Fixed Sagittal Plane Imbalance

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Abstract

Study Design   Literature review.

Objective   To discuss the evaluation and management of fixed sagittal plane imbalance.

Methods   A comprehensive literature review was performed on the preoperative evaluation of patients with sagittal plane malalignment, as well as the surgical strategies to address sagittal plane deformity.

Results   Sagittal plane imbalance is often caused by de novo scoliosis or iatrogenic flat back deformity. Understanding the etiology and magnitude of sagittal malalignment is crucial in realignment planning. Objective parameters have been developed to guide surgeons in determining how much correction is needed to achieve favorable outcomes. Currently, the goals of surgery are to restore a sagittal vertical axis < 5 cm, pelvic tilt < 20 degrees, and lumbar lordosis equal to pelvic incidence ± 9 degrees.

Conclusion   Sagittal plane malalignment is an increasingly recognized cause of pain and disability. Treatment of sagittal plane imbalance varies according to the etiology, location, and severity of the deformity. Fixed sagittal malalignment often requires complex reconstructive procedures that include osteotomy correction. Reestablishing harmonious spinopelvic alignment is associated with significant improvement in health-related quality-of-life outcome measures and patient satisfaction.

Keywords
► adult spinal deformity
► sagittal plane imbalance
► pedicle subtraction osteotomy

Introduction

Adult spinal deformity is a broad diagnostic classification that includes idiopathic scoliosis as well as de novo or degenerative curves, which often result in coronal and/or sagittal plane decompensation. Sagittal plane malalignment is an increasingly recognized cause of pain and disability.[1] Several recent studies have shown that positive sagittal plane imbalance is directly associated with decreased health-related quality-of-life (HRQOL) outcome scores,[2–4] and postoperative improvement in sagittal plane alignment has been shown to significantly improve patient outcomes.[2,5] Treatment of sagittal plane imbalance varies according to the etiology, location, and severity of the deformity.[1] Furthermore, fixed sagittal malalignment often requires complex reconstructive procedures that include osteotomies to adequately correct and restore global balance.

Understanding Normal Sagittal Alignment and Its Significance

Ideal spinal alignment allows an individual to assume standing posture with minimal muscular energy expenditure.[5] Normally, this is accomplished through a complex relationship that exists between the physiologic curvatures of the spine, the morphology of the pelvis, and the musculature of the axial and appendicular skeleton. The Dubousset cone of economy concept illustrates the importance of spinopelvic balance in maintaining an upright posture and minimizing energy expenditure with standing and walking (►**Fig. 1**).[5] Increasing positive sagittal imbalance causes the body to
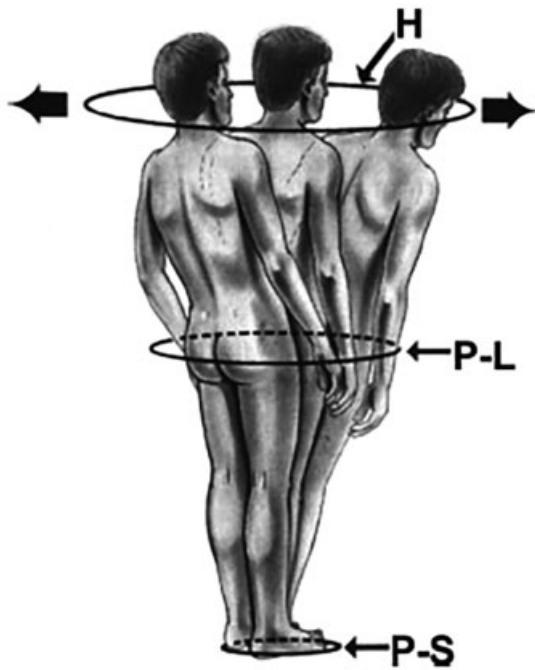
Fig. 1 Cone of economy. The figure outlines the "stable" zone surrounding the individual that is conical in shape from the feet to the head. Deviation from the center within the zone results in greater muscular effort and energy expenditure to maintain an upright posture. Deviation of the body outside the cone results in falling or requiring support. Abbreviations: H, head; P-L, pelvic level; P-S, polygon of sustentation. (Reprinted with permission from Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976) 2010;35(25):2224–2231.[5])

assume a position toward the periphery of the cone, which results in increased muscular effort and energy expenditure causing pain, fatigue, and disability.[5] If the body is shifted beyond the periphery of the cone, external supports such as a cane, crutch, or walker may be required to maintain balance.

Recently, the role of the pelvis in the complexity of human standing sagittal spinal alignment has been described.[6] Three pelvic parameters have been defined in the literature (►**Fig. 2A–C**).[7] Pelvic incidence (PI) is a constant morphologic parameter, which has been demonstrated to influence lumbar alignment and specifically the degree of lumbar lordosis (LL). In general, LL should approximately match PI (PI = LL ± 9 degrees). Pelvic tilt (PT) and sacral slope (SS) are dynamic pelvic parameters that measure pelvic version, a compensatory mechanism to help maintain an upright posture in the setting of sagittal malalignment. Hip extension and knee flexion are other compensatory mechanisms that result in the classic "crouched gait" often seen in these patients. Lafage et al have shown that positive sagittal plane imbalance and increased PT strongly correlate with poor HRQOL.[4] Failure to restore a sagittal vertical axis (SVA) of <50 mm and PT of <20 degrees in spinal fusion surgeries is associated with poor surgical outcomes.[4]

Clinical and Radiographic Evaluation

A detailed history should be obtained and a thorough physical examination should be performed in all patients with adult spinal deformity. Prior surgical procedures and a description of symptomatology must be documented. Patients with sagittal imbalance often complain of the inability to stand upright, with worsening pain and fatigue with increased activities. The level of disability and its effect on quality of life should be characterized and documented.
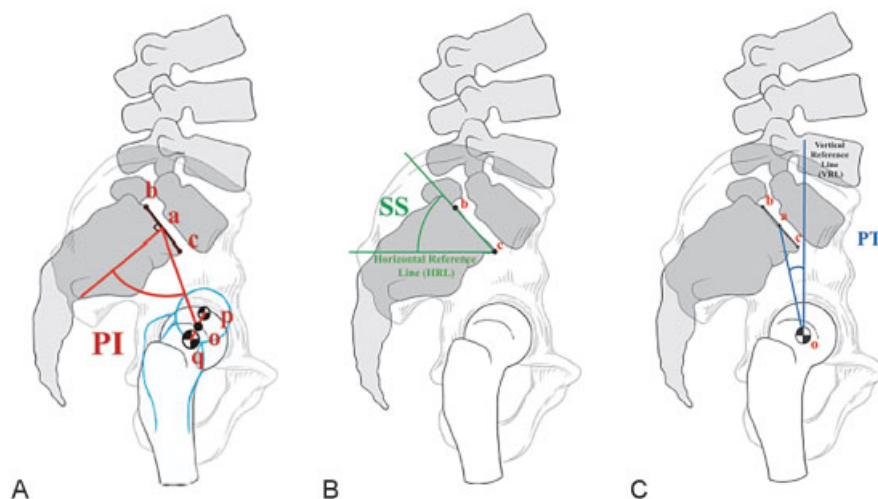

Fig. 2 (A) Pelvic incidence (PI) is defined as an angle subtended by line oa, which is drawn from the center of the femoral head to the midpoint of the sacral end plate and a line perpendicular to the center of the sacral end plate. (B) Sacral slope (SS) is defined as the angle subtended by a horizontal reference line (HRL) and the sacral end plate line (bc). (C) Pelvic tilt is defined as the angle subtended by a vertical reference line (VRL) originating from the center of the femoral head (o) and the pelvic radius (oa). It is positive when the hip axis lies in front of the middle of the sacral end plate. (Reprinted with permission from Labelle H, Roussouly P, Berthonnaud E, Dimnet J, O'Brien M. The importance of spino-pelvic balance in L5-S1 developmental spondylolisthesis: a review of pertinent radiologic measurements. Spine (Phila Pa 1976) 2005;30(6, Suppl):S27–S34.[7])

Evaluation of the patient's standing posture is critical, and compensatory mechanisms, such has hip extension and knee flexion, must be noted to accurately evaluate the severity of deformity. Patients should be evaluated for coronal and sagittal plane decompensation with the patient standing with hips and knees fully extended. A comprehensive neurologic exam must be performed, and any motor or sensory deficits documented.

Standard full-length 36-inch anteroposterior and lateral radiographs are the baseline imaging studies for the patient with adult spinal deformity. The patient must be positioned with the hips and knees extended to negate compensatory mechanisms. Horton et al reported that the clavicle position is the optimal patient stance for obtaining accurate and reproducible lateral scoliosis X-rays.[8] This is done with the elbows fully flexed and the wrists/hands placed in the supraclavicular fossa with no external supports.

Global sagittal alignment is assessed by a vertical line dropped from the center of the C7 vertebral body, termed the *C7 plumb line* or *sagittal vertebral axis* (SVA; ►Fig. 3). In the sagittally balanced spine, the SVA passes through the posterior superior corner of the S1 vertebral body. If it falls anteriorly or posteriorly, the sagittal balance is said to be positive or negative, respectively. An offset greater than 2.5 cm is considered abnormal.[9] Regional sagittal alignment is assessed by thoracic kyphosis (T5–T12, average: 41 ± 12), and LL (T12–S1, average: 60 ± 12; ►Fig. 4).[5]

Pelvic morphology and orientation are essential components of standing alignment. PI is an anatomic parameter that is both constant and specific to each individual and is independent of spatial orientation of the pelvis.[1] PI is defined as the angle between the perpendicular to the upper sacral end plate at its midpoint and the line connecting this point to the femoral head axis. PT is a compensatory mechanism that is often used to maintain upright posture in a patient with progressive sagittal plane deformity. It is defined by the angle between the vertical and the line through the midpoint of the sacral end plate to the femoral head axis. Finally, the SS is defined as the angle between the horizontal and the upper sacral end plate. $PI = PT + SS$, and the average values are $52 \pm 10, 15 \pm 7, 30 \pm 9$, respectively.[5] As PT increases (pelvic
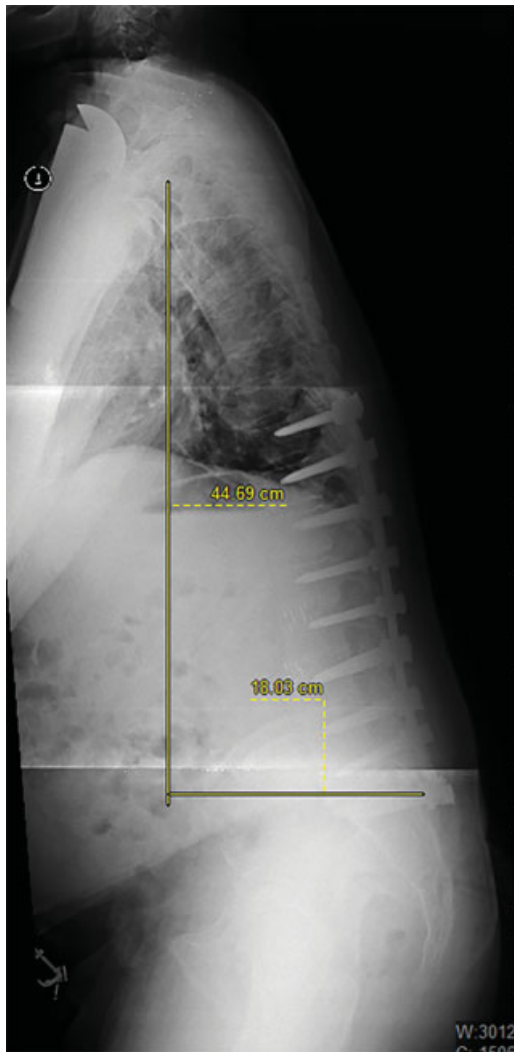

Fig. 3 Lateral scoliosis X-ray of a 72-year-old man after a T10–S1 posterior spinal fusion. The sagittal vertical axis (SVA) is defined as the horizontal offset from the posterosuperior corner of S1 to the vertebral midbody of C7 (C7 plumb line).
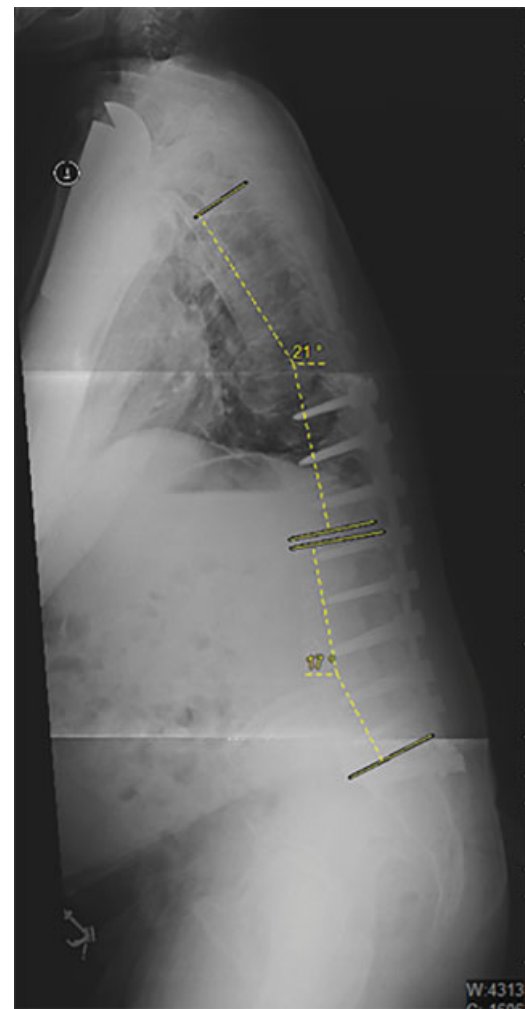

Fig. 4 Sagittal spinal radiographic parameters. Thoracic kyphosis measures from the superior end plate of T4 to the inferior end plate of T12. Lumbar lordosis measured from the superior end plate of L1 to the superior end plate of S1.

retroversion), the SS decreases and PI remains constant. Quantifying the degree of pelvic retroversion, a compensatory maneuver, is essential in understanding the severity of sagittal plane imbalance and plays a key role in determining the amount of correction needed in surgical reconstruction (►Fig. 5).

Advanced imaging studies can be used to better characterize the underlying pathology. Magnetic resonance imagining (MRI) can be used to evaluate neurologic compression. Computed tomography (CT) scans are often helpful for preoperative planning and for evaluating the presence of nonunion or pseudarthrosis. A CT myelogram can be useful especially in the setting of existing spinal instrumentation.

Finally, the flexibility of the sagittal plane deformity should be evaluated. This can be done with the use of supine X-rays with or without a bolster to assess for a change in the degree of LL due to positioning alone. MRI or CT can also be used to evaluate the status of the disk spaces and facet joints. Advanced degenerative changes on MRI or CT with evidence of ankylosis (facet fusion, bridging anterior osteophyte formation, circumferential fusion, among others) is associated with more rigid deformity, whereas anterior mobile disk spaces often allow for some flexibility with positioning and for anterior column lengthening with posterior column-based osteotomies. Surgical correction and technique are critically dependent on differentiating rigid from flexible deformities.

Etiology of Sagittal Malalignment

Adult spinal deformity with sagittal plane imbalance may result from iatrogenic causes or may be related to genetic or metabolic disease processes.[1] Fixed sagittal plane malalignment can be classified into primary or secondary causes.[10] The most common primary presentation is that of multilevel

Fig. 5 For a given structural deformity, how pelvic retroversion compensates for spinal deformity. Left: No pelvic retroversion and high sagittal vertical axis (SVA). Middle: Moderate pelvic retroversion and SVA. Right: High pelvic retroversion and no SVA. (Reprinted with permission from Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976) 2010;35 (25):2224–2231.[5])

disk degeneration, often with associated degenerative scoliosis. This often results in loss of anterior column height and flattening of normal LL. Secondary causes of sagittal plane deformity are usually iatrogenic in nature and are related to previous spinal fusion surgeries. Flat back syndrome has been attributed to the use of distraction instrumentation in the posterior column (i.e., Harrington rods) as well as to the use of compressive anterior instrumentation.[1,11–13] Failure to maintain or obtain adequate LL during lumbar spinal fusion surgery can also lead to iatrogenic flat back and sagittal plane malalignment. Other secondary causes include posttraumatic kyphosis or kyphosis that develops following spinal fusion surgery, which often progresses either through an area of pseudarthrosis or adjacent to a previous fusion.[1]

Nonsurgical Management

The treatment of patients with back pain and neurologic symptoms should not differ from that of patients without spinal deformity.[1] Nonsteroidal anti-inflammatory medications can be used to treat pain symptoms, and narcotics should be avoided. Physical therapy focusing on core and pelvic stabilization should be initiated, and the presence of hip or knee flexion contractures addressed. It is important to note that the utility of physical therapy in the treatment of adult spinal deformity has not been clarified in the literature.

Patients presenting with neurologic symptoms may benefit from injection therapy. Selective nerve root blocks and/or epidural steroid injections may be of value in the setting of radiculopathy or symptomatic neurogenic claudication.[14] Bracing has not been shown to be effective in the overall treatment of adult spinal deformity.[2] In general, symptomatic deformity is often unresponsive to nonsurgical treatment.[11,12] Farcy and Schwab reported an overall long-term success rate of only 27% with conservative treatment.[12]

Surgical Management

Preoperative Planning

A meticulous preoperative plan is essential to achieve predictable restoration of sagittal alignment and therefore good clinical outcomes. All patients should be initially evaluated with standing scoliosis (36-inch) X-rays with the knees and hips extended. The regional and global alignment must be measured, with specific attention paid toward SVA, thoracic kyphosis, and LL. Spinopelvic parameters should also be documented and the degree of compensation through PT noted. In the setting of previous spine surgery, a CT scan should be obtained to accurately evaluate for pseudarthrosis and appropriate positioning of the existing instrumentation. In the setting of previous spinal fusion, special attention must be paid to the status of the lumbosacral junction, as well as the most cephalad level in the previous construct. The presence of a pseudarthrosis at L5–S1 may dictate the use of iliac fixation in revision procedures. A supine lateral scoliosis X-ray with or without an extension bolster can be taken to assess the flexibility of the sagittal plane deformity. The realignment objectives to
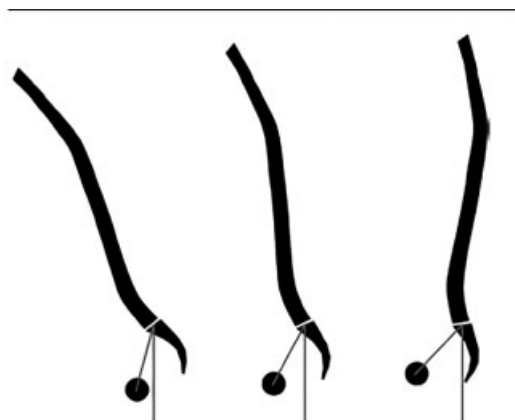
achieve "spinopelvic harmony" are an SVA < 5 cm, PT < 20 degrees, and LL = PI ± 9 degrees (►**Fig. 6**).[5] Preoperative hip flexion contractures should be corrected prior to spinal reconstruction, as this often significantly contributes to the overall malalignment.

Flexible deformities may be addressed through anterior or posterior spinal decompression/release with instrumentation. Fixed deformities require corrective osteotomies.

Calculating the Amount of Correction

Several methods have been described for calculating the amount of correction required for spinal deformity and malalignment. However, many of these methods are complex and difficult to implement in practice.

Ondra et al described a mathematical equation to help determine the degree of pedicle subtraction osteotomy (PSO) needed for correction of fixed sagittal plane deformity.[15] This technique utilizes a trigonometric formula based on the angle formed between the C7 plumb line and the posterior sacral perpendicular line. The authors found that this technique is reproducible and has led to successful clinical outcomes. This formula does not take into consideration spinopelvic parameters and therefore neglects to account for the compensatory mechanism of PT in calculating the overall malalignment. Using this formula alone will often result in undercorrection of the global deformity.

As a result, Lafage et al developed a predictive model for key spinopelvic parameters and found that using a morphologic pelvic parameter (PI) and spinal parameters modifiable through surgery (LL and thoracic kyphosis), postoperative sagittal alignment can be predicted.[16] It is now commonly accepted that the degree of lordosis required by an individual may be estimated with the formula LL = PI ± 9 degrees. Several computer-based programs are now available that use this predictive formula to aid in preoperative realignment planning.
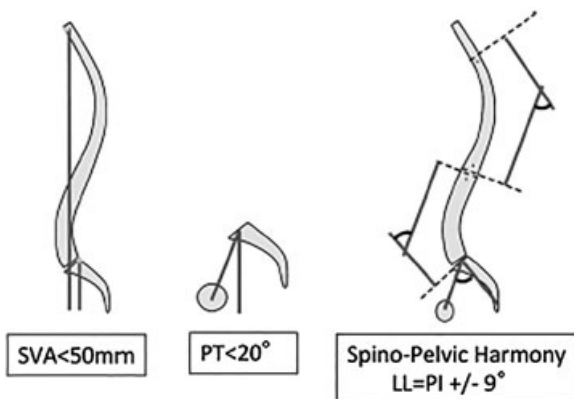

Fig. 6 Realignment objectives in the sagittal plane. Sagittal vertical axis (SVA) < 50 mm, pelvic tilt (PT) < 20 degrees, and lumbar lordosis (LL) = pelvic incidence (PI) ± 9 degrees. (Reprinted with permission from Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976) 2010;35(25):2224–2231.[5])

Special Instructions, Position, and Anesthesia

The patient is positioned prone on a radiolucent frame with four to six posts allowing the abdomen to be free of pressure. The patient is typically "built up" on a chest pad with the hips in maximum extension to render the lumbar spine as lordotic as possible. This can be achieved on a standard open Jackson table or a specialized osteotomy frame. In cases where there is a mobile anterior column, patients often obtain a reasonable degree of correction simply by proper positioning.

A Mayfield head holder or cranial tongs are often used to prevent any pressure on the eyes throughout the duration of the procedure. Intraoperative monitoring is used (somatosensory evoked potentials, motor evoked potentials, electromyography) to help recognize and prevent neurologic injury, especially at the time of osteotomy closure.

Type of Osteotomy

The choice of osteotomy depends on the goals of the procedure, the correction requirements, the underlying etiology of the deformity, the native bone quality of the patient, and the anatomic variations that may be present. Each type of osteotomy has specific advantages as well as inherent limitations. The different osteotomies can be used individually or in combination to achieve the desired correction.

Posterior column osteotomies (Smith Peterson or Ponte) offer up to 10 degrees of correction per level.[17] This can be performed at any level in the thoracolumbar spine and is the ideal osteotomy for mild to moderate deformities with mobile disk spaces anteriorly (►**Figs. 7A–D**). This osteotomy requires lengthening of the anterior column and therefore cannot be performed in the circumferentially fused spine. Posterior column osteotomies are powerful correction tools when performed over multiple levels in the presence of mobile disk spaces.

The PSO is a powerful technique that can reliably achieve 30 degrees of correction at a single level.[18] If the disk space above is included in the osteotomy, an additional 10 to 15 degrees of correction can be obtained. A closing three-column wedge osteotomy hinges on the anterior column and causes shortening/closing of the middle and posterior columns. PSO is a common means of correcting global fixed sagittal plane imbalance, especially in the circumferentially fused spine. Recent studies have shown that the level of PSO (L3 versus L4) does not affect the degree of correction; however, lower lumbar PSOs correlate with an increased correction in PT but not LL.[19]

A vertebral column resection is the removal of an entire segment (vertebral body and disk above/below) and provides profound correction, often up to 40 to 60 degrees from a single level.[20] A vertebral column resection is typically utilized to address focal and combined coronal and sagittal plane abnormalities. This is the most complex osteotomy to perform and is associated with significant morbidity and a high risk of complications.

Pedicle Subtraction Osteotomy Technique

After placing pedicle screws above and below the osteotomy level, the PSO begins with a pedicle preparatory hole. The amount of bone to be removed should be calculated to match
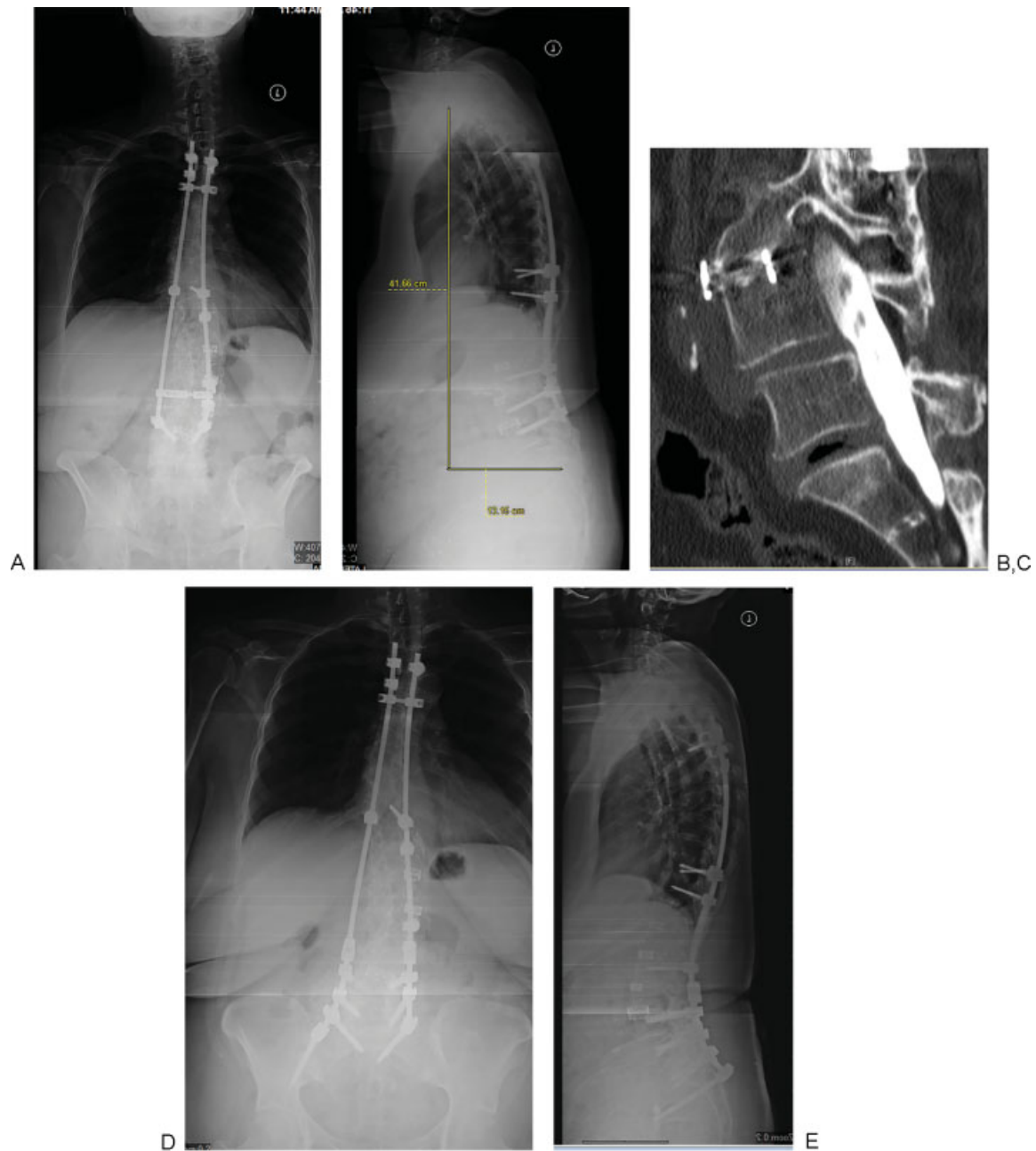
Fig. 7 (A–E) A case example. A 68-year-old woman after a T4–L4 posterior spinal fusion with multilevel interbody fusions for adult idiopathic scoliosis. She has adjacent segment degeneration at L4–L5 and sagittal plane imbalance. (B) The magnitude of the deformity (sagittal vertical axis [SVA] = 13 cm, pelvic incidence [PI] = 75 degrees, pelvic tilt [PT] = 40 degrees, and lumbar lordosis [LL] = 35 degrees). There is an L4–L5 degenerative spondylolisthesis with 15 degrees of focal kyphosis. (C) An "open disk space" at L4–L5 with advanced degenerative changes in the facet joints without ankylosis. An L4–L5 posterior column osteotomy and revision L4–sacrum with iliac fixation was performed. (E) Degree of correction and restoration of sagittal balance (SVA = 4 cm, PI = 75 degrees, PT = 25 degrees, and LL = 65 deg). The mobility of the L4–L5 disk space allowed for significant correction with the posterior column osteotomy (15 degrees of kyphosis to 25 degrees of lordosis = 40 degrees of correction).

the amount of closure needed. It should involve the superior and inferior facet of the osteotomy level, the inferior facet of the cephalad level, and the superior facet of the level below. The decompression should be bilateral from the pedicle above to the pedicle below, resulting in two nerve roots exiting a single neural foramen on each side. In the case of a prior posterior fusion mass, the fusion mass must be resected with osteotomes, rongeurs, and curettes, and bone is saved for later fusion.

The pedicle is then fully removed with a rongeur and/or bur. Care should be used to fully remove the pedicle base. Small spicules of bone can result in radiculopathy once the osteotomy is closed. In revision cases, it is also important to remove all scar tissue from the dura to avoid soft tissue crowding/buckling once closure has been done. Once the pedicle has been removed, the lateral vertebral body wall is dissected bilaterally. Penfield dissectors and elevators are

used, with the dissection from the level of the disk that immediately lies above the resected pedicle caudally as far as necessary. The body should be dissected all the way to the anterior vertebral body to get adequate exposure and resection.

The bone is removed with rongeurs and a bur, in a precise wedge based on the calculated degrees of closure. The apex of the wedge is at the anterior vertebral body wall. This wall should be preserved as a pivot point. The base of the osteotomy is the floor of the spinal canal. This is more easily done today with specialized vertebral body retractors to assist in exposure. The cancellous bone is then removed with curettes and rongeurs in a wedge-shaped fashion, matching the cuts on the lateral walls. Again, all bone is saved for later grafting. Drills can be used for final shaping. The final bone resected is the posterior vertebral body wall, or the floor of the spinal canal. The lateral edge can be removed with rongeurs. The final removal is an impaction technique into the vertebral body cavity created by the resection. This can be done with curettes or with specialized impactors.

It is important to place a temporary rod to maintain vertebral body orientation and prevent early collapse of the body when the posterior wall is removed. With all bone resected and the canal and root exit zones inspected for any tissue that could impinge on neurologic structures, the osteotomy is closed with gentle pressure by hand on the spine on each side of the osteotomy. Typically, very little compressive pressure is needed on the screws above and below the osteotomy. If a standard operating table is used, the patient's body can also be flexed. The closure is further completed with hyperlordosis of the rod in the area of the osteotomy and adding cantilever force. Final closure is performed by gentle rod compression.

Anteroposterior and lateral scoliosis radiographs are used to confirm osteotomy closure and ensure there is no translation (►**Figs. 8A–D**). The posterior elements should be completely or nearly completely closed and not translated. The lateral wall closure and the root exit zones are inspected, and the roots above and below the pedicle are now both contained in a single foramen.

Outcomes

The association between sagittal malalignment and poor HRQOL outcomes is well documented in the literature.[2–5] This includes the correlation between specific radiographic parameters and patient-reported pain and disability.[3–5] This information has led to the development of specific goals to achieve during realignment surgery. Schwab et al described the importance of achieving "harmonious spinopelvic re-alignment."[5] They found that HRQOL outcomes significantly improve when the global alignment is restored (SVA < 50 mm) and spinopelvic parameters are normalized (PT < 20 degrees, and LL = PI ± 9 degrees). Therefore, these three pragmatic parameters serve as "alignment objectives" when treating adult spinal deformity with sagittal plane imbalance.
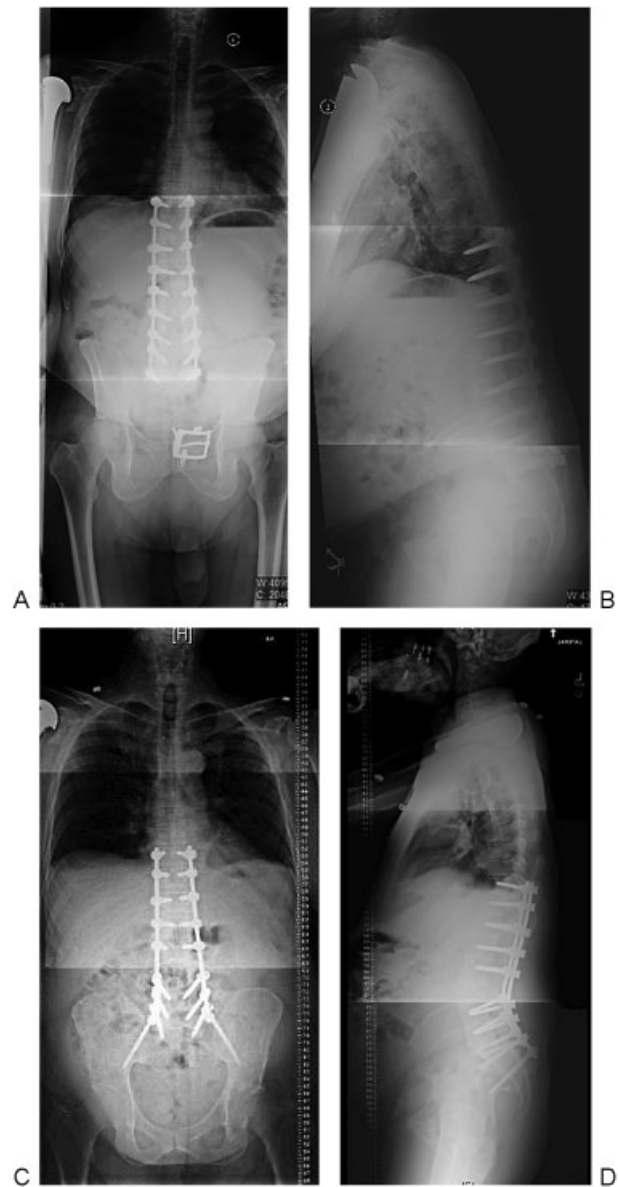

Fig. 8 (A–D) A case example. A 72-year-old man after a T10–S1 posterior spinal fusion with multilevel interbody fusions. He has iatrogenic flat back with sagittal plane deformity and disability. A computed tomography scan revealed a pseudarthrosis at L5–S1. (B) Sagittal malalignment pelvic incidence (PI) and lumbar lordosis (LL) mismatch and compensatory pelvic retroversion (sagittal vertical axis [SVA] 18 cm, PI = 60 degrees, pelvic tilt = 35 degrees, and LL = 17 degrees). An L3 pedicle subtraction osteotomy and revision T10-S1 posterior spinal fusion with iliac fixation was performed and 33 degrees of correction was obtained. (D) Improvement in lumbar lordosis (50 degrees) and overall sagittal alignment (SVA < 5 cm). The pelvic tilt remains elevated (25 degrees), indicating slight undercorrection.

The clinical and radiographic results of pedicle subtraction osteotomies for the treatment of fixed sagittal plane deformities are also well documented in the literature. Several authors have reported that the average correction obtained with a single-level PSO is ~30 degrees and is maintained over time.[21] Furthermore, the HRQOL scales, including the Oswestry Disability Index and Scoliosis Research Society outcome scores, are favorable after realignment surgery.[21–23]

Complications

The surgical management of patients with adult spinal deformity with sagittal plane imbalance poses great challenges to the surgeon and is fraught with complications. These patients often have significant medical comorbidities, and a multidisciplinary approach must be taken to optimize outcomes. The mortality rate after adult spinal deformity surgery is ~4%.[24] The overall complication rate has been reported to be as high as 37%, with a major complication rate of 20%.[25] Howe et al reported a 17% rate of postoperative neurologic deficit, and 35% of patients underwent at least one unplanned reoperation.[24] The reoperation rate after a three-column osteotomy (PSO) is ~19% and has been shown to significantly affect the 1-year HRQOL outcomes.[26] The incidence of radiographic proximal junctional kyphosis (PJK) after long fusions to the sacrum in adult spinal deformity has been reported to be 41%.[27] In this series, 13% of patients with PJK were treated surgically with proximal extension of the instrumented fusion. Achievement of "ideal global sagittal realignment" (SVA < 50 mm, PT < 20 degrees, and LL = PI ± 9 degrees) protected against the development of PJK.

Summary

Adult spinal deformity with sagittal plane imbalance is associated with poor HRQOL scores. A correlation exists between certain radiographic parameters and disability. Reestablishing harmonious spinopelvic alignment is associated with significant improvement in HRQOL outcome measures and patient satisfaction. Rigid deformities often require major reconstructive procedures, including osteotomies, to adequately restore acceptable sagittal plane alignment. Despite good clinical and radiographic outcomes, these procedures are fraught with complication.

Disclosures
Jason W. Savage, Consultant: Stryker Spine
Alpesh A. Patel, Board membership: CSRS, LSRS, IndoAmerican Spine Alliance; Consultant: Amedica, Biomet, Stryker, Depuy, Zimmer; Royalties: Amedica, Ulrich; Stock/stock options: Amedica, Nocimed, Vital5

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