication probably was due to a period of hypotension that occurred at the end of the operative procedure, during which there was substantial blood loss. Two patients had a dural tear that was repaired at the time of surgery.

One patient had urinary retention at one week postoperatively. A computerized tomographic myelogram showed a block at the level of the pedicle subtraction osteotomy. Therefore, on that same day, a wide central decompression was performed at the site of the osteotomy, which had been previously

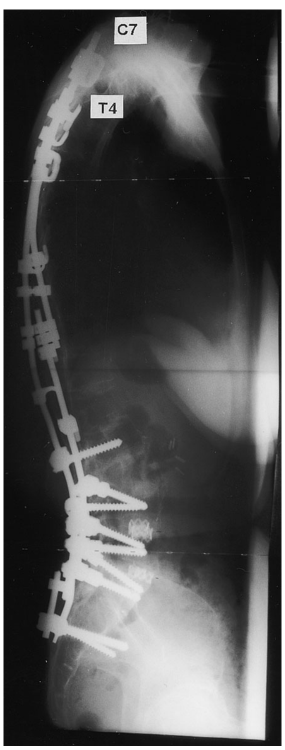


Fig. 3-D

Fig. 3-E

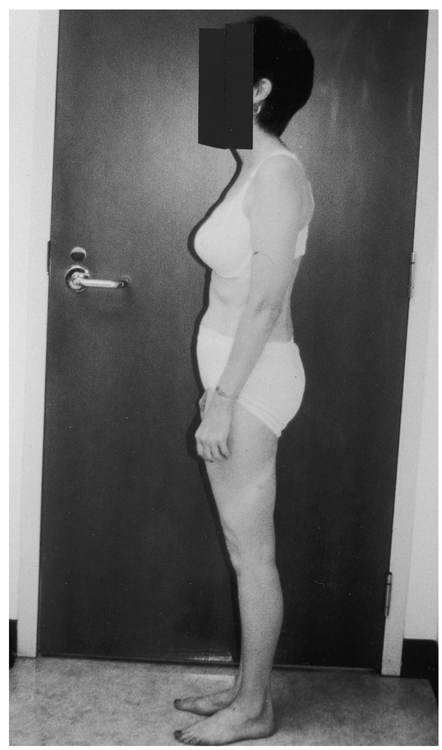


Fig. 3-F

Fig. 3-D Long-cassette sagittal radiograph made three years postoperatively with the patient standing and the knees extended. The sagittal correction was achieved during the posterior operation, which involved a pedicle subtraction osteotomy at L3. Pseudarthrosis was identified at all levels of the lumbar spine intraoperatively; therefore, a subsequent anterior arthrodesis was performed from T11 to the sacrum after posterior correction had been achieved. **Fig. 3-E** Clinical photograph made at the time of presentation, with the patient attempting to stand as erect as possible. **Fig. 3-F** Clinical photograph made three years postoperatively with the patient standing.

TABLE I Summary of Early and Late Complications

	No. of Patients (N = 27)
Early Complications	
Dural tear	2
Postoperative respiratory distress (reintubation)	2
Deep-vein thrombosis	2
Incomplete correction of sagittal alignment (C7 plumb line >6 cm relative to posterior aspect of L5/S1)	3
Urinary retention (cauda equina compression)	1
Upper extremity compartment syndrome secondary to intravenous infiltration	1
Visual field defect in one eye	1
Myocardial infarction	1
Abdominal compartment syndrome	1
Wound infection	0
Late Complications	
Pseudarthrosis/implant failure in thoracic spine	6
Pseudarthrosis/implant failure in lumbar spine	1
Breakdown of L5-S1 disc caudad to long posterior spinal fusion	2
Prominent iliac screws	1
Wound infection	0

closed with complete posterior osseous apposition. The canal was enlarged centrally, and the lateral masses were reclosed tightly after the decompression. The patient subsequently had a complete neurological recovery.

Late Complications

Six patients had development of a pseudarthrosis in the thoracic region cephalad to the osteotomy site. A seventh patient, who had had a previous laminectomy and pseudarthrosis in the same area, had development of a pseudarthrosis at L1-L2 and L2-L3 through the osteotomy site. At the time of the present study, four of these seven patients had had a subsequent revision procedure. No patient had development of a pseudarthrosis at the site of an osteotomy that had been performed through a previous fusion. In three patients, the deformity was too great to be corrected by a single pedicle subtraction osteotomy and the spine remained in positive sagittal alignment. Two patients, with long fusions to L5, had development of breakdown (progressive disc degeneration and kyphosis) at the level of the L5-S1 disc with some loss of sagittal correction. One patient complained of prominence of the iliac screws, which were subsequently removed. No patient had a superficial or deep wound infection.

Radiographic Findings

The mean C7 sagittal plumb line for all twenty-seven patients improved from 17.74 ± 7.95 cm preoperatively to 1.99 ± 3.91 cm at the first postoperative visit ($p < 0.0001$). At the final postoperative visit, the mean C7 sagittal plumb line increased to 4.23 ± 6.73 cm ($p < 0.0001$ compared with the preoperative value). Loss of correction due to breakdown of the L5-S1 disc was seen in two patients who had had a fusion to L5. Loss of correction was also observed in three of the six patients who had development of a thoracic pseudarthrosis. Substantial loss of correction did not occur in the other three patients who had a thoracic pseudarthrosis; in two of those three patients, only one of the bilateral rods broke. In the remaining twenty-two patients, the sagittal correction was maintained and there were no significant differences in the values between the two-month and most recent postoperative visits (Table II and Figs. 3-A through 3-F).

Patient Height

There was a significant increase in the mean standing height of the twenty-seven patients, from 156.87 cm preoperatively to 160.30 cm at the time of the most recent postoperative visit ($p < 0.0002$) (Table II).

Patients with Previous Laminectomies

Ten patients had had a previous laminotomy or laminectomy at the level of the osteotomy. The dural sac was retracted adequately to perform the procedure in all of these patients, without the need to abandon the desired level. Two patients sustained a dural tear that was repaired without further difficulties.

Osteotomies Performed Through a Lumbar Scoliosis

Twelve patients had the osteotomy through the apex of a lumbar curve that was classified as grade-2 or greater according to the criteria described by Nash and Moe[36]. There were no cases of worsening of coronal balance (the relationship of the C7 plumb line to the midline of the sacrum) for those patients, in contrast with what was reported by Booth et al.[1] following Smith-Petersen osteotomies performed through rotated segments.

Outcome Analysis

Pain Scale

All twenty-seven assigned pain-scale scores prospectively, preoperatively and postoperatively (Appendix). The average score was 6.96 preoperatively and 4.41 postoperatively; this difference was significant ($p = 0.0002$).

Oswestry Score

Twenty-four patients completed items from the Oswestry questionnaire both preoperatively and postoperatively (Appendix). The average Oswestry score for these patients was 51.21 preoperatively and 35.75 postoperatively; this difference was significant ($p < 0.0001$). An analysis of individual variables within the Oswestry score (dressing, lifting, walking, and standing) is presented in the Appendix.

SRS Outcomes Data

Twenty-six of the twenty-seven patients completed the Scolio-

TABLE II Change in Variables Over Time*

		P Value	
Variable	Mean and Standard Deviation	Compared with Preop.	Compared with Immediate Postop.
Sagittal plumb line			
Preop.	17.74 ± 7.95 cm		
Immediate postop.	1.99 ± 3.91 cm	<0.0001	
Final postop.	4.23 ± 6.73 cm	<0.0001	0.04
Thoracic kyphosis T5-T12			
Preop.	21.59° ± 18.37°		
Immediate postop.	29.70° ± 16.01°	<0.0001	
Final postop.	31.70° ± 16.58°	<0.0001	0.24
Lumbar lordosis T12-S1			
Preop.	–14.52° ± 21.82°		
Immediate postop.	–50.85° ± 16.48°	<0.0001	
Final postop.	–48.63° ± 19.01°	<0.0001	0.27
PSO angle (one level above/one level below osteotomy level)†			
Preop.	1.93° ± 11.93°		
Immediate postop.	–31.59° ± 11.31°	<0.0001	
Final postop.	32.22° ± 12.22°	<0.0001	0.65
Height			
Preop.	156.87 ± 8.18 cm		
Immediate postop.	160.83 ± 6.83 cm	<0.0001	
Final postop.	160.30 ± 7.09 cm	<0.0002	0.39

*The means and standard deviations (calculated on the basis of all twenty-seven patients) are reported preoperatively, immediately postoperatively, and at the time of the final postoperative evaluation. P values are based on mixed-model repeated measures analysis of variance and indicate the comparisons of changes in measurements between specific time-points. When effect due to time was found to be significant ($p < 0.0001$ for all variables), specific contrasts were used to test the null hypothesis that changes between two time points were equal to zero (no change). †PSO = pedicle subtraction osteotomy.

sis Research Society outcome questionnaire postoperatively (Appendix). Six patients believed that the spine treatment had reduced their function and daily activity. Nine patients believed that the treatment had reduced their ability to enjoy sports and hobbies. Three patients believed that the treatment had increased their back pain. One patient had increasing pain due to metastatic cancer. The data for one patient were collected following implant failure and pseudarthrosis in the caudad part of the thoracic spine. One patient reported low pain scores, low Oswestry scores, and high SRS scores until she presented with bilateral rod breakage and pseudarthrosis in the cephalad part of the lumbar spine. A substantial number of patients believed that the spine treatment had improved their confidence and personal relationships with others, improved the way in which others viewed them, and improved their self-image. All but one of the patients believed that they looked better than they had looked preoperatively. The overall satisfaction scores (questions 22 and 24) were high. Twenty-four of the twenty-six patients were "satisfied" with the treatment. Twenty-three of the twenty-six patients would have the treatment again, and three were not sure.

Discussion

Purpose

The purposes of the present study were to analyze the clinical and radiographic results for patients undergoing pedicle subtraction osteotomy for complex deformities, often following multiple previous procedures on the spine. To our knowledge, the present study represents the largest series of patients with multiplanar deformity and diagnoses other than ankylosing spondylitis who have been managed with pedicle subtraction osteotomy for fixed sagittal imbalance.

Outcome Analysis

On the basis of the pain scores that were assigned at the latest examination after a minimum of two years of follow-up, sixteen of the twenty-seven patients expressed relief of pain that was equal to 2 points or more on the 9-point pain scale. On the basis of the SRS questionnaire, twenty patients believed that the pain had decreased, three believed that the pain had not changed, and three believed that the pain had increased. Nineteen of twenty-six patients believed that their self-image had improved, six believed that it had not changed, and one believed that it had gotten worse. Twenty-four of twenty-six patients believed that they looked better than they had looked preoperatively. Of the twenty-four patients who had answered Oswestry questions prospectively both preoperatively and postoperatively, twenty demonstrated improvement. Of the four patients who did not have improvement, one had sustained multiple compression fractures of the thoracic spine, one had had development of systemic rheumatoid arthritis, one had had development of metastatic ovarian cancer, and one had had development of a thoracic pseudarthrosis since the time of the operative procedure. All three of the patients who had not answered Oswestry questions preoperatively had very low scores postoperatively, suggesting a low degree of abnormality at the time of assessment (the maximum score, 100 points, indicates maximum abnormality). The Oswestry domains in which the greatest functional improvement occurred were those of dressing, lifting, walking, and standing.

Pseudarthrosis

One lumbar pseudarthrosis occurred through an area of previous laminectomy and previous pseudarthrosis. Six pseudarthroses occurred in the caudad part of the thoracic spine, cephalad to the site at which the pedicle subtraction procedure had been performed. No pseudarthroses occurred in any of the sixteen patients in whom the osteotomy had been performed through a previous fusion mass. All of the pseudarthroses in the present study occurred in patients with primary degenerative etiologies rather than previously treated idiopathic scoliosis. Thoracic pseudarthroses were particularly common in older patients who had a degenerative etiology. These patients were managed, by us, with an arthrodesis into the middle or cephalad part of the thoracic spine because of coexistent thoracic hyperkyphosis. Perhaps more aggressive harvesting of autogenous bone, more extensive use of segmental fixation throughout the thoracolumbar spine in the form of pedicle screws bilaterally at all levels, or combined anterior and posterior surgery in the caudad part of the thoracic spine might have reduced the prevalence of pseudarthrosis in this region in older patients. Although many of these patients had had previous laminectomy or had been treated by us with wide central decompression, we always made every effort to compress the lateral masses tightly together at the completion of the closure of the osteotomy site. We continue to expect that the pseudarthrosis rate will be low in patients managed with pedicle subtraction osteotomy when the procedure is done through a previous fusion.

Role of Anterior Surgery

One of the concepts behind the pedicle subtraction procedure is that surgery on all three columns is performed through a posterior approach and no gap is created in the anterior column that would require anterior structural grafting. However, this procedure does not completely obviate the need for anterior surgery. For instance, in two patients who had had a previous fusion to L5 with subsequent breakdown and kyphosis at L5/S1, anterior surgery was performed. In these cases, we performed structural grafting at L5/S1 through a limited anterior paramedian approach. If we had performed a Smith-Petersen osteotomy, then a more extensive anterior surgical procedure with multiple-level anterior discectomy and arthrodesis (through a flank or thoracoabdominal approach) would have been required. We believed that when the arthrodesis was being extended one or two levels to the sacrum, it was important to use structural bone graft anteriorly because of the known difficulty of obtaining a long fusion to the sacrum. No pseudarthroses occurred through areas that were also treated with bone graft anteriorly.

The other situation in which we used bone graft anteriorly was when a patient presented with multiple pseudarthroses. Those segments were treated with bone graft both anteriorly and posteriorly. However, it was not our routine practice to use bone graft anteriorly for thoracic segments that were added to the arthrodesis.

Neurological Complications

One patient had a neurological complication. One week postoperatively, following an osteotomy for posttraumatic kyphosis, the patient presented with urinary retention that was neurogenic in origin. A computerized tomographic myelogram revealed a block at the level of the osteotomy. After the spinal canal had been enlarged centrally, neurological function fully recovered. For the majority of the patients in the present series who had not had a previous laminectomy, we tried to undercut the previous fusion mass across the width of the osteotomy site in order to compress bone on bone centrally and laterally. However, on the basis of our experience with this particular patient, we now enlarge the canal somewhat centrally and then pass either a Woodson elevator or a nerve hook up and down the canal through the area of central decompression to ensure that no nerve root compression is created dorsally by closure of the osteotomy site.

Many of the patients in the present study had had a previous laminectomy. There is a concern that if scar tissue is not fully débrided off the dorsal part of the dura, the scar tissue might implode into the cauda equina and create a neurologic problem when the osteotomy site is closed. However, we did not observe this complication. Furthermore, we found that we were able to dissect the dura adequately and did not note an increased number of dural tears in patients who had had a previous laminectomy.

Loss of Correction

We did not see any substantial loss of correction through the site of the pedicle subtraction osteotomy, except in one patient who had development of a pseudarthrosis at that level. This patient had had a previous laminectomy and pseudarthrosis at the same level. Nor did we see any loss of correction in the lumbar spine cephalad to L5, except in the patient just described.

In three patients, the operation did not adequately correct the sagittal imbalance, which measured 28 cm, 28 cm, and 43.2 cm preoperatively. When sagittal imbalance exceeds 25 cm, consideration should be given to performing more than just one pedicle subtraction osteotomy to obtain correction.

In conclusion, we believe that pedicle subtraction osteotomy can provide acceptable clinical and radiographic results for patients who have had multiple previous operations. The osteotomy can be performed through rotated and angled segments without the risk of substantial coronal decompensation, and there should be no adverse effects when the osteotomy is performed through previously decompressed levels. The operative times in the present study were long, and some patients lost a substantial amount of blood. Early complications were seen in approximately one-third of the patients. Pseudarthrosis and loss of correction at the level of the pedicle subtraction osteotomy was not observed when the procedure had been performed through a previous fusion. However, breakdown caudad to the fusion at L5/S1 (two patients), thoracic pseudarthrosis (six patients), and pseudarthrosis at the site of a previous lumbar pseudarthrosis and laminectomy (one patient) were problematic. The mean correction through the osteotomy site was 33.5° immediately postoperatively and 34.5° at the most recent follow-up. The mean improvement in the C7 sagittal plumb line was 15.8 cm immediately postoperatively and 13.5 cm at the most recent follow-up. The level of patient satisfaction was high after more than two years of follow-up, with most patients having improved pain-scale and Oswestry scores. The major determinants of success after a minimum of two years of follow-up were fusion throughout the construct and the absence of major comorbidities.

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Appendix

eA Tables presenting the pain-scale scores, the Oswestry-score data, and the SRS outcome data are available with the electronic versions of this article, on our web site at www.jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

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