Review Article

Scheuermann's Kyphosis: Diagnosis, Management, and Selecting Fusion Levels

Zeeshan M. Sardar, MD, MSc
Robert J. Ames, MD
Lawrence Lenke, MD

Abstract

Scheuermann's kyphosis (SK) is a rigid structural deformity of the thoracic spine defined radiographically as three or more contiguous vertebrae with at least 5° of wedging anteriorly. Prevalence of the disease is thought to be between 0.4% and 10%. The true cause of SK remains unclear; however, various theories include growth irregularities, mechanical factors, genetic factors, and/or poor bone quality as the causes. Patients with mild disease (less than 70°) generally have a favorable prognosis with good clinical outcomes. Most patients with SK are successfully treated nonsurgically with observation, anti-inflammatory medications, and physical therapy. Surgical intervention is indicated in patients with greater than 70° to 75° thoracic curves, greater than 25° to 30° thoracolumbar curves, intractable pain, neurologic deficit, cardiopulmonary compromise, or poor cosmesis. Because of advances in posterior spinal instrumentation, surgery can typically be performed through a posterior-only approach. When surgical treatment is planned, appropriate selection of the upper- and lower-instrumented vertebrae is important to achieve a well-balanced spine, preserve motion segments, and reduce the risk of junctional kyphosis.

From the Department of Orthopedic Surgery, Columbia University College of Physicians and Surgeons, New York, NY (Dr. Sardar and Dr. Lenke), and the Department of Orthopaedic Surgery and Sports Medicine, Lewis Katz School of Medicine, Temple University, Philadelphia, PA (Dr. Ames).

Correspondence to Dr. Sardar: zeeshan.sardar@hotmail.com

J Am Acad Orthop Surg 2018;00:1-11

DOI: 10.5435/JAAOS-D-17-00748

Scheuermann's kyphosis (SK) is a rigid spinal kyphosis affecting the mid-thoracic or thoracolumbar spine, which was first described by Holger Werfel Scheuermann in 1920.[1,2] The condition is associated with anterior wedging of the vertebrae, end plate irregularities, and Schmorl's nodes.[3] In 1964, Sorensen[4] was the first to define SK radiographically by the presence of at least three adjacent vertebrae wedged a minimum of 5°. Prevalence of the disease is thought to be between 0.4% and 10%,[4,5] affecting men and women equally.[6] The etiology of SK remains unclear; however, multiple theories have been proposed. Scheuermann[1] believed that osteonecrosis of the vertebral ring apophysis resulted in longitudinal growth arrest of the anterior vertebral body, thus causing a wedging of the vertebrae. Schmorl postulated that disk material herniated through the vertebral end plates lead to loss of disk height, vertebral body wedging, and node formation.[3] Both these early theories have since been called into question. Some authors noted a familial predilection for the disease, including a high rate of heritability and an autosomal dominant pattern, suggesting possible genetic causes.[4] Growth hormone abnormalities have also been implicated as a causative factor; however, the true cause of the disease remains unknown.

Classification

SK can be classified into two distinct groups: typical and atypical. In the more common typical SK, the apex of the deformity is usually in the mid-thoracic spine (T7-T9) and Sorensen's criteria (greater than three adjacent vertebrae wedged 5° or more) are met. In atypical SK, the apex of the deformity is frequently in the thoracolumbar or lumbar spine. Classic radiographic findings such as disk space narrowing, end plate changes, and Schmorl's nodes are still present, but Sorensen's criteria are not always met.[2]

Natural History

The natural history of SK tends to be benign. In patients with a smaller degree of kyphosis (less than 60°), good clinical outcomes can be expected.[6] Murray et al[6] followed 67 patients for 32 years. For patients with curves less than 85°, the authors found no differences in the number of days absent from work because of back pain, extent that the pain interfered with activities of daily living, self-consciousness, self-esteem, or level of recreational activities. Also, the patients reported little preoccupation with their physical appearance. Patients with SK had normal or above normal pulmonary function overall. Only in patients with severe kyphosis of greater than 100° was pulmonary function affected negatively. Patients with SK did report more spine tenderness and limited thoracic extension on physical examination. They also pursued jobs that required less strenuous physical activity. Ristolainen et al[7] investigated 19 untreated patients with mild thoracic SK, with a mean follow-up of 46 years. The authors found that the degree of radiographic deformity increased only slightly during long-term follow-up. Over the course of the study, the mean thoracic kyphosis increased from 46° (range, 25° to 78°) at baseline to 60° (range, 34° to 82°) ($P < 0.001$), and the mean of the vertebrae wedge angle increased from 8.8° to 9.9° at final follow-up ($P = 0.046$). No correlation existed between the extent of kyphosis progression and the function at final follow-up. In severe kyphosis, neurologic complications have been reported in a small number of patients.[8]

Nonsurgical Treatment

In contrast to idiopathic scoliosis, in which most surgeons agree on threshold ranges for surgical intervention, clinical equipoise still exists on when to intervene in SK. Conventionally, most clinicians have treated curves less than 50° to 80° nonsurgically.[9-11] Hard indications for surgical intervention are still being investigated in the literature.[9] There is a paucity of data to support bracing treatment of SK, and the effect of bracing treatment on the natural history and progression of disease remains unknown.[12,13] In addition, all available studies investigating bracing treatment in SK have been small, retrospective, and limited to level IV evidence. Criteria for bracing treatment include smaller and more flexible curves (ie, curves less than 55° to 80°, with passive correction of 40% or more). Some authors supported bracing treatment in immature patients, with the goal of vertebral body remodeling.[13,14] Brace wear is recommended for 16 to 23 hours per day until apical wedging is corrected. Riddle et al[14] reported that initial bracing treatment can achieve an almost 50% reduction in kyphosis in many patients, but some loss of correction occurred after termination of brace treatment. Another paper by Sachs et al reported on 120 patients with SK treated with a Milwaukee brace. Of the patients who were compliant with brace wear, 76 patients displayed improvement in their kyphosis, 10 were unchanged, and 24 demonstrated some worsening. Seven of the 24 patients who worsened went on to require surgical intervention.

Regardless of brace treatment, a formal exercise program that emphasizes thoracic extensor strengthening and endurance can be helpful. Weiss et al reported on long-term results of physical therapy, osteopathy, manual therapy, an exercise program, and psychological therapy for a group of 351 patients. At the end of the treatment regimen, male and female patients both reported a statistically significant reduction in pain.[15]

Surgical Management

Indications for surgical intervention include progressive kyphosis despite brace compliance, neurologic deficit, persistent pain, or notable deformity in a skeletally mature individual.

Dr. Lenke or an immediate family member has received IP royalties from Medtronic and Quality Medical Publishing; serves as a paid consultant to DePuy, K2M, and Medtronic; has received research and institutional support from AOSpine, Depuy, EOS, Scoliosis Research Society, and Setting Scoliosis Straight Foundation; has received nonincome support (such as equipment or services), commercially derived honoraria, or other non-research–related funding (such as paid travel) from Evans Family Donation-grateful patient-philanthropic support, Fox Family Foundation-philanthropic research funding from grateful patient, and Fox Rothschild, LLC-expert witness in a patent infringement case; and serves as a board member, owner, officer, or committee member of Global Spine Outreach and Orthopaedic Research and Education Foundation. Neither of the following authors nor any immediate family member has received anything of value from or has stock or stock options held in a commercial company or institution related directly or indirectly to the subject of this article: Dr. Sardar and Dr. Ames.

Measurements of 55° to 80° of kyphosis have been used as a threshold for surgical intervention; however, a hard curve magnitude threshold is not currently supported in the literature.[9,10] Polly et al[9] and the Spinal Deformity Study Group recently reviewed outcomes of 150 patients from various centers with SK treated surgically and nonsurgically. Their results confirmed the notable variability in treatment decisions among various surgeons. Mean curve magnitude in the surgical population was 73° versus 70° in the nonsurgical group. Maximal Cobb angle was not found to be a notable predictor for surgical intervention or patient-reported outcome scores. The authors did note that surgically managed patients were older, had more pain, had lower self-appearance scores, and had higher body mass index than those treated nonsurgically. Overall, the authors concluded that pain and patient dissatisfaction played important role in determining when to proceed with surgical intervention.

Surgical Approach and Technique

The surgical management of SK has evolved greatly over time, particularly with the advent of segmental spinal instrumentation and ultimately pedicle screw (PS)-based posterior-only approaches. Harrington compression instrumentation was initially used in the management of SK. Bradford et al[5] reported on 22 patients treated with this technique; the authors observed a notable loss of correction postoperatively. The reason for failure was likely because of the posterior-based tension-sided fusion and lack of anterior column support. The authors ultimately advocated for a combined staged AP approach to minimize this complication. In their next series, using anterior discectomies and interbody fusions through thoracotomy, only 5 of 24 patients experienced loss of correction of more than 10°.[11] Luque and Cotrel-dubousset instrumentation was also implemented historically in the management of SK. However, particularly high rates of junctional kyphosis plagued these techniques.[12,16]

Herndon et al[17] studied the results of a combined approach by evaluating 13 patients who underwent anterior release and fusion, followed by posterior fusion. The authors reported an average correction of 51° and that 12 of 13 patients had good pain relief. Lowe and Kasten[16] similarly noted good results in patients who underwent staged AP spinal fusion. Yang et al[18] showed 16 patients who underwent a similar AP approach to have had adequate initial correction and good maintenance of correction at follow-up. In one of the largest retrospective reviews of surgically treated SK, Lonner et al[10] noted a markedly higher overall complication rate with combined AP surgery compared with a posterior-only approach (23.8% versus 5.5%). Most of these complications were approach related (such as pneumothorax and pulmonary effusions) or related to the magnitude of the procedure; patients who underwent combined approaches had markedly greater preoperative Cobb angles.

In 39 well-matched patients, Lee and Lenke compared a combined AP versus a posterior-only approach using PS fixation with rods. The authors found that the posterior-only surgery provided superior results with regard to surgical time, blood loss, and overall complication rate (0.00% versus 38%). Equivalent results in terms of kyphosis correction and SRS-30 outcome measures were reported. Koptan et al[19] also reported on PS-only techniques; the authors compared a PS-only approach with a hybrid construct using hooks, PSs, and sublaminar wires. Although this was a relatively small series of 33 subjects, they found that patients treated with PS only had greater percentage correction, less loss of correction, and statistically significant decrease in estimated blood loss and surgical time.

In a more recent report, Koller et al[20] investigated a combined AP versus a posterior-only approach in 92 well-matched patients. The authors primarily investigated radiographic parameters and found that AP and posterior-only approaches both averaged similar degrees of final correction. The authors concluded that satisfactory clinical results can be obtained with either procedure; however, in select patients with severe deformity, posterior-based three-column osteotomies may be required to achieve adequate correction if the surgeon chooses a posterior-only approach. Therefore, the morbidity of these osteotomies should be balanced against the potential complications associated with anterior releases. Ponte and Shufflebarger also investigated a posterior-only surgical approach. The authors argued against the need for anterior releases and that successful outcomes can be obtained with a posterior-only approach using primarily PS anchors and posterior column osteotomies. Seventeen patients were treated with the procedure, with a mean correction of 9.3° per osteotomy site and an overall correction of 49%. They reported only two minor complications.[21]

In our practice, multilevel posterior column osteotomies (Schwab type 2 or Ponte Osteotomies)[22] generally are used across the apex of the deformity to improve spinal flexibility before correction; these osteotomies can afford approximately 5° to 10° of correction per level.[23] For sharp angular and more rigid curves, advanced three-column osteotomy

Figure 1

Case 1: 18-year-old male patient with thoracic kyphosis that is accentuated by bending forward.

techniques with higher grades of resection may be required; these osteotomies involve resecting the pedicles (Pedicle Subtraction Osteotomy, Schwab types 3 to 4) and/or parts of the vertebral body along with the adjacent disks (Vertebral Column Resection, Schwab types 5 to 6).[20] The sagittal deformity angular ratio (DAR) is the maximum kyphotic angle divided by the number of vertebral levels involved.[24] The DAR can be used to differentiate a sharp angular kyphosis from a smooth kyphosis that is spread over multiple levels and can help determine the potential need for advanced osteotomies. A patient with a high DAR may be better served with a three-column spine shortening osteotomy than with posterior column osteotomies. The DAR also strongly correlates with the risk of intraoperative spinal cord monitoring alerts, with up to 75% incidence of a motor-evoked potential alert for a sagittal DAR greater than 22°.[24]

In terms of implant choice, an overall lack of consensus exists in the literature. Number and type of fixation points, rod material and its diameter, and the most appropriate corrective techniques are all areas of debate. Some authors recommend a minimum of eight fixation points above and below the apex of the kyphotic deformity.[19] We recommend cobalt chromium or stainless steel rods measuring at least 6.0 mm in diameter. Smaller, less rigid rods have a tendency to loose correction over time in patients with kyphosis. However, in general, the use of larger and stiffer implants should be balanced against the potential risk of junctional kyphosis.

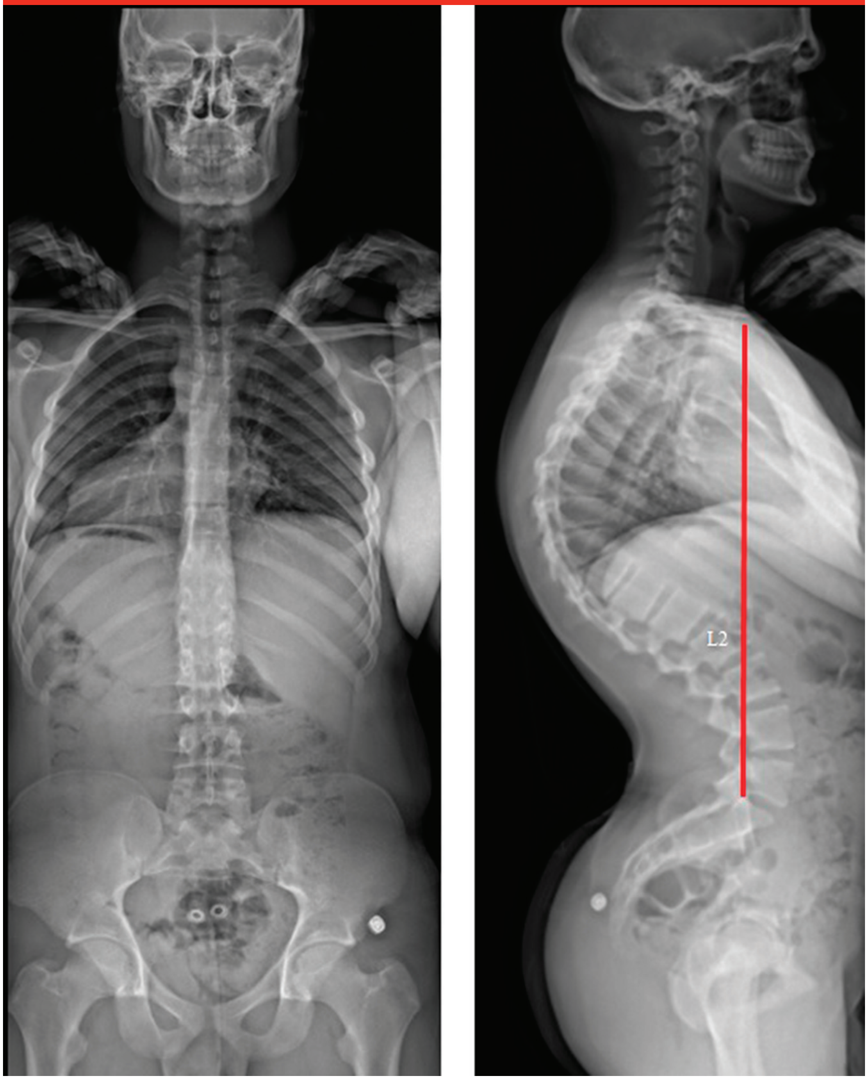
Level Selection and Junctional Kyphosis

No matter the technique implemented, junctional kyphosis has been a major issue for surgeons treating SK and has been reported in multiple series.[11,25,26] Reinhardt and Bassett reported a 40% rate of junctional loss of correction between the fused and unfused segments. Lowe and Kasten[16] also noted an incidence between 20% and 30%. In their series, proximal junctional kyphosis (PJK) was found to be related to obtaining greater than 50% correction at the time of surgery. The authors also noted that overcorrection and PJK can be avoided if the postoperative kyphosis remains greater than 40°. More recently, Lonner et al reviewed 78 patients treated with either combined AP or posterior-only spinal fusions. The authors noted a 32% rate of PJK and a 5.1% rate of distal junctional kyphosis (DJK).[10] Junctional kyphosis was defined as a Cobb measurement of greater than 10° between the fused and unfused segments. Other authors reported DJK in up to 28% of patients.[27] In Lonner's report, a larger magnitude of kyphosis both before surgery and at final follow-up tended to be associated with the development of PJK. PJK was also found to be directly correlated with the magnitude of pelvic incidence, that is, the greater the pelvic incidence for the individual, the higher the magnitude of PJK. Importantly, patients who were fused at or proximal to the Cobb end vertebra were markedly less likely to develop PJK.

Various techniques have been recommended to avoid junctional problems. Proximally, a general consensus exists in recommending the inclusion of the proximal end vertebra in the construct.[27] However, some surgeons argue that the construct should extend to one neutral vertebra above the end Cobb vertebra. Careful analysis of preoperative radiographs and diligent surgical planning are critical to ensuring the surgeon is selecting the appropriate level. It is important to obtain high-quality upright and hyperextension radiographs, and close attention should be given to the upper end of the intended construct.

In addition to appropriate level selection, other techniques have been used to avoid PJK. It is paramount to ensure appropriate maintenance of the facet joints, soft tissue, and ligamentous structures between the fused and unfused segments. It is important to preserve the interspinous ligament between the fused and unfused segments. Denis et al[27] pointed to disruption of the junctional ligamentum flavum (in addition to other factors) as a possible cause of PJK in their series. Some have advocated for a "soft landing" with hooks or wires at the top of the PS construct or ligament augmentation with tape or allograft. Biomechanical studies also confirmed a more gradual transition to normal motion when hooks, ligament augmentation, or tethers are used.[28] Hassanzadeh et al[29] compared hooks with PSs at the upper instrumented vertebra (UIV) in adults treated with long posterior spinal fusion. PJK did not develop in any of the patients treated with hooks versus 29.6% of patients in the PS group, and patients with hooks were noted to have markedly

Figure 2



Case 1: Radiographs showing thoracic kyphosis measuring 90°. L2 is the sagittal stable vertebra as it is the most proximal vertebra touched by the posterior sacral vertical line (red line).

Figure 3

Case 1: Postoperative radiographs showing instrumentation from T2 to L2, with kyphosis measuring 50°.

higher SRS-22 functional scores at final follow-up. In adolescent idiopathic scoliosis (AIS), using hooks at the top of the construct has been shown to reduce the rate of PJK as well.[30] However, in Lonner's SK series, proximal anchor type (screw versus hook) had no effect on the development of PJK.[10] Last, the use of transition rods may potentially transmit stress more gradually between the fused and unfused segments.[31]

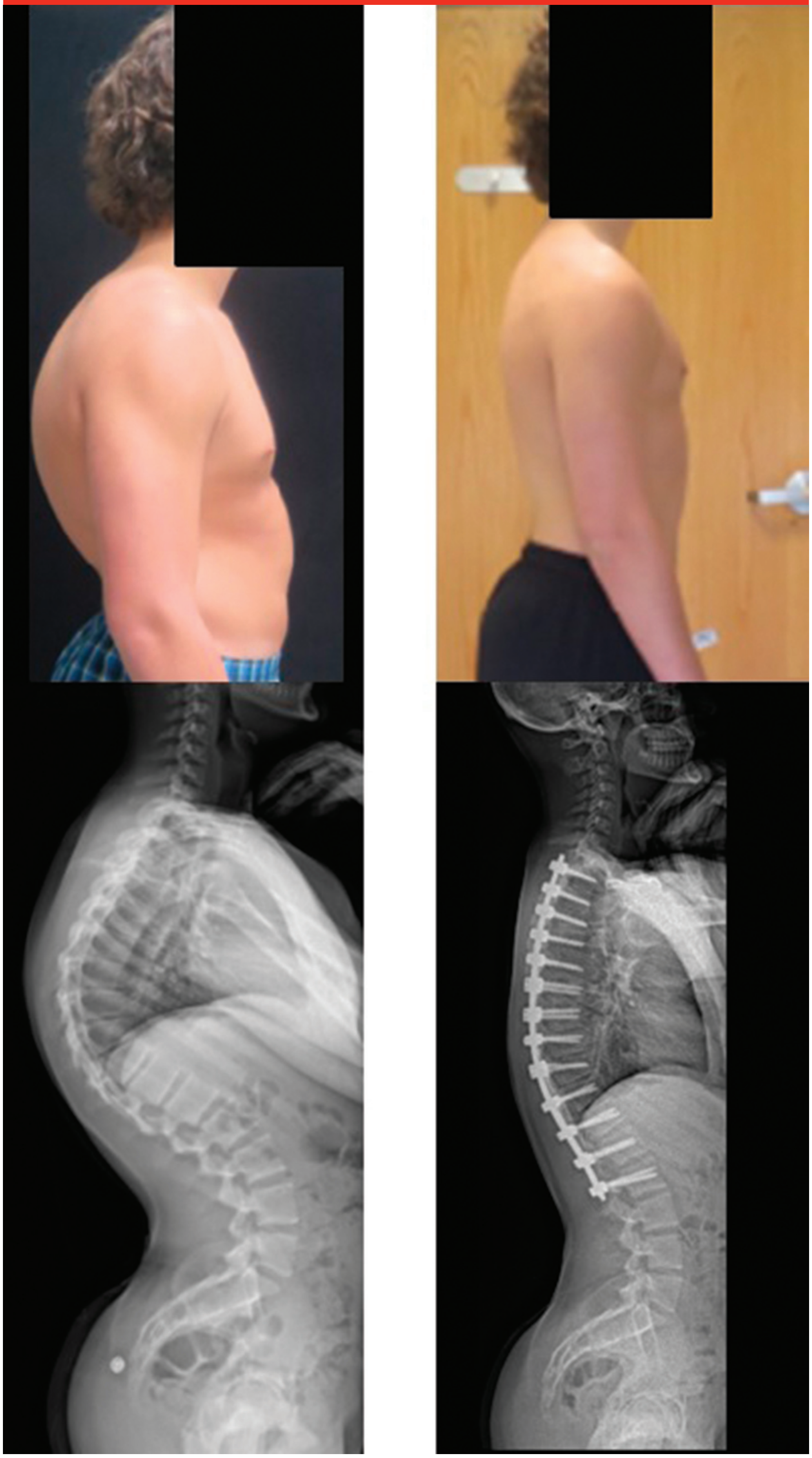
Both Koller et al and Lonner et al noted a relationship between global spinopelvic morphology and PJK.[10,32] Their data showed that among patients in whom junctional kyphosis had developed, increasing pelvic incidence correlated with increasing magnitude of PJK.[15] In addition, Lowe and Kasten[16] found that patients with SK tend to be in negative sagittal balance, and this may become further negative with surgery, particularly if the patient is overcorrected, thus predisposing them to junctional kyphosis. Although further research is needed in this area, restoration of proper sagittal alignment and global spinopelvic alignment is paramount to ensuring good clinical outcomes. Overcorrection of the kyphotic deformity should be avoided in general, and particularly in the setting of high pelvic incidence; the unfused spinal segments may not be able to adjust for postoperative changes to achieve appropriate overall alignment.[32]

Until recently, the most appropriate lowest instrumented vertebra (LIV) was thought to be the level below the first lordotic disk (FLD).[16,33] The FLD is defined as the most proximal thoracolumbar or lumbar disk below the level of the kyphosis with ≥5° of anterior opening. Because of hyperlordosis in the lumbar spine in patients with SK, determining the FLD can sometimes be difficult, thus leading to fusion short of the true FLD and subsequent DJK. Cho et al[34] reported on using the sagittal stable vertebra (SSV) instead of the FLD. The stable vertebra is defined as the most proximal touched vertebra by the posterior sacral vertical line. The authors noted a markedly decreased incidence of DJK (4% versus 71%) compared with patients whose constructs ended at the FLD (which typically is more proximal than the SSV). However, it is important to note that patients in this series were treated with hook instrumentation at the LIV, which may be an independent risk factor for DJK.[27] This may explain the high incidence of DJK in their patients fused to the FLD. In an attempt to avoid screw pullout and subsequent DJK, many surgeons now opt for longer PSs at the LIV to obtain maximum vertebral body purchase and fixation into the anterior column.

Using a PS-only posterior construct, Kim et al[35] investigated the incidence of DJK in patients who were fused at or below the SSV versus above the SSV. Patients who were fused at or below the SSV were found to have markedly greater lordotic disk angles below the LIV and lower revision surgery rates for DJK (5% versus 36.3%). The authors concluded that the SSV method may reduce complications secondary to DJK, such as screw pullout, loss of fixation, and/or sagittal decompensation, but at the expense of incorporating additional motion segments, which can be worrisome, especially in a relatively young patient population. Conversely, Yanik et al[36] found no difference in the incidence of DJK in patients based on LIV choice. Patients who were instrumented to the SSV and the FLD had similar radiographic measurements and clinical outcome scores at most recent follow-up. The authors concluded that it is not necessary to extend the fusion down to the SSV, thus sparing motion levels.

Based on our experience, we recommend using the SSV concept for distal level selection. If the selected SSV is just barely touched by the sacral vertical line, the adjacent disk space should be evaluated further. If the proximal disk space is lordotic, the "barely touched" SSV is still a safe choice. After the distal fusion level is selected, we recommend maintaining symmetry of the construct overall. The fusion should extend roughly the same extent from the apex proximally and distally, with some consideration for adding one additional proximal fusion level to ensure that the proximal end vertebra is also included in the fusion construct. For example, if the SSV is L2 and the apex of the kyphosis on upright radiograph is T8, the construct should start at the level of T2.[37]

Figure 4



Case 1: Comparison of pre- and postoperative clinical images and radiographs.

Complications

In a retrospective review, 693 surgically treated patients with SK were evaluated through the Scoliosis Research Society morbidity and mortality database.[38] The investigators reported an overall complication rate of 14%. Complications were markedly more common in adult patients. The overall incidences

Figure 5

Case 2: Radiographs showing thoracic kyphosis measuring 82°. L1 is just touched by the posterior sacral vertical line (red line).

of complications associated with the posterior, anterior, and same-day AP procedures were 14.8%, 4.1%, and 16.9%, respectively. These data are in stark contrast to the paper by Lee et al[39] in which the posterior spinal fusion-alone group displayed a markedly lower complication rate compared with the patients in combined AP approach (0.00% versus 38%). The most common complication in the Scoliosis Research Society (SRS) study was wound infection at 3.8%. Acute neurologic complication rate was 1.9%, which included four documented spinal cord injuries (0.6%), one of which was complete (0.15%). Four patients (0.6%) died of surgical complications, including sepsis, pulmonary embolism, and cardiorespiratory failure. More recently, Lonner et al[40] reviewed data from the Harms Study Group. The authors reported a 16.3% major complication rate in SK, with a revision surgery rate of 14.4%. Again, the most common complication was wound infection (10.3%), followed by instrumentation-related complication (3.1%) and neurologic complications (2.1%).

Intraoperative Neuromonitoring

Intraoperative neuromonitoring (IONM) has become increasingly prevalent in spinal deformity surgery over the past several decades, and multimodal monitoring should be implemented during surgical correction of SK. Cheh et al[41] reported on loss of IONM signals in 42 pediatric patietns with kyphosis treated with posterior column osteotomies and fusion. Fourteen patients in their cohort carried a diagnosis of SK, of which five had a true positive loss of IONM signals. Signals returned in all five patients after partial or complete release of correction and optimization of blood pressure. No patient sustained a neurologic deficit. Kundnani et al[42] reported a sensitivity of 100%, a specificity of 98.5%, and a positive predictive value of 85% when multimodality neuromonitoring was used for the surgical management of AIS. Buckwalter et al investigated IONM in a large cohort of patients with idiopathic scoliosis. They reported a positive IONM alert incidence of 3.6%, with 0.3% of patients waking up with a deficit. In another more recent paper, Samdani et al[43] reviewed 676 patients with AIS treated with spinal fusion. Overall, 5.3% of their cohort experienced an IONM alert. Importantly, no three-column osteotomies were performed in this cohort. Overall, there is a paucity of data on spinal cord neuromonitoring in SK, and its specific use in the management of this disease is an area in need of further investigation.

Case Examples

Case 1

An 18-year-old male patient presented with severe kyphosis and moderate apical thoracic back pain. His physical examination revealed thoracic kyphosis that was accentuated by bending forward (Figure 1). Radiographs confirmed a diagnosis of thoracic Scheuermann's kyphosis measuring 90° from T3 to T12 with apex at T9 to T10 (Figure 2). Posterior spinal instrumentation and fusion from T2 to L2 was planned. Including the first distal lordotic disk in the fusion would lead to choosing L1 as the LIV. However, L2 was found to be the SSV (Figure 2) and was therefore selected as the LIV. While the upper end vertebra for the kyphosis was T3, the UIV was selected as T2 to include the proximal FLD in the construct. Multiple posterior column osteotomies were used intra-op from T6 to T12. After placing the PSs, 6.0 mm cobalt chrome alloy rods were engaged into the proximal screws and a cantilever maneuver was used to reduce the rods into the distal screws. Postoperative thoracic kyphosis measured 50° (Figures 3 and 4).

Case 2

A 17-year-old male patient presented with gradually progressive thoracic kyphosis and mild back pain. Imaging revealed a Scheuermann's 82° kyphosis from T3 to T12 with a more proximal apex at T7 to T8 (Figure 5). Posterior spinal instrumentation and fusion from T2 to L1 was performed. The SSV, L1, was just barely touched by the posterior sacral vertical line. A closer look at the imaging revealed that the T12-L1 disk was lordotic; therefore, L1 was chosen as the appropriate LIV. The UIV was selected as T2 to maintain a symmetrical fusion from the apex and to include the proximal FLD in the construct. Posterior column osteotomies were performed from T5 to T11. The intraoperative correction maneuver performed was similar to that in case 1 to yield a postoperative kyphosis of 45° (Figure 6).

Figure 6

Case 2: Postoperative radiographs showing instrumentation from T2 to L1, with kyphosis measuring 45°.

Summary

Surgical intervention in SK is indicated in patients with deformity greater than 70° to 75°, intractable pain, neurologic deficit, cardiopulmonary compromise, or poor cosmesis. Thanks to advances in posterior spinal instrumentation, surgery is now typically able to be performed through a posterior-only approach. However, junctional kyphosis remains a challenging problem. It is paramount to ensure appropriate maintenance of facet joints and soft tissue and ligamentous structures between the fused and unfused segments. It is also recommended to limit correction to 50% or less of the original deformity. Although some controversy remains regarding fusion level selection, most surgeons agree that the construct should be symmetrical from the apex of the kyphosis and include the end Cobb vertebra proximally. Distally, some authors maintain that the LIV should be the level below the FLD, whereas others argue that the construct should extend further to the SSV. Instrumenting to the SSV may markedly reduce the incidence of distal junctional failure while typically incorporating just one additional motion segment into the fusion.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 6, 9, 10, 19, 20, 26, 29, 30, 34-36, 39 are level III studies. References 1, 2, 5, 7, 8, 11, 14-16, 18, 21, 23-25, 27, 32, 33, 38, 40-42 are level IV studies. References 3, 17, 22 are level V expert opinion.

References printed in **bold type** are those published within the past 5 years.

1. Scheuermann H: Kyfosis dorsalis juvenilis. *Ugeskr Laeger* 1920;82:385-393.
2. Blumenthal SL, Roach J, Herring JA: Lumbar Scheuermann's. A clinical series and classification. *Spine (Phila Pa 1976)* 1987;12:929-932.
3. Schmol G: Die pathologenese der juvenile kyphose. *Fortschr Ger Roentgen* 1930;41: 359-383.
4. Sorensen K: *Scheuermann's Juvenile Kyphosis: Clinical Appearances, Radiography, Aetiology, and Prognosis*. Copenhagen, Denmark, Munksgaard, 1964.
5. Bradford DS, Moe JH, Montalvo FJ, Winter RB: Scheuermann's kyphosis: Results of surgical treatment by posterior spine arthrodesis in twenty-two patients. *J Bone Joint Surg Am* 1975;57:439-448.
6. Murray PM, Weinstein SL, Spratt KF: The natural history and long-term follow-up of Scheuermann kyphosis. *J Bone Joint Surg Am* 1993;75:236-248.
7. **Ristolainen L, Kettunen JA, Kujala UM, Heinonen A, Schlenzka D: Progression of untreated mild thoracic Scheuermann's kyphosis: radiographic and functional assessment after mean follow-up of 46 years. *J Orthop Sci* 2017;22:652-657.**
8. Bradford DS, Garica A: Neurological complications in Scheuermann's disease: A case report and review of the literature. *J Bone Joint Surg Am* 1969;51:567-572.
9. **Polly DW Jr, Ledonio CG, Diamond B, et al: What are the indications for spinal fusion surgery in scheuermann kyphosis? *J Pediatr Orthop* 2017; Jan 30 [Epub ahead of print].**
10. Lonner BS, Newton P, Betz R, et al: Operative management of Scheuermann's kyphosis in 78 patients: Radiographic outcomes, complications, and technique. *Spine (Phila Pa 1976)* 2007;32:2644-2652.
11. Bradford DS, Ahmed KB, Moe JH, Winter RB, Lonstein JE: The surgical management of patients with Scheuermann's disease: A review of twenty-four cases managed by combined anterior and posterior spine fusion. *J Bone Joint Surg Am* 1980;62: 705-712.
12. Wenger DR, Frick SL: Scheuermann kyphosis. *Spine (Phila Pa 1976)* 1999;24: 2630-2639.
13. Lowe TG, Line BG: Evidence based medicine: Analysis of scheuermann kyphosis. *Spine (Phila Pa 1976)* 2007; 32(19 suppl):S115-S119.
14. Riddle EC, Bowen JR, Shah SA, Moran EF, Lawall H Jr: The duPont kyphosis brace for the treatment of adolescent Scheuermann kyphosis. *J South Orthop Assoc* 2003;12:135-140.
15. Weiss HR, Dieckmann J, Gerner HJ: Effect of intensive rehabilitation on pain in patients with Scheuermann's disease. *Stud Health Technol Inform* 2002;88: 254-257.
16. Lowe TG, Kasten MD: An analysis of sagittal curves and balance after Cotrel-Dubousset instrumentation for kyphosis secondary to Scheuermann's disease: A review of 32 patients. *Spine (Phila Pa 1976)* 1994;19:1680-1685.
17. Herndon WA, Emans JB, Micheli LJ, Hall JE: Combined anterior and posterior fusion for Scheuermann's kyphosis. *Spine (Phila Pa 1976)* 1981;6:125-130.
18. Yang C, Askin G, Yang SH: Combined thoracoscopic anterior spinal release and posterior correction for Scheuermann's kyphosis [Chinese]. *Zhonghua Wai Ke Za Zhi* 2004;42:1293-1295.
19. Koptan WM, Elmiligui YH, Elsebaie HB: All pedicle screw instrumentation for Scheuermann's kyphosis correction: Is it worth it? *Spine J* 2009;9:296-302.
20. **Koller H, Lenke LG, Meier O, et al: Comparison of anteroposterior to posterior-only correction of Scheuermann's kyphosis: A matched-pair radiographic analysis of 92 patients. *Spine Deform* 2015; 3:192-198.**
21. Geck MJ, Macagno A, Ponte A, Shufflebarger HL. The Ponte procedure: Posterior only treatment of Scheuermann's kyphosis using segmental posterior shortening and pedicle screw instrumentation. *J Spinal Disord Tech* 2007;20:586-593.
22. **Schwab F, Blondel B, Chay E, et al: The comprehensive anatomical spinal osteotomy classification. *Neurosurgery* 2015;76(suppl 1):S33-S41.**
23. Chang KW, Cheng CW, Chen HC, Chang KI, Chen TC: Closing-opening wedge osteotomy for the treatment of sagittal imbalance. *Spine (Phila Pa 1976)* 2008;33: 1470-1477.
24. **Lewis ND, Keshen SG, Lenke LG, et al: The deformity angular ratio: Does it correlate with high-risk cases for potential spinal cord monitoring alerts in pediatric 3-column thoracic spinal deformity corrective surgery? *Spine (Phila Pa 1976)* 2015;40: E879-E885.**
25. Reinhardt P, Bassett GS: Short segmental kyphosis following fusion for Scheuermann's disease. *J Spinal Disord* 1990;3:162-168.
26. Hosman AJ, Langeloo DD, de Kleuver M, Anderson PG, Veth RP, Slot GH: Analysis of the sagittal plane after surgical management for Scheuermann's disease: A view on overcorrection and the use of an anterior release. *Spine (Phila Pa 1976)* 2002;27:167-175.
27. Denis F, Sun EC, Winter RB: Incidence and risk factors for proximal and distal junctional kyphosis following surgical treatment for scheuermann kyphosis: Minimum five-year follow-up. *Spine (Phila Pa 1976)* 2009;34:E729-E734.
28. **Lange T, Schmoelz W, Gosheger G, et al: Is a gradual reduction of stiffness on top of posterior instrumentation possible with a suitable proximal implant? A biomechanical study. *Spine J* 2017;17: 1148-1155.**
29. Hassanzadeh H, Gupta S, Jain A, El Dafrawy MH, Skolasky RL, Kebaish KM: Type of anchor at the proximal fusion level has a significant effect on the incidence of proximal junctional kyphosis and outcome in adults after long posterior spinal fusion. *Spine Deform* 2013;1:299-305.
30. Helgeson MD, Shah SA, Newton PO, et al: Evaluation of proximal junctional kyphosis in adolescent idiopathic scoliosis following pedicle screw, hook, or hybrid instrumentation. *Spine (Phila Pa 1976)* 2010;35:177-181.
31. Cahill PJ, Wang W, Asghar J, et al: The use of a transition rod may prevent proximal junctional kyphosis in the thoracic spine after scoliosis surgery: A finite element analysis. *Spine (Phila Pa 1976)* 2012;37: E687-E695.
32. **Koller H, Juliane Z, Umstaetter M, Meier O, Schmidt R, Hitzl W: Surgical treatment of Scheuermann's kyphosis using a combined antero-posterior strategy and pedicle screw constructs: Efficacy, radiographic and clinical outcomes in 111 cases. *Eur Spine J* 2014;23:180-191.**
33. Otsuka NY, Hall JE, Mah JY: Posterior fusion for Scheuermann's kyphosis. *Clin Orthop Relat Res* 1990;251:134-139.
34. Cho KJ, Lenke LG, Bridwell KH, Kamiya M, Sides B: Selection of the optimal distal fusion level in posterior instrumentation and fusion for thoracic hyperkyphosis: The

sagittal stable vertebra concept. *Spine (Phila Pa 1976)* 2009;34:765-770.

35. **Kim HJ, Nemani V, Boachie-Adjei O, et al: Distal fusion level selection in Scheuermann's kyphosis: A Comparison of lordotic disc segment versus the sagittal stable vertebrae. *Glob Spine J* 2017;7: 254-259.**

36. **Yanik HS, Ketenci IE, Coskun T, Ulusoy A, Erdem S: Selection of distal fusion level in posterior instrumentation and fusion of scheuermann kyphosis: Is fusion to sagittal stable vertebra necessary? *Eur Spine J* 2016;25:583-589.**

37. Kim HJ, Lenke LG, Kim YJ, Rinella AS: Posterior spinal instrumentation techniques for spinal deformity, in ZdeblickTA, AlbertT, eds: *Master Techniques in Orthopaedic Surgery: The Spine*, ed 3. Philadelphia, PA, Lippincott Williams & Wilkins, 2013, pp 250-257.

38. Coe JD, Smith JS, Berven S, et al: Complications of spinal fusion for scheuermann kyphosis: A report of the scoliosis research society morbidity and mortality committee. *Spine (Phila Pa 1976)* 2010;35:99-103.

39. Lee SS, Lenke LG, Kuklo TR, et al: Comparison of Scheuermann kyphosis correction by posterior-only thoracic pedicle screw fixation versus combined anterior/posterior fusion. *Spine (Phila Pa 1976)* 2006;31:2316-2321.

40. **Lonner BS, Toombs CS, Guss M, et al: Complications in operative scheuermann kyphosis: Do the pitfalls differ from operative adolescent idiopathic scoliosis? *Spine (Phila Pa 1976)* 2015;40:305-311.**

41. Cheh G, Lenke LG, Padberg AM, et al: Loss of spinal cord monitoring signals in children during thoracic kyphosis correction with spinal osteotomy: why does it occur and what should you do? *Spine (Phila Pa 1976)* 2008;33:1093-1099.

42. Kundnani VK, Zhu L, Tak H, Wong H: Multimodal intraoperative neuromonitoring in corrective surgery for adolescent idiopathic scoliosis: Evaluation of 354 consecutive cases. *Indian J Orthop* 2010;44:64-72.

43. **Samdani AF, Bennett JT, Ames RJ, et al: Reversible intraoperative neurophysiologic monitoring alerts in patients undergoing arthrodesis for adolescent idiopathic scoliosis: What are the outcomes of surgery? *J Bone Joint Surg Am* 2016;98: 1478-1483.**