Revision Deformity Surgery

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OVERVIEW

This chapter focuses on the management of patients who have had previous surgery for correction of spinal deformity that requires further surgical intervention. Patients who present with failed surgical correction or with new surgical issues are typically complex and require a thorough physical examination and complete diagnostic evaluation. A combination of laboratory, radiologic, and electrodiagnostic testing often provides critical information in formulating a diagnosis and plan for revision surgery. A treatment plan can then be established, consisting of any required provocative preoperative testing followed by revision surgical management and comprehensive postoperative care.

Revision spine deformity surgery, also known as salvage reconstruction, presents several challenges to the spine surgeon. The biologic environment for fusion is often unfavorable and requires meticulous attention to both optimizing preparation of the intended fusion bed and stabilizing the reconstructed spine with implants. Additional technical considerations, including osteotomies and subtotal vertebrectomies, are also quite complex and require special training. Both the patient and surgeon need be aware that the risks and complications of revision deformity surgery are significantly greater than those of primary procedures. Nevertheless, successful outcomes can be obtained with careful preoperative, intraoperative, and postoperative decision making.

CLASSIFICATION

Clinical Presentation

Typical complaints at presentation for patients who are undergoing revision surgery are back or leg pain, increasing spine deformity, neurologic involvement, or any combination of these. Patients usually present several years after the index corrective procedure, but it is not uncommon for patients to report symptom-free intervals of 20 years or longer following their index surgeries. Symptoms may have an insidious onset and may be the result of motion segment degeneration below a long fusion or indolent infection, which can take months or years to be noticed by the patient, or they may be more precipitous in their onset because of the immediate loss of mechanical stability in the setting of instrumentation failure secondary to a pseudarthrosis. It is very important to characterize the nature, intensity, and duration of complaints to best utilize this information logically in diagnosis and ultimately treatment. Although tedious, the art of eliciting a complete and accurate historical vignette and performing a complete physical examination is what provides the practitioner with the most critical information for diagnosing the problem.

Pain that occurs in the area of previous surgery can be secondary to several pathologic processes. Pseudarthrosis is a particularly common etiology in this regard, is often overlooked as a possibility, and should be considered to be the diagnosis until proven otherwise. Posteroanterior, lateral, and oblique radiographs of the fusion mass; computed tomography (CT) scans with reconstructions; and bone scans are all instrumental for evaluating for the bony healing defect. Pathognomonic of pseudarthrosis is the presence of failed or broken implants, which are commonly associated with this process. Other etiologies to consider include indolent infection, prominent instrumentation, or crankshafting (in an adolescent population) in addition to less likely mechanisms, including acute fracture within the fusion mass or superimposed spinal stenosis. Vague pain symptoms that are difficult to localize are more consistent with indolent infection, crankshaft, or diffuse spinal stenosis, whereas point tenderness is consistent with a suppurating infection, acute fracture of the fusion mass, or prominent implants. Evaluation of these etiologies requires the imaging listed previously and might also require magnetic resonance imaging (MRI) or CT myelography in addition to blood work to evaluate markers for correlates of infection (e.g., complete blood count, erythrocyte sedimentation rate, C-reactive protein). Although implants can certainly be painful, this is a diagnosis of exclusion; all other etiologies, in particular pseudarthrosis and infection, need to be formally eliminated as diagnoses prior to concluding that the symptoms are due to symptomatic implants.

The pain generator might not be based within the fusion mass proper but rather could be at a level adjacent to it proximally or distally. It is important to elicit the specific character of the pain, its chronicity, and any diurnal variability. An inflammatory process would classically be expected to generate complaints of morning stiffness that gradually gets better with activity during the day. The patient might report that the complaints are responsive to, and relatively well controlled with, over-the-counter anti-inflammatory medications. Pain symptoms that are worst at the end of the day or that are associated with activity suggest a mechanical origin of the pain such as might be seen with generalized junctional degeneration. More specifically, if mechanical symptoms are aggravated with sitting, positions of flexion, or vibratory movements, a discogenic source of the pain should be sought. Radicular symptoms should raise diagnostic suspicion of a disc herniation or spinal stenosis. Systematic and logical application of the historical vignette will guide imaging and other evaluations that might be required to confirm the diagnosis.

Increasing deformity is commonly attributable to one of three causes: pseudarthrosis, crankshaft phenomenon, or the adding-on phenomenon. The patient presents complaining of “falling forward” or “leaning to the side” or has the subjective sensation that this is happening. The patient is usually aware of the progressive nature of the deformity and might relate a history of balance difficulty with ambulation, a loss of height, waistline asymmetry, or an increase in a rotational prominence. Fixed sagittal imbalance, or flat-back syndrome, often presents with low back pain, hip flexion deformity and contracture, and quadriceps fatigue. On physical examination, coronal decompensation can be measured clinically by using a plumbline from C7 to the gluteal fold and can be monitored serially to document progression. Sagittal plane decompensation can be demonstrated by viewing the standing patient from the side and noticing the loss of natural sagittal contour or the frank forward thrust of the shoulders anterior to the hips. Sagittal and coronal imbalance can be monitored both radiographically, with full-length spine radiographs, and by using plumblines dropped from T1 to the back of the S1 vertebral body or the center sacral line, respectively.

Clinical clues to the etiology of progressive deformity can be provided by careful scrutiny of the history and physical examination, radiographs and supplementary imaging, and review of the prior operative reports. Deformity that is related to pseudarthrosis occurs due to a defect within the fusion mass itself. A failure to achieve arthrodesis at a particular level or levels can then lead to coronal imbalance, sagittal imbalance, or both and, as was mentioned previously, is frequently accompanied by pain. Failure to use autogenous bone graft or osteogenic factors at the principal operation and poor arthrodesis technique are risk factors for pseudarthrosis. Meticulous decortication of the posterior elements and placement of either rib autograft or iliac crest autograft is crucial for a successful union. The crankshaft phenomenon is seen only in skeletally immature individuals. This occurs in patients with infantile or juvenile scoliosis who have undergone a posterior spinal fusion alone. The healthy anterior vertebral apophyses allow for continued growth and subsequently a rotational deformity. These patients present with a significant rotational deformity, frequently with excessive rib prominences. By definition, crankshafting can be diagnosed only in a growing individual. Finally, the adding-on phenomenon refers to a new deformity above or below the prior surgical site. This may also be described as junctional deformity or lengthening of the curve. It is caused by unpredictable remaining spinal growth and/or inadequate selection of fusion levels at the index procedure. Rotation is not nearly as severe as that seen in crankshaft cases. The presentation can be one of sagittal or coronal decompensation on either end or on both ends of a previous fusion. Junctional kyphosis, a specific subset of junctional deformity, commonly develops cranially to a fusion mass when fusions are terminated in the midthoracic or thoracolumbar spine.

Physical Examination

Prior to a comprehensive spine examination, a pertinent general medical examination needs to be performed. Fever might indicate an underlying infection and must be thoroughly evaluated. On pulmonary auscultation, wheezes, rales, or rhonchi might suggest underlying pulmonary or cardiac disease. Salvage surgery is frequently lengthy in duration, and it is critical that the patient be systemically healthy enough to undergo such an event. The abdomen and thorax should be inspected in anticipation of anterior surgery, and prior surgical incisions should be noted. Lower-extremity pain should mandate a hip and knee examination to rule out local pathology, and palpation of distal pulses should be performed to evaluate large-vessel peripheral vascular disease.

After completion of a relevant medical examination, the spine examination is performed to evaluate pain, document deformity, and assess neurologic status. Inspection of the prior surgical incision reveals erythema, drainage, prominent implants, and cutaneous healing potential. The entire spine, including the sacroiliac joints, is palpated both in the midline and along the paraspinal musculature. Points of maximal tenderness must be noted and correlated to the spinal levels that were previously instrumented. Standing posture is observed, and sagittal and/or coronal decompensation is noted. Subtleties of stance need to be appreciated: Are one knee and hip flexed to compensate for coronal imbalance, or are both hips and knees flexed to correct sagittal imbalance? With the patient's hips and knees extended, a plumbline should be dropped from the vertebra prominens, and the magnitude and direction of horizontal displacement from the gluteal fold should be recorded. Similarly, a visual estimation of the sacrovertebral angle allows for quantification of forward tilt. The Adams forward-bending test permits documentation of thoracic and lumbar rotational prominences. Trunk range of motion must be measured in flexion, extension, and lateral bending; this measurement also allows an estimation of curve flexibility. Gait and station are evaluated, with emphasis on global spinal balance and hip abductor/extensor weakness or contracture. A detailed neurologic examination is an essential component of the clinical examination. Thorough motor and sensory testing of upper and lower extremities must be performed and documented, with emphasis placed on unambiguously defining deficits that the patient has at presentation. Normal and pathologic reflexes, balance, and tension signs must also be included in the assessment, along with assessment of rectal tone as indicated by the clinical scenario.

Diagnostic Evaluation

A complete diagnostic workup encompasses a medical, radiologic, electrodiagnostic, and occasionally interventional evaluation. The medical assessment should fulfill two criteria: clearing the patient for surgery and addressing specific issues pertinent to each individual's circumstance. Medical clearance consists of routine blood work, a chest radiograph, electrocardiogram, and echocardiogram (in males over 40 years and females over 50 years of age). If anterior thoracic surgery is necessary, pulmonary function tests are recommended as well. Attention is then directed toward patient-specific problems, such as infection or pseudarthrosis. A preoperative complete blood count with differential, erythrocyte sedimentation rate, and C-reactive protein should be obtained for diagnostic purposes and baseline values. Finally, radionuclide bone scans (e.g., technetium, gallium, or labeled white blood cells) can help to detect the presence of a spinal infection. If a prior surgical site is draining or there is evidence of a fluid collection, aspiration and/or swabbing of this site (after meticulous sterile preparation) can be performed, although cultures from draining wounds frequently are not helpful for guiding management. Antibiotics are held until the cultures return unless there is clear evidence of infection or systemic manifestation of sepsis. Preferably, cultures can be obtained in the operating room, where biopsies of bone and soft tissue can be collected simultaneously.

Preoperative diagnostic imaging can be critical in formulating the treatment plan. The radiologic evaluation begins with full-length standing posteroanterior and lateral views of the entire spine to assess global coronal and sagittal balance. In addition, the presence of scoliosis, kyphosis, pelvic obliquity, shoulder asymmetry, and any prior instrumentation is documented. Areas proximal or distal to a prior fusion are assessed for junctional degeneration or decompensation. The fusion mass itself is assessed for evidence of crankshafting or pseudarthrosis. Supine oblique radiographs are often helpful in establishing the latter diagnosis; 70% of pseudarthroses can be detected with the addition of oblique views. In addition, coned-down views of an area of interest (e.g., lumbosacral junction) can prove to be useful.

Three-dimensional imaging and provocative testing provide detailed and novel information to confirm clinical diagnoses. CT scans can highlight bony detail such as bridging trabecular bone if a pseudarthrosis is in question. Spinal stenosis is typically evaluated with multisequence MRI examinations, which are also used to evaluate patients for canal or neuroforaminal compromise. However, metallic instrumentation makes visualization of the spine difficult with MRI. Revision surgical candidates who are being evaluated for spinal stenosis can be assessed by a CT-myelogram, which has better ability to visualize the stenosis in this setting. However, the status of intervertebral discs distal to the instrumentation can be evaluated with MRI. MRI examination of intervertebral discs is often an important preoperative test in considering terminating a fusion in the distal lumbar spine. More commonly, patients with suspected discogenic back pain and positive MRI findings can have their diagnoses confirmed by using provocative discography. The authors recommend testing multiple disc spaces during this examination, if possible, to decrease false-positive results.

Neurodiagnostics encompasses nerve conduction studies, electromyography, somatosensory evoked potentials, and motor evoked potentials. Such electrodiagnostic testing can be extremely useful in both the preoperative and the intraoperative setting. Patients who present with radicular symptoms and/or weakness can be evaluated preoperatively with electromyography and nerve conduction studies. In addition, cases that involve significant deformity correction or shortening, placement of thoracic pedicle screws, placement of intracanicular implants (e.g., hooks, wires), or any complex cervical reconstruction should have intraoperative spinal cord monitoring with somatosensory evoked potentials, motor evoked potentials, and electromyography. If motor evoked potentials are not available, a Stagnara wake-up test must be performed after the correction and before completion of the surgery.

Physiatric and pain management consultations can also offer valuable modalities and therapies that can mitigate or control pain symptoms. Patients with symptoms of spinal stenosis might elect to undergo epidural steroid injections or selective nerve root blocks. Similarly, facet injections or instrumentation injections (injecting local anesthetic adjacent to a prominent implant) not only can temporarily reduce the pain, but also might offer a solution for permanent relief. These interventions should be seen as providing a dual service of both symptomatic treatment and aid in confirming the diagnosis. The surgeon who takes on the challenge of revision deformity surgery should be equipped with as much information as possible before proceeding to operative intervention.

TREATMENT OPTIONS

After the patient has been fully assessed and a working diagnosis has been established, the surgeon can formulate a treatment plan to best address the clinical problems. Preoperative planning involves assessing the patient's general state of health, including any particular risk factors that might have an adverse effect on surgical outcome. Patients who have overwhelming medical comorbidities or patients with insufficient physiologic reserves to tolerate the stresses of the operating room might not be suitable candidates for revision surgery. Medical clearance and risk stratification are mandatory for all patients, regardless of age, as is preoperative medical optimization from pharmacologic, physiologic, and nutritional standpoints. Planned surgical intervention is much better delayed for the patient who is at increased risk for complications secondary to medical or nutritional issues, such as uncontrolled diabetes or hypertension, anemia, physical deconditioning, or occult pulmonary or genitourinary infection. Revision spine deformity surgery demands a tremendous physiologic response from the patient, and properly preparing the patient for the procedure will increase the chances of an optimal outcome.

Modifiable risk factors, such as cigarette smoking and poor bone density, should be addressed well in advance of surgery. Patients should be counseled to quit smoking at some time prior to the surgery, owing to the known detrimental effects of nicotine on wound healing and union rates, but there is no generally agreed-on length of time for presurgical abstinence. In addition to the problems with healing, heavy smokers have poorer postoperative pulmonary recovery and may be at increased risk for longer duration of mechanical ventilation and pneumonia. Bone density can occasionally be apparent on preoperative radiographs; however, by the time mineralization differences are noted on plain radiographs, the amount of bone loss is excessive (greater than 30%). The current standard for assessing bone density is DEXA (dual-energy X-ray absorptiometry). DEXA is much more sensitive and accurate than are plain films or quantitative CT and, if positive for osteopenia or frank osteoporosis, can be used to monitor response to pharmacologic treatment. For patients with diagnosed osteopenia or osteoporosis, preoperative treatment with antiresorptive bone medications (e.g., bisphosphonates) or bone anabolic agents (e.g., PTH/Forteo) must be considered in collaboration with the medical consultant.

Each aspect of the planned surgical revision procedure needs to be carefully considered and discussed with the patient. Many of these concerns will be included in the informed consent document, including intraoperative bleeding, neurologic injury, infection, and the possibility of paralysis or death. It is important to discuss these issues with the patient preoperatively to assess the patient's agreement with the preoperative plan and to prevent potential problems postoperatively. If the patient agrees to accept blood transfusion, preoperative blood donation by the patient or a direct donor can limit the amount of indirect donor blood transfused intraoperatively or postoperatively. In addition, blood preservation techniques such as hypotensive anesthesia and intraoperative salvage with cell saver can further limit the use of communally banked blood. Intraoperative monitoring, if it is to be used, must be arranged, and the patient must be made aware that this system is not infallible or without its own risks. Finally, the actual surgical intervention itself needs to be outlined, and methods for reconstruction need to be planned on the basis of the patient's needs as developed in the preoperative evaluation. Revision deformity procedures include posterior spinal fusion (PSF), anterior spinal fusion followed by PSF (or vice versa), PSF with extension-type (Smith-Petersen) osteotomy, PSF with pedicle subtraction or decancellation osteotomy, and vertebral resection with PSF. With this array of bony procedures and the addition of spinal instrumentation and bone grafts, deformity correction and stabilization are possible for the most complex reconstruction requirements.

Before working out the details of what will be performed in the operating room, the operating surgeon must obtain a copy of the patient's prior operative reports. This simple action will provide a surprisingly large amount of useful information, including the instruments that are needed to remove existing implants (depending on the manufacturer) and any problems that were encountered in the prior procedures (e.g., anomalous vasculature or dural ectasia). Intraoperative surprises should be avoided whenever possible, particularly when this is within the control of the operating surgeon. Having the required instruments to remove the existing implants can make that portion of the operation go quite smoothly. In addition, a variety of revision implants, including large-diameter pedicle screws, dual-diameter connectors, and sacropelvic fixation instrumentation, may be required during the reinstrumentation and should be available. If both iliac crests have been harvested in the past, commercially available bone graft substitutes or biologic agents, particularly bone morphogenetic protein and demineralized bone matrix, can be planned to be used with allograft or as autograft extenders.

The final decision the surgeon must make is whether or not to stage the reconstruction. This determination can be made preoperatively or intraoperatively and is based on medical comorbidities, estimated surgical blood loss, length of surgery, hemodynamic parameters, and the surgeon's expertise in executing both procedures in a timely fashion. Preoperative factors that would necessitate staging a reconstruction include ruling out or treating an infection of the spine in the region of planned implant or graft placement or when multiple osteotomies are planned and blood loss is expected to be excessive. Intraoperative parameters that prompt surgical staging include total surgical time in excess of 12 hours, unanticipated excessive blood loss, devastating neurologic injury, and hemodynamic changes that make safe anesthesia management difficult. If surgery is to be staged, the authors recommend waiting a week to 2 weeks between procedures for improved nutrition, coagulation, hematologic, and cardiopulmonary status. For staged procedures, the authors favor interval hyperalimentation administration.

SPECIAL COMPLICATIONS: HOW TO AVOID AND TREAT

Pseudarthrosis

The most common late complication following adult spine deformity surgery is pseudarthrosis occurring in the fusion mass, with resultant pain and patient dissatisfaction. Complaints of pain associated with the pseudarthrosis are almost universal and correlate with lower SRS-24 outcomes measurements. Patients may demonstrate radiographic changes, including loss of implant fixation (>60%), deformity progression (50%), disc space collapse (19%), and motion on stress views as well as the classic intraoperative finding of gross motion (94%) at the pseudarthrosis site. Increased rates of pseudarthrosis are seen with age over 55 years, fusions spanning more than 12 vertebrae, and thoracolumbar (T10-L2) kyphosis over 20 degrees. Recent rates of pseudarthrosis from primary deformity surgeries range from 11% to 17%, and rates for revision surgery range from 0% to 15%. Pseudarthroses are often present at more than one level in the fusion mass.

Appropriate surgical intervention has the goals of limiting or eliminating pain symptoms, restoring sagittal balance and arresting progressive deformity, and protecting neurologic function. The preoperative patient workup should include determination of previous surgery (anterior or posterior only or combined procedures), as well as standard imaging and laboratory assessments. Anterior procedures are required in the setting of pseudarthrosis after failed anterior fusion attempts and where anterior column structural support must be added. Posterior revision procedures are the mainstay of treatment of pseudarthroses, either alone (in certain clinical settings) or in combination with anterior fusions. Posterior procedures involve exposure of the implants and bone in the region of the diagnosed pseudarthrosis, removal of implants, mechanical testing of the fusion mass, and then bony preparation and reinstrumentation. The standard of care has become circumferential fusions at the pseudarthrosis site, along with anterior and posterior osteotomies to allow restoration of proper sagittal balance of the spine. A recent report challenged this dictum for pseudarthroses of the thoracic spine; in a small series of patients, posterior-only procedures were shown to be uniformly successful in treating the pseudarthroses.

Studies describing surgical outcomes for dedicated revision procedures for pseudarthrosis are limited but are supportive of the role of revision reconstruction. In a 2001 study, Voos and colleagues reported on 17 patients with pseudarthroses in a population of 27 patients who were subjected to combined anterior-posterior fusions with osteotomies and had three pseudarthroses postoperatively (11%), with only one persistent pseudarthrosis present from the original population (6%). In a 1997 study, Buttermann and colleagues reported on 38 patients with pseudarthroses after lumbar fusions who underwent anterior-posterior fusions with anterior structural grafts of either tricortical autograft or femoral ring allograft. They found 4 patients in the allograft group ($N = 26$ patients, $N = 64$ levels) to have residual pseudarthroses and none in the autograft group, for a cumulative successful pseudarthrosis treatment rate of 89%. These findings suggest that appropriate surgical intervention can lead to predictable success in treatment of this difficult problem.

Fixed Sagittal Imbalance (Flat-Back Syndrome)

The loss of normal lumbar lordosis can be multifactorial, but the most common reported cause is iatrogenic, secondary to distraction (Harrington) instrumentation to the lower lumbar spine or sacrum. Other etiologies include hypolordotic lumbar fusion for spondylolisthesis, other malaligned fusions, pseudarthrosis with progression of deformity, thoracolumbar kyphosis, decompensation of inferior or superior adjacent segments secondary to inadequate scoliosis fusion length or segmental degeneration, hip flexion contractures, and hip extensor weakness. The result is positive sagittal imbalance with anterior translation of the plumbline and the body's center of gravity. Patients attempt to compensate for this imbalance by hyperextending the remaining mobile spine segments (mid/upper thoracic and cervical spine) as well as by flexing the hips and knees. These compensatory maneuvers allow the patient to stand upright and/or to achieve horizontal gaze.

The loss of lumbar lordosis directly correlates with the number of caudad levels included in the fusion: Aaro and colleagues, in a 1983 report, showed that patients treated with Harrington instrumentation stopping at T12 averaged 38 degrees of lumbar lordosis, whereas those whose fusions terminated at L4 and L5 averaged only 21 degrees and 16 degrees, respectively. Further study by this and other groups demonstrated decreased lordosis in patients who were fused to the sacrum and normal lordosis in those who were instrumented cephalad to L3.

Patients with flat-back syndrome often complain of painful fatigue in the cervical, upper thoracic, or lower lumbar region. Physical examination reveals obvious flattening of the lumbar region with an obligatory forward tilt of the trunk. A biomechanical study by Tveit and colleagues from 1984 demonstrated that increased paraspinal muscle forces are necessary to maintain erect posture in this patient population and suggested that this was a likely contributory source to the fatigue symptoms. Moreover, more than 50% of patients who are treated with Harrington rods have degenerative cervical changes on radiographs at late follow-up. Using an explanation similar to the first, this could be due to persistent attempts to achieve horizontal gaze with neck extension that result in increased stresses placed on the cervical spine.

The goal of corrective surgery in the management of flat-back syndrome is the restoration of physiologic (or supraphysiologic) lordosis and sagittal balance. Normal sagittal balance is such that the vertical axis falls within 2.5 cm of the posterior aspect of the sacral end plate. An osteotomy is typically performed as the principle corrective maneuver for loss of lordosis; the type and location depend on the site of the deformity, the magnitude of the deformity, and the presence of a solid anterior fusion. The osteotomy can be an opening-type or a closing-type (shortening-type) procedure and can be performed as a stand-alone posterior construct or combined with anterior column support.

Posterior correction alone can be achieved with a Smith-Petersen (extension-type) osteotomy or a pedicle subtraction (or decancellation) osteotomy. A Smith-Petersen osteotomy entails resection of the posterior elements with undercutting of the cephalad spinous process. The entire inferior articular facet of the cephalad vertebra and the superior articular facet of the caudad vertebra are excised; the pars interarticularis is transected. The osteotomy can be repeated at multiple levels, and sagittal correction is achieved via posterior compression with segmental instrumentation; this results in distraction anteriorly through the anterior longitudinal ligament and disc space. It is important to note that this osteotomy lengthens the anterior column and, as a result, can destabilize the spine if the instrumentation fails prior to bony fusion. Additionally, this anterior distraction can injure calcified great vessels or result in superior mesenteric artery syndrome. For these reasons, it has been recommended to add anterior releases and fusion in conjunction with the SmithPetersen osteotomies. An average of 1 degree of correction can be expected for each millimeter of posterior bone resection, yielding 5 to 20 degrees of total segmental correction.

When a larger deformity exists or in the presence of a solid anterior fusion, it is necessary to remove bone from the anterior column in addition to the posterior elements to obtain adequate correction. The pedicle subtraction osteotomy, or transpedicular decancellation osteotomy, is a three-column posterior closing-wedge osteotomy with the anterior column acting as the hinge. An eggshell variation, or transpedicular vertebrectomy, which was popularized by Heinig, is the preferred technique of the authors if larger corrections are needed. The operation consists of removal of all posterior elements at the level of the desired correction, including the pedicles and facet joints. The cephalad disc might or might not be included. A posterior wedge of bone or a complete decancellation is then performed.

The authors prefer three levels of rigid transpedicular fixation both above and below the level of the osteotomy. The osteotomy is usually performed at L3 or L2 to protect conus medullaris and spinal cord function. For an L3 osteotomy, removal of the entire neural arch of L3 and resection of any overhanging lamina from L2 or L4 are performed. The dura and nerve roots are completely mobilized, and the transverse processes and pedicles are excised. This frees the L2 and L3 nerve roots bilaterally, as well as the central dura. Copious bleeding may occur as the resection continues laterally down the pedicles, but hemostasis can be obtained with bipolar electocautery, bone wax, and thrombin-soaked Gelfoam. Then the posterior wedge decancellation procedure is carried out by careful elevation of the dura off the posterior wall of the vertebral body. Prior to decancellation, it is important to place temporary fixation on the side away from the surgeon to prevent inadvertent collapse as the osteotomy is completed. This can be moved from side to side as the surgeon moves from one pedicle to the next. The osteotomy is closed by compression through the instrumentation and/or by gradual extension of the operating table. A single-level osteotomy delivers an average of 30 degrees of correction.

In some instances, bony apposition is insufficient at the level of the osteotomy; in this case, the authors prefer to insert an autograft-filled cage through a posterior lumbar interbody fusion approach. Anterior surgery or adjacent segment posterior lumbar interbody fusions may be added in cases of concomitant pseudarthrosis, compromised bone stock, or extension to the sacrum. Pelvic fixation should be considered for fusions that extend to or above the thoracolumbar junction. Advantages of the pedicle subtraction osteotomy include significant sagittal correction at a single level, the ability to achieve coronal correction (modifying the technique to a biplanar osteotomy), preservation of anterior column length, and promotion of rapid fusion by compressed, interdigitating cancellous bone. Drawbacks include its technically demanding nature, significant blood loss, and risk of neurologic injury.

Vertebral column resection, or vertebrectomy, is a shortening procedure that should not be utilized for isolated flat-back syndrome; it can be useful, however, in patients with fixed sagittal imbalance and concomitant degenerative or adult scoliosis with severe coronal plane deformities or hyperkyphosis. Dramatic correction can be achieved at a single level, but the procedure is extremely challenging and should be performed only by a surgeon who is experienced with this technique. Complication rates are as high as 60%.

Coronal Imbalance

Coronal plane imbalance with lateral trunk shift is usually associated with rotational deformity. Patients often complain of an inability to maintain an upright posture; in some instances, flank pain may be caused by impingement of the concave side rib cage on the iliac crest. Significant coronal decompensation with translation can lead to nerve root entrapment or traction, resulting in a radiculopathy.

Coronal imbalance can occur because of curve progression within a prior fusion site or at adjacent levels. If the etiology lies within the prior operative site, a pseudarthrosis, fracture, or crankshaft phenomenon is the likely culprit. When the imbalance occurs proximally or distally to the prior fusion, the cause may be inadequate fusion length (the adding-on phenomenon), juxtafusion disc degeneration with loss of disc height and progressive instability, severe facet degeneration, facet joint or pars interarticularis fracture, or dislodgement of a terminal implant prior to arthrodesis at that level.

Treatment of pure coronal imbalance is quite challenging, given the frequent rotation that is associated with this scenario. Therefore, the best treatment is prevention: Care should be taken in planning fusion levels. The surgeon should consider including an additional caudal level in the presence of angular instability, translational instability (anterolisthesis or retrolisthesis), laminectomy, discectomy, oblique takeoff, or disc degeneration at that level.

For severe and rigid deformities, a circumferential release with multilevel discectomies and fusion, or osteotomies through an existing fusion mass at multiple levels, provides the desired balanced correction in the coronal plane without stressing the correction at a single level with one osteotomy. In the presence of a pseudarthrosis in the thoracic spine, a vascularized rib graft with its intercostal pedicle can be considered. In the lumbar spine, iliac crest autograft or rib autograft supplemented with anterior structural grafts for distal levels should suffice. Supplementation with bone morphogenetic protein can also be contemplated. An extension to the sacropelvic region is the most sound option for patients with significant oblique takeoff of L4 or L5 or for patients with degenerative disc disease at L4-5 or L5-S1 and those that had a long fusion past the thoracolumbar junction. This entails anterior structural graft placement and unilateral or bilateral Galveston-type fixation posteriorly.

Junctional Deformity (Adding-on Phenomenon)

Progressive deformity in juxtaposition to a fusion performed for spinal deformity correction can result from the adjacent segments that were not previously included in the fusion. This complication is most frequently encountered where inappropriately short deformity fusions were performed on younger patients with significant growth remaining in an effort to preserve motion segments. Other settings in which such junctional deformities are seen include neuromuscular deformity and in proximity to large uninstrumented curves. Attempts to prevent this type of junctional deformity and to optimize postsurgical balancing of the spine have led to the routine assessment of curve flexibility in addition to standard standing AP and lateral full-length radiographs, leading to various recommendations for vertebrae to include in a particular fusion.

Surgical goals for junctional deformity are to correct or at least arrest the deformity, to restore spine balance, to relieve pain symptoms if these are present, and to preserve and protect neurologic function. Proper assessment of the patient preoperatively should include determination of the rigidity of the minor or compensatory curves and selection of appropriate extensions of the index fusion. Anterior discectomies and fusion might be required for rigid or large deformities or where anterior column structural support is needed. Osteotomies of the fusion mass might be also be required if overall sagittal and coronal balance cannot be achieved via mobilization of the junctional deformity segments. Typically, posterior-only procedures are utilized to provide direct extensions of the existing fusion mass to include the involved junctional segments.

Adjacent Segment Degeneration (Junctional Degeneration)

Deterioration of the motion segments proximal or distal to a fusion mass is referred to as *adjacent segment* or *junctional degeneration*. This deterioration may be in the form of desiccation of adjacent discs and degenerative disc disease or degeneration of facet joints and arthrosis of adjacent levels often accompanied by a new deformity such as kyphosis. The true etiology of junctional degeneration has not been established. Suggestions for causation include (1) compromised stability of adjacent levels secondary to the stripping of soft tissues and local damage incurred during the index fusion or (2) increased rate of normal wear and tear at adjacent levels incurred by the increased motion imparted by the long fusion segment. Junctional degeneration is encountered after posterior fusions for Scheuermann's disease or neuromuscular scoliosis and can be seen proximal to short thoracic fusions done for thoracolumbar scoliosis. Perhaps the best-recognized example of junctional degeneration is in the lumbar intervertebral discs below long deformity fusions;

however, there is controversy over whether this degeneration is clinically relevant. The experience from patients who have undergone limited lumbar fusions for degenerative disease suggests that degenerative discs adjacent to lumbar fusion masses did not have a predictable negative impact on clinical outcomes.

Surgical goals for junctional degeneration are pain relief, correction of spinal imbalance, correction of deformity if this is present, and protection and preservation of neurologic functioning. Lesions in the thoracic spine are typically amenable to posterior-only procedures and simple extensions of the fusion mass to include the degenerative involved segment. Lumbar lesions should be worked up with appropriate three-dimensional imaging to evaluate the neural elements and rule out stenosis or impingement as well as to evaluate the status of the discs at subjacent levels of a planned fusion extension. Extensions of the fusion mass might require anterior procedures if anterior support is needed, especially as this pertains to the lumbosacral junction, but posterior-only procedures typically are sufficient.

Crankshaft Phenomenon

The term *crankshaft phenomenon* was coined by Dubousset as a progression of rotational and angular deformity within a posterior spinal fusion in young patients as a result of continued growth and not due to pseudarthrosis within the fusion mass. Crankshaft deformity has been reported in populations including those with paralytic, congenital, and idiopathic scoliosis diagnoses that have been subjected to posterior-only fusions at young ages. The Risser stage and status of the triradiate cartilage at the time of surgery do not predict the risk of crankshaft deformity, but peak height velocity and a multivariate method using chronologic/skeletal ages and rib vertebral angle difference are effective. In that residual anterior spinal growth drives the crankshaft deformation, standard care of patients of skeletal age 10 years or younger, or Risser 0 or 1, has become combined anterior and posterior fusions, which successfully prevent the deformity. However, when adolescent idiopathic patients are examined as a subpopulation, the magnitude of crankshaft deformity is typically small, and this finding has led to the recommendation that these patients do not need anterior-posterior fusions.

Surgical goals are to arrest and correct the deformity, to restore balance of the spine, to preserve and protect neurologic functioning, and to alleviate pain symptoms if these are present. In that the deforming force is the continued anterior growth of the spine, anterior or combined anterior and posterior procedures are the mainstay of treatment. Anterior procedures should include complete discectomies and fusion with anterior column support and grafting within the prior fusion mass. Posteriorly, surgical intervention includes removal of appropriate implants and mechanical testing of the fusion mass to evaluate pseudarthrosis and may include osteotomies to correct deformity and to restore proper spine balance prior to replacement of instrumentation.

Painful Instrumentation

Pain is the most common presentation in patients who require revision deformity surgery. Many patients report a history of chronic pain with continued narcotic use. Often, it is impossible to wean these patients off such medications if the source of their pain (e.g., the spine) is not addressed. Nevertheless, a preoperative and postoperative consult with a chronic pain specialist should be ordered. These specialists can also help with diagnostic injections in the preoperative period.

The pain may be coming from prominent instrumentation, pseudarthrosis, infection, fracture, degenerative disc disease, facet arthrosis, instability, spinal stenosis, or nerve root compression. The revision surgeon needs to be aware that the diagnosis of prominent or painful implants is strictly a diagnosis of exclusion. All other potential etiologies should be ruled out prior to removal of instrumentation. Symptomatic relief with peri-implant injections of local anesthetic supports this diagnosis. If no specific site is particularly painful, all of the implants are usually removed, and the entire extent of the fusion is explored. The exception is in a patient with prominent instrumentation and site-specific pain. In this case, offending implants are removed, and the fusion is explored in the area of pain for evidence of a pseudarthrosis. All fibrous tissue is removed with a rongeur or large curette to allow for careful inspection of bony union. If a nonunion is identified, it should be treated as described earlier.

If the fusion appears solid and implants are removed, postoperative bracing is often recommended. Bone removal is frequently necessary to remove screws, hooks, or rods, and the fusion might thus become biomechanically weaker. Consequent loss of coronal or sagittal plane correction may be encountered in the setting of a weakened fusion mass. External support protects the fusion and decreases fracture risk.

Infection

An infection in a postoperative spine patient falls into one of three groups: (1) early infection, prior to fusion; (2) late infection, after fusion has been achieved; (3) late infection with a pseudarthrosis. In all cases of presumed infection (concordant laboratory values and imaging studies), antibiotics should be held until operative cultures can be obtained. Multiple superficial and deep cultures should be sent to pathology as well as specimens of soft tissue and bone.

When an infection is present in the immediate or early postoperative period, the fusion has not yet taken. Here, every attempt is made to eradicate the infection while leaving the implants in place. This often involves multiple visits to the operating room with meticulous debridement and copious irrigation with antibiotic solution. All loose bone graft can be removed or irrigated and replaced, according to the surgeon's preference. The patient is started on broad-spectrum antibiotics, which are then modified according to culture results and infectious disease input. If the infection cannot be eradicated, all instrumentation is removed, and a postoperative brace is issued.

A late infection alone in the presence of a solid fusion is the easiest subset to treat. All instrumentation is removed, and all infected tissue is debrided, including removal from screw and rod tracts. A high-speed burr or small curettes can be quite helpful. After the debridement and irrigation are complete, it is wise to pack the wound open with peroxide-soaked gauze or close the incision over drains. Repeat debridements should occur every other day until the wound is clean enough to be definitely closed over drains. If the condition of the soft tissues or the shape of the wound prohibits wound closure, a vacuum-assisted wound closure system may be utilized. Antibiotics are selected on the basis of organism, and duration of treatment is usually 6 to 8 weeks.

The final scenario, a late infection with concomitant pseudarthrosis, is the most challenging to manage from both a surgical and an infectious disease standpoint. The metallic implants serve as foreign bodies where bacteria can flourish, while the instability of the nonunion often requires rigid structural support in the form of instrumentation. Treatment often requires meticulous debridement and irrigation followed by revision instrumentation. Management of the pseudarthrosis itself was covered in a previous section. Wound closure over drains and a prolonged course of intravenous antibiotics (based on culture sensitivity) are necessary. Occasionally, some patients who have had multiple infections require chronic suppressive antibiotic therapy.

Postoperative Management

In the postoperative period, the patient is cared for by a multidisciplinary team composed of the surgical team, medical consultant, nursing staff, rehabilitation staff, social worker, and appropriate ancillary consultations, including nutrition and pain management. Initial management includes maintenance of wound drains and chest tube, wound care, routine laboratory assessments, and intravenous fluid to support the patient until the return of bowel function and reinitiation of enteral nutrition. Parenteral perioperative antibiotics are given routinely for not less than 48 hours, and parenteral pain medications are provided until the patient is able to tolerate a solid diet. Orthoses (thoracolumbosacral orthosis) are routinely used in osteoporotic patients, those who have undergone osteotomies, and those for whom the surgeon wants to otherwise “protect” the internal fixation. Mobilization begins postoperative day number one and consists of “logroll” training and progression to ambulation as tolerated, as well as posture and balance training. Patients have daily dressing changes and wound checks and full bedside motor-sensory examinations. Oral nutrition is initiated with clear liquids on passage of flatus and is advanced as tolerated to full diet, complete with protein or other supplementation, as directed by the nutritionist. The patient meets with the social worker on a regular basis to determine the patient's needs, and when the multidisciplinary team thinks that the patient has made an adequate hospital convalescence, the team helps to arrange a fluid transition to home or a rehabilitation facility.

Complications

Adult deformity surgery has a late complication rate that has recently been estimated to be between 12% and 48%. Revision deformity surgeries that specifically require osteotomies have complication rates of 33% to 60%. Minor perioperative complications include deep venous thrombosis without embolus, urinary tract infection, superficial wound infection, dural tear and pneumonia without respiratory compromise, prolonged gastrointestinal dysfunction including ileus requiring nasogastric suction, and intravenous catheter infection. Major perioperative complications include deep wound infections, pneumonia, cardiovascular embarrassment, implant failure or dislodgement, pulmonary embolus, neurologic deficits, cauda equina syndrome or paralysis, and death. Late complications include deep wound infections (4%), pseudarthrosis (4% to 11%), junctional degeneration requiring revision, and instrumentation problems requiring a second procedure (12% to 15%). A comparison of complication rates between primary and revision adult deformity surgeries does not demonstrate significant differences, but revision patients did have significantly lower self–image, and patients who required revision for pseudarthrosis had lower SRS-24 total scores.

SUMMARY

Revision surgery in the adult deformity patient population is technically challenging and is associated with a high rate of complications. However, when properly performed, revision deformity surgery has a tremendous positive impact on the patient's quality of life. Surgical indications need to be clear, preoperative planning must be complete, and both patient and surgeon need to be aware of the goals of the intended surgery. Postoperative care is approached on a team basis with close coordination between orthopedic, rehabilitation, medical, social work, and other consultants.

PEARLS & PITFALLS

- Revision deformity surgery can be intellectually and technically very challenging. Use of a multidisciplinary team approach and proper education of the patient as to what to expect from the surgery are important factors to optimize success.
- Pseudarthrosis is the most common late complication of adult deformity surgery. Pseudarthroses correlate with poorer patient satisfaction, implant breakage and loosening, and perceived pain. Diagnosis can be made by static or dynamic radiographs, nuclear medicine bone scans, or three-dimensional imaging such as CT scans, but the "gold standard" is surgical exposure and assessment. Pseudarthroses must be debrided and stabilized and might require combined anterior and posterior fusions or osteotomies to restore sagittal and coronal balance in affected patients.
- Flat-back syndrome is often the result of distraction (Harrington) instrumentation and results in a posterior fusion with a relatively elongated posterior column. Forward trunk station, with resultant muscular back pain, and complaints of "falling forward" are very common. Surgical intervention involves shortening of the posterior column either by segmental Smith-Petersen osteotomies and compressive segmental instrumentation or by posterior closing-wedge osteotomies, including pedicle subtraction osteotomy and decancellation osteotomy. Smith-Petersen osteotomies can produce 5 to 10 degrees of correction per level, while decancellation osteotomy can produce 30 degrees of lordosis in a single level. Bleeding can be profuse in using the decancellation osteotomy, and the surgical team should be in constant coordination with their anesthesiologist to manage volume replacement intraoperatively and postoperatively.
- Coronal imbalance is often associated with rotational deformity and clinically with trunk shift. Radiographs should be analyzed to determine whether the imbalance is secondary to an angulation within the fusion mass (possibly requiring anterior osteotomies and revision posterior fusion) or outside of the fusion mass (possibly manageable with an extension posterior fusion).
- Junctional deformity (the adding-on phenomenon) is typically encountered when inappropriate fusion levels are chosen, and deformity occurs proximal or distal to a fusion. Typically, posterior-only fusions can be used to extend fusion from the existing fusion mass to stabilize and correct the added-on segments. Care must be taken to maintain coronal and sagittal balance.
- Adjacent segment degeneration is thought to be secondary to increased stresses transferred below and above the fusion mass. There is preliminary evidence to suggest that MRI assessments of discs below long fusions show signs of degeneration, but strict clinical correlation and alteration in outcomes are lacking. If preoperative studies demonstrate degeneration of segments below the planned lowest vertebra of a fusion, consideration of further degeneration at that level and inclusion of it into the index fusion should be made.
- Crankshaft deformity after posterior-only spinal fusions in young patients can be definitively avoided by performing combined anterior and PSFs. There is limited evidence to suggest that use of rigid segmental instrumentation with pedicle screws in posterior-only spine fusions could be able to overcome the crankshaft phenomenon in patients who have surgery prior to their peak growth velocity, but large studies have not yet validated this observation. Surgical goals are to arrest the deformity and to restore physiologic coronal and sagittal balance.
- Painful instrumentation is a diagnosis of exclusion and should be applied only after infection, pseudarthrosis, ongoing degeneration or stenosis, and other pain generators have been ruled out. Peri-implant injections of local anesthetics can help to confirm the diagnosis, as can tenderness to gentle palpation over prominent implants. Definitive treatment in the setting of a solid fusion is implant removal and otherwise requires revision of instrumentation.
- Infection must be treated aggressively in the postoperative setting. Early infections are managed with irrigation and debridement, implants being maintained if needed for stability or maintenance of deformity correction. Late infections can allow removal of implants if no pseudarthroses are present, but spinal stability must be maintained if the infection is to be definitively eradicated.

- Complication rates for revision deformity surgery range from 33% to 60%, and patients who require these surgeries tend to have more pain, lower SRS scores, and poorer self-image. Revision surgical outcomes can be good when care is taken to achieve sagittal balance and patient goals emphasize restoring function and limiting pain symptoms.

Illustrative Case Presentations

CASE 1. Pseudarthrosis

A 53-year-old woman presented with 1 year of back and bilateral leg pain. She had previously undergone posterior lumbar decompression and fusion along with combined anterior and posterior spine instrumented fusion from T12 to S1 and from L4 to S1, respectively, for spinal stenosis and scoliosis (Fig. 25-1A). Lumbar stiffness, first noted at 1 year from surgery, ultimately was diagnosed as an L3-4 pseudarthrosis (Fig. 25-1B), and the patient was counseled that revision surgery was necessary. Medical and anesthesia consults were obtained, and a full preoperative workup was completed.

At 3 years and 1 month after her index procedure, she returned to the operating room for exploration of the fusion mass and revision fusion. Because neither progressive nor significant deformity was present at the pseudarthrosis site, the decision was made that osteotomies would not be needed for the revision surgery. After removal of a portion of the instrumentation, an obvious pseudarthrosis was confirmed at L3-4. The pseudarthrosis site was debrided from the posterior exposure, and posterior elements were debrided of scar and soft tissue from L1 to S1, excluding the site of the prior decompression. A revision posterolateral spinal fusion with instrumentation was then performed from L1 to S1, with placement of pedicle screws from L1 to L4 and attachment to prior instrumentation to S1 (Fig. 25-1C). At this time, decortication of the bony fusion surfaces was completed, and these were packed with autogenous bone graft taken from the left iliac crest. To further increase the probability of fusion at the pseudarthrosis site, an EBI bone stimulator was also implanted, with electrodes applied to the posterolateral fusion graft. The patient had no adverse events postoperatively and was completely asymptomatic by 6 months postoperatively from the revision surgery. She underwent elective removal of the EBI stimulator 10 months following the revision surgery and remains symptom free 2 years after the first revision surgery.

CASE 2. Flat-Back Syndrome

A 34-year-old man presented with a 4- to 5-year history of progressively intense low back pain that interfered with his activities of daily living. He had undergone posterior spine fusion from T8 to L5 with Harrington instrumentation for scoliosis 18 years previously. Radiographs at presentation were notable for lumbar hypolordosis, measured to be 18 degrees (Fig. 25-2A). He was given the diagnosis of flat-back syndrome and was counseled that revision surgery was required to restore alignment and sagittal balance. Medical and anesthesia consults were obtained, and a full preoperative workup was completed.

Our surgical plan was to remove the Harrington instrumentation, explore the fusion mass, perform extension-producing osteotomies, and reinstrument with extension of the fusion mass to the pelvis. By utilizing the old scar and continuing distally, the spine was exposed from T8 to the sacrum posteriorly out to the transverse processes, Harrington instrumentation was identified, and the distal portion was removed. No pseudarthrosis was identified in the fusion mass. Pedicle screws were placed bilaterally at L1, L2, L4, and S1 and on the right at L5. An iliac screw was placed on the left side to augment the distal fixation. A posterior lumbar fusion was then completed at L5-S1 by using a carbon cage and local autograft bone. At this point, a posterior lumbar transpedicular decancellation closing-wedge osteotomy was performed at the L3 level, and the table was placed in extension to close the osteotomy site. The wound was irrigated, bony surfaces were prepared with a high-speed burr, and the remainder of the instrumentation was placed and tightened. A bone stimulator was placed just prior to closure, owing to the patient's preoperative history of smoking. His postoperative course was uneventful, and his lumbar spine was restored to 63 degrees of lordosis (Fig. 25-2B). He returned to the operating room 2.5 years later for removal of his bone stimulator. He remains without complaints 7.5 years after his index revision surgery.

CASE 3. Junctional Deformity

An 81-year-old woman presented with the complaint that she had pain and deformity in her upper back in the 8 months since her last surgery. She had had four spine surgeries in the past, beginning with two posterior lumbar decompression and fusion procedures. These did not control her mild scoliosis deformity (18 degrees), and lumbar deformity progressed postoperatively from the second procedure to 40 degrees. She was treated with staged posterior and anterior spinal fusions from T9 to S1 and from T12 to S1, respectively (Fig. 25-3A). Radiographs and a CT scan demonstrated T8 compression fracture and acute kyphosis proximal to the prior instrumented fusion (Fig. 25-3B). She was given the diagnosis of junctional deformity and counseled that she needed revision posterior spine fusion to extend the fusion to T2 and an extension osteotomy through the compression fracture to allow deformity correction.

She was evaluated by medical and anesthesiology consultants preoperatively, was cleared by both, and completed full preoperative surgical evaluation. Owing to the osteoporosis that was noted on her preoperative radiographs, a decision was made to use thoracic pedicle screws and to augment the fusion with OP-1 putty and other allograft extenders for the local bone graft. The spine was exposed from T2 to T11 out to the transverse processes, and prior instrumentation was visualized. Facetectomies were then performed from T2-3 down to T7-8, and pedicle screws were placed in the thoracic levels. The proximal extent of the prior instrumentation was loosened, and T9 pedicle screws were removed. T8 vertebral osteotomy was then performed. The wound was irrigated, and proximal rods were placed and connected to the distal rods by using parallel connectors (Fig. 25-3C). Bony surfaces were prepared for fusion with a high-speed burr, and a combination of OP-1 putty, local bone, and allograft was placed in the intended fusion bed. The wound was closed in layers over a drain. The patient tolerated the procedure well, had no immediate postoperative complications, and is without symptoms 3 months postoperatively.

CASE 4. Adjacent Segment Degeneration (Junctional Degeneration)

A 58-year-old woman presented with complaints of pain in her back for several years and new radicular pain in her right leg. She had undergone Harrington rod instrumented posterior spinal fusion from T6 to L3 for adolescent idiopathic scoliosis 15 years prior. She had had intermittent back pain since the time of the operation that was tolerable, but with the new leg pain, she sought medical attention. Radiographs at presentation demonstrated a fusion mass down to the L4 level and lateral listhesis of L4 on L5 of approximately 1.5 cm (Fig. 25-4A). A myelogram demonstrated central, lateral, and foraminal stenosis at the L4-5 level (Fig. 25-4B). She was given the diagnosis of distal junctional degeneration and associated spinal stenosis and was counseled that she would need revision surgery.

After preoperative assessment and clearances by internal medicine and anesthesiology, the patient submitted to anterior and posterior procedures under a single anesthesia. A thoracolumbar incision and a retroperitoneal dissection technique were used to expose the lumbar spine with the patient in a left lateral decubitus position. Segmental vessels were identified, dissected free, and ligated prior to performing complete discectomies at L4-5 and L5-S1. Allograft-filled titanium mesh Harms cages were then placed at each of these levels. The spontaneous ankylosis of L3-4 was then taken down, complete discectomy was performed, and the disc space was filled with allograft. Wounds were irrigated and closed in layers, and the patient was repositioned for the second procedure. Utilizing the prior posterior scar, the spine was exposed from the thoracolumbar spine to the sacrum out to the transverse processes. The Harrington instrumentation was identified, and the distal extent of this implant was removed. Pedicle and iliac screws were placed distally, and claw hooks were placed proximally. Laminectomy of L4 and extensive decompression of L4-5 was completed. Bony surfaces for fusion were prepared with a high-speed burr; bone graft was placed; and quarter-inch ISOLA rods were placed, connected to the other implants, and tightened (Fig. 25-4C). Wounds were irrigated and closed in layers. The patient tolerated the procedures well, had no immediate postoperative complications, and remains without complaints 2.5 years postoperatively.

CASE 5. Crankshaft Deformity

A 15-year-old boy presented with progressive spine deformity and difficulty breathing for the past few years. He was a full-term boy who was noted to have scoliosis early in life and had a poorly described muscular dystrophy diagnosed later in life. At the age of 8 years (Fig. 25-5A), he underwent posterior spine fusion for a 63-degree thoracic curve with Luque instrumentation. Five years later, he was treated for provisional diagnosis of the adding-on phenomenon (junctional deformity), and he underwent surgery for instrumentation removal and revision to control the proximal and distal deformities. At presentation, he had significant decompensation coronally, with a plumbline from the occiput 8 cm to the left of the gluteal fold, the T1 plumbline in midline, and the T8 plumbline 8 cm to the right of the gluteal fold. Radiographs that were brought with the patient demonstrated a 65-degree curve from T3 to L2 with Luque instrumentation in place (Fig. 25-5B), while current films showed this curve to be 100 degrees with an apparent solid posterior fusion (Fig. 25-5C). The clinical and radiographic findings were detailed to the patient and his parents, and the diagnosis and pathology of crankshaft deformity were explained. The opinion was given that optimal treatment would require revision surgery with osteotomies for deformity correction and fusion of the spine both anteriorly and posteriorly to prevent continued or recurrent curve progression.

The patient submitted to pediatric and anesthesia evaluations, pulmonary function testing, electrocardiography, and echocardiogram analysis. Pulmonary function tests revealed significant restrictive disease and a vital capacity of 26% of predicted. Electrocardiograms and echocardiograms demonstrated no change from prior examinations. Blood gas assessment was acceptable, with no evidence of retention of carbon dioxide. The patient and his parents were given informed consent documents with risks including but not limited to infection, pseudarthrosis, instrumentation-related problems, respiratory complications including tracheostomy, prolonged intubation and ventilator dependency, residual deformity, the possible need for multiple future surgical procedures, and death. He underwent combined anterior and posterior spinal fusion surgeries, including posterior osteotomies and posterior segmental instrumentation from T3 to L4 (Fig. 25-5D). He tolerated the procedure well and was discharged from the hospital to home on postoperative day 7. He has been followed by his local physician (the patient lives at quite a distance from our institution), has been doing well, and remains without complaints 5 years postoperatively.

CASE 6. Failed Implants

A 19-year-old woman presented with the complaint of back pain that she had been experiencing since being involved in a motor vehicle accident 2 years previously. She had suffered multiple injuries, including a lumbar spine fracture that was originally missed but several months later was treated with posterior spinal fusion from T10 to L4. Pain in the vicinity of the proximal extent of the implants, in addition to motion through the intended fusion segment with flexion and extension lateral views, led to the diagnosis of painful implants and implant failure (Fig. 25-6A). She was counseled that she required revision surgery to achieve bony stability of the injured portion of her spine and that this would require anterior and posterior spinal fusion procedures.

After preoperative assessment and clearances by internal medicine and anesthesia, the patient submitted to anterior and posterior procedures under a single anesthesia. The anterior procedure was performed through a thoracoabdominal retropleural and retroperitoneal approach to expose the T11-L4 disc spaces. Complete discectomies were performed, allograft was placed within the prepared disc spaces, and femoral ring structural allograft was used at the L3-4 interspace with a blocking screw. Wounds were irrigated and closed in layers, and the patient was repositioned for the second procedure. By utilizing the prior scar and continuing proximally and distally, exposure of the spine was completed out to the transverse processes. The prior instrumentation was removed, the fusion mass was explored, and pseudarthrosis was identified. Pedicle screws were placed proximally and distally, and the pseudarthrosis sites were debrided and prepared for revision fusion with a high-speed burr. The remainder of the T10-L4 fusion bed was also prepared with a high-speed burr; bone graft was placed; and quarter-inch ISOLA instrumentation was placed, connected to the pedicle screws, and tightened (Fig. 25-6B). Two sublaminar wires were placed proximally, and the wound was irrigated and closed in layers over a drain. The patient tolerated the procedure well, had no difficulties in the immediate postoperative period, and remains without complaints 9 years postoperatively.

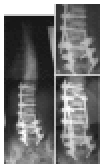


Figure 25-1 A 53-year-old woman presented with pseudarthrosis 3 years following anterior and posterior spinal arthrodesis for scoliosis. **A**, Preoperative anteroposterior full-length radiograph at presentation showing good coronal alignment. **B**, Preoperative anteroposterior close-up view at the L3-4 level illustrating transverse lucency of pseudarthrosis. **C**, Postoperative anteroposterior radiograph illustrating revision instrumentation and healing of pseudarthrosis.

Figure 25-2 A 34-year-old man presented with painful flat-back deformity 18 years after posterior spine fusion with Harrington instrumentation. **A**, Preoperative lateral full-length radiograph demonstrating loss of lumbar lordosis (L1-S1 measured 18 degrees by Cobb method). **B**, Postoperative lateral full-length radiograph demonstrating restoration of lumbar lordosis (L1-S1 measured 63 degrees by Cobb method) and sagittal alignment.

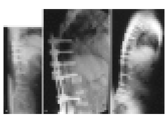


Figure 25-3 An 81-year-old woman with osteoporosis presented with compression fracture and junctional deformity 8 months following revision anterior and posterior surgery. **A**, Full-length lateral radiograph preceding compression fracture. **B**, Scout image from CT examination showing a compression fracture of T8 vertebral body. **C**, Postoperative lateral full-length radiograph illustrating deformity correction, restoration of sagittal balance, and revision instrumentation utilizing thoracic pedicle screws.

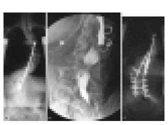


Figure 25-4 A 58-year-old woman presents with junctional degeneration at L4-5 15 years after long thoracolumbar fusion. **A**, Preoperative anteroposterior full-length radiograph at presentation showing listhesis and disc space narrowing at L4-5 and prior Harrington instrumentation. **B**, Preoperative myelogram image demonstrating central and foraminal stenosis at the L4-5 level. **C**, Postoperative anteroposterior full-length radiograph illustrating revision fusion and instrumentation connected to prior hardware and extending to pelvis. L4-5 laminectomy and bond canal decompression are not visible, owing to fusion mass and instrumentation.

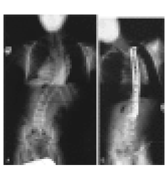
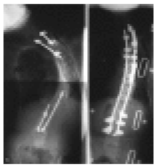


Figure 25-5 A 15-year-old boy presented with crankshaft phenomenon 7 years after index posterior spine fusion. **A**, Anteroposterior radiograph at age 8 years prior to any surgical intervention. The thoracic curve measured 63 degrees by the Cobb method. **B**, Anteroposterior radiograph at age 13 years prior to revision surgery for presumed adding-on phenomenon. With Luque instrumentation in place, the thoracic curve measured 65 degrees by the Cobb method. **C**, Anteroposterior radiograph at presentation demonstrating discontinuous compression and distraction instrumentation. The thoracic deformity has progressed in the interval to 100 degrees by the Cobb method. **D**, Postoperative anteroposterior full-length radiograph illustrating revision segmental instrumentation and restoration of



coronal balance. The thoracic curve measured 42 degrees by the Cobb method.

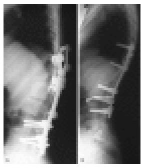


Figure 25-6 A 19-year-old woman presented 2 years after a car accident with failed instrumentation. **A**, Preoperative lateral radiograph illustrating proximal instrumentation disengagement from the posterior spinal elements. **B**, Postoperative lateral radiograph showing healed anterior and posterior fusion masses, corrected sagittal plane balance, and revision instrumentation with thoracic pedicle screws.

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Tveit P, Daggfeldt K, Hetland S, Thorstensson A: Erector spinae lever arm length variations with changes in spinal curvature. *Spine* 1994; 19:199-204.
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Yang SH, Chen PQ: Proximal kyphosis after short posterior fusion for thoracolumbar scoliosis. *Clin Orthop Relat Res* 2003.152-158.

SUGGESTED READINGS

Balderston RA, Albert TJ, McIntosh T, et al: Magnetic resonance imaging analysis of lumbar disc changes below scoliosis fusions: A prospective study. *Spine* 1998; 23:54-58.discussion 59.

Prospective study to evaluate the disks below long fusions for scoliosis terminating in the mid to lower lumbar spine, with outcomes of clinical pain symptoms and MRI grade of disc. At a 3-year follow-up from surgery, up to one third of patients demonstrated disc space narrowing and herniated discs one or two levels below their fusions, and up to 50% had decreased signal intensity on T2-weighted MRI. Patients with back or leg pain had worse imaging outcomes.

Boachie-Adjei O, Girardi FP: *Surgical treatment of rigid sagittal plane deformity*. In: Margulies YJ, ed. Spine State of the Art Reviews, 12. Philadelphia: Hanley and Belfus; 1998:65-72.

A review of the history of the eggshell procedure, indications for the osteotomy, surgical technique, and typical postoperative management of the patient.

Boachie-Adjei O, Girardi FP, Hall J: *Posterior lumbar decancellation osteotomy*. In: Margulies JY, Aebi M, Farcy J-PC, ed. *Revision Spine Surgery*, St. Louis: Mosby; 1999:568-575.

A review of the history of the decancellation osteotomy procedure, indications, preoperative planning, anesthesia, positioning, surgical technique, postoperative management, and complications.

Burton DC, Asher MA, Lai SM: Scoliosis correction maintenance in skeletally immature patients with idiopathic scoliosis: Is anterior fusion really necessary?. *Spine* 2000; 25:61-68.

Retrospective review of 18 Risser stage 0 patients, 7 with open triradiate cartilages, treated with isolated posterior fusion and assessed at follow-up for crankshaft phenomenon (progression of deformity of 10 degrees). One patient (with sublaminar wiring used as distal fixation) showed progressive deformity, but all others were controlled with segmental instrumentation. The authors suggest that anterior surgery can be avoided in young patients with the use of stiff segmental instrumentation constructs.

Buttermann GR, Glazer PA, Hu SS, Bradford DS: Revision of failed lumbar fusions: A comparison of anterior autograft and allograft. *Spine* 1997; 22:2748-2755.

Retrospective study of patients treated with revision anterior-posterior spinal fusion, stratified according to use of femoral ring allografts or tricortical iliac autografts. Although numbers were limited, patients who received allografts used less pain medication, showed greater functional improvement, and had improved patient-perceived "success."

Dubousset J, Herring JA, Shufflebarger H: The crankshaft phenomenon. *J Pediatr Orthop* 1989; 9:541-550.

A classic article describing the crankshaft phenomenon in 40 patients who received posterior spine fusions prior to Risser stage 1. Continued anterior growth of the spine was identified as a causative factor for the deformity, and anterior-posterior combined surgery in the younger patient population was suggested as a preventive measure.

Emami A, Deviren V, Berven S, et al: Outcome and complications of long fusions to the sacrum in adult spine deformity: Luque-Galveston, combined iliac and sacral screws, and sacral fixation. *Spine* 2002; 27:776-786.

A retrospective study comparing differing instrumentation techniques to the sacropelvis with radiographic, clinical, and Scoliosis Research Society outcomes assessed. Revision sugery was as safe as primary surgery but adversely affected self-image scores. Sagittal balance is a primary factor for success, and pelvic screws are recommended for long fusions unless anterior column support and triangulated screws are used at the lumbosacral junction.

Kim YJ, Bridwell KH, Lenke LG, et al: Pseudarthrosis in primary fusions for adult idiopathic scoliosis: Incidence, risk factors, and outcome analysis. *Spine* 2005; 30:468-474.

Retrospective study of primary surgery for adult idiopathic scoliosis to assess pseudarthrosis with radiologic and clinical outcomes. Pseudarthrosis rate was 17% and was more likely in patients older than 55 years, fusions of more than 12 segments, and fusions at the thoracolumbar junction, thoracolumbar kyphosis 20 degrees or greater being an independent negative predictor.

Lagrone MO, Bradford DS, Moe JH, et al: Treatment of symptomatic flatback after spinal fusion. *J Bone Joint Surg Am* 1988; 70:569-580.

A retrospective case series of patients treated with osteotomies for sagittal plane imbalance assessed for radiographic and clinical outcomes. Sixty percent of patients had complications, and 50% reported being satisfied. Pseudarthrosis correlated with failure to restore sagittal balance, and combined anterior-posterior revision surgeries resulted in better maintenance of correction.

Lapp MA, Bridwell KH, Lenke LG, et al: Long-term complications in adult spinal deformity patients having combined surgery: A comparison of primary to revision patients. *Spine* 2001; 26:973-983.

A minimum 2-year follow-up consecutive case series of anterior-posterior combined surgeries stratified by primary or revision status and assessed for complication and radiographic and clinical outcomes. Patients who underwent revision surgery had similar complication rates and better satisfaction but lower function scores postoperatively, possibly owing to relative preoperative debility.

Linville DA, Bridwell KH, Lenke LG, et al: Complications in the adult spinal deformity patient having combined surgery: Does revision increase the risk?. *Spine* 1999; 24:355-363.

A short-term follow-up (within 6 months of surgery) consecutive case series of anterior-posterior combined surgeries stratified by primary or revision status and assessed for major and minor complications. Complication rates were similar in the two groups. Nutrition appears to be important in preventing wound problems and infection, and the authors advocate total parenteral nutrition in patients who are thought to be at increased risk for wound problems.

Rinella A, Bridwell K, Kim Y, et al: Late complications of adult idiopathic scoliosis primary fusions to L4 and above: The effect of age and distal fusion level. *Spine* 2004; 29:318-325.

A retrospective study of adult idiopathic scoliosis stratified by age, lowest instrumented vertebra, complications, and clinical outcomes, including the Scoliosis Research Society questionnaire. Higher rates of transition syndrome were seen with LIV at L3-4 than in higher LIV levels, but there was no change in pseudarthrosis rate, and there was no change in complications with age; SRS scores were lower when pseudarthrosis or revision surgeries were required.

Sanders JO, Little DG, Richards BS: Prediction of the crankshaft phenomenon by peak height velocity. *Spine* 1997; 22:1352-1356.discussion 1356–1357.

A retrospective review of 40 patients who were managed with posterior spine fusion and Risser stage 0, stratified by open or closed triradiate cartilages and assessed for crankshaft deformity (10 degrees of progression) as an outcome. All patients with closed triradiates were beyond their peak height velocity, and only one of these patients demonstrated crankshafting. A recommendation was made for isolated posterior fusions to be performed after the peak height velocity has been reached.

Throckmorton TW, Hilibrand AS, Mencio GA, et al: The impact of adjacent level disc degeneration on health status outcomes following lumbar fusion. *Spine* 2003; 28:2546-2550.

A retrospective review of patients who received limited lumbar fusions, stratified by fusion ending adjacent to an MRI diagnosed “normal” or “degenerated” disk. Patients were evaluated at a minimum 2-year follow-up with the SF-36 instrument. The authors found no difference in any of the eight SF-36 subgroups in the patients who were fused adjacent to a “degenerated” disk.

Voos K, Boachie-Adjei O, Rawlins BA: Multiple vertebral osteotomies in the treatment of rigid adult spine deformities. *Spine* 2001; 26:526-533.

A retrospective review of patients undergoing revision deformity surgery including osteotomies, assessed by radiography, clinical evaulation, and Scoliosis Research Society questionnaires. Use of osteotomies carried a 33% complication rate but provided good correction, balance, and patient satisfaction.