Thoracic adolescent idiopathic scoliosis: selection of fusion level

Mohammad I. Badra[a], David S. Feldman[b] and Robert A. Hart[c]

Selection of the appropriate fusion levels in thoracic adolescent idiopathic scoliosis has been traditionally a subject of debate among surgeons. Landmarks that have been suggested include the end vertebra, stable vertebra and neutral vertebra. Various results have been reported with multiple theories proposed to explain them.
The clinical appearance of the patient, the type of the curve and its flexibility, the surgical technique and the instrumentation used all seem to play major roles in selecting the appropriate levels of fusion. ***J Pediatr Orthop B*** **19:465–472 © 2010 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

Journal of Pediatric Orthopaedics B 2010, **19**:465–472

Keywords: classification, fusion level, instrumentation, neutral vertebra, stable vertebra, thoracic scoliosis

[a]Department of Orthopedics Surgery, Clemenceau Medical Center, Beirut, Lebanon, [b]Center for Children, NYU Hospital for Joint Diseases, New York, New York and [c]Department of Orthopedics and Rehabilitation, Oregon Health and Sciences University, Portland, Oregon, USA

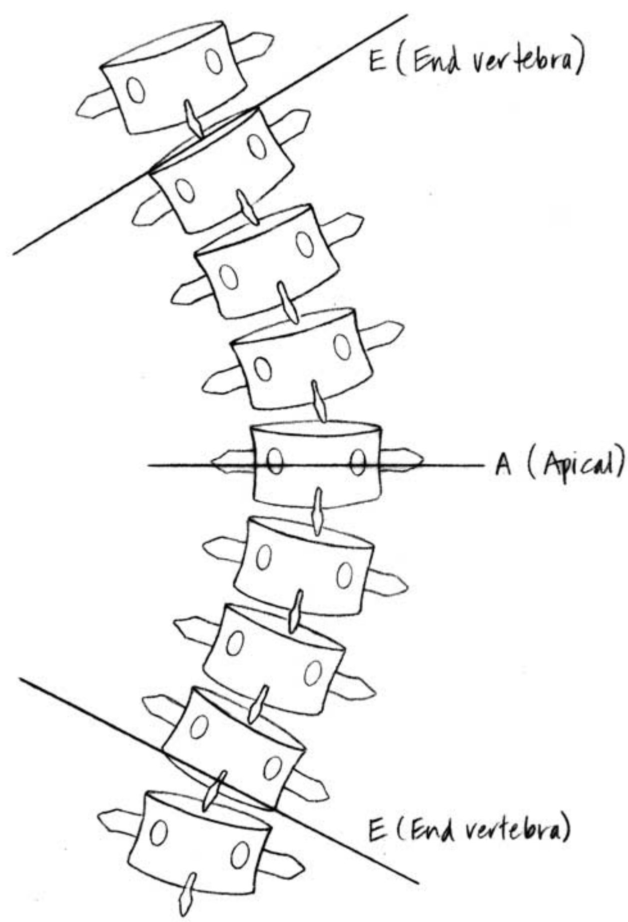
Correspondence to Dr Mohammad Badra, MD, Department of Orthopedics Surgery, Clemenceau Medical Center, PO Box 11-2555-Beirut, Lebanon
Tel: +961 3 020322; fax: 961 1 364464;
e-mail: mohammad.badra@cmc.com.lb

In preoperative planning for a case of adolescent idiopathic scoliosis (AIS), the primary concern is choosing the appropriate level of fusion. The surgeon identifies the upper and lower vertebrae to be instrumented, and in the case of combined thoracic and lumbar or double thoracic curves, decides which curve(s) should be included in the fusion. The aim of this review is to determine the factors that should be considered to surgically obtain a well-balanced and compensated spine.

Historical review

The selection of the appropriate levels of instrumentation and fusion in AIS has been the subject of much debate [1–6]. Traditionally, most surgeons advocated including all the vertebrae within a curve, that is, fusing from the upper end vertebra to the lower end vertebra. The end vertebra was defined as the vertebra that is most tilted into curve (Fig. 1). Both Ferguson and Risser suggested including the vertebrae that are parallel after application of a turnbuckle or Risser cast [7,8]. In the early 1970s, Harrington [3] proposed that the fusion should extend from one level above the upper end vertebra to two levels below the lower end vertebra provided that this lower level of fusion falls within the 'stable zone of Harrington'. This zone was defined as the area between two parallel lines passing through the lumbosacral (LS) joints (Fig. 2). Goldstein [1,2] and subsequently Moe [5] recommended the fusion from neutral vertebra proximally to neutral vertebra distally, stating that this would lead to good results in most cases. The neutral vertebra was defined as the vertebra without axial rotation based on Nash-Moe definition of vertebral rotation (Fig. 3). For the combined thoracic and lumbar curves, some surgeons have suggested that the level

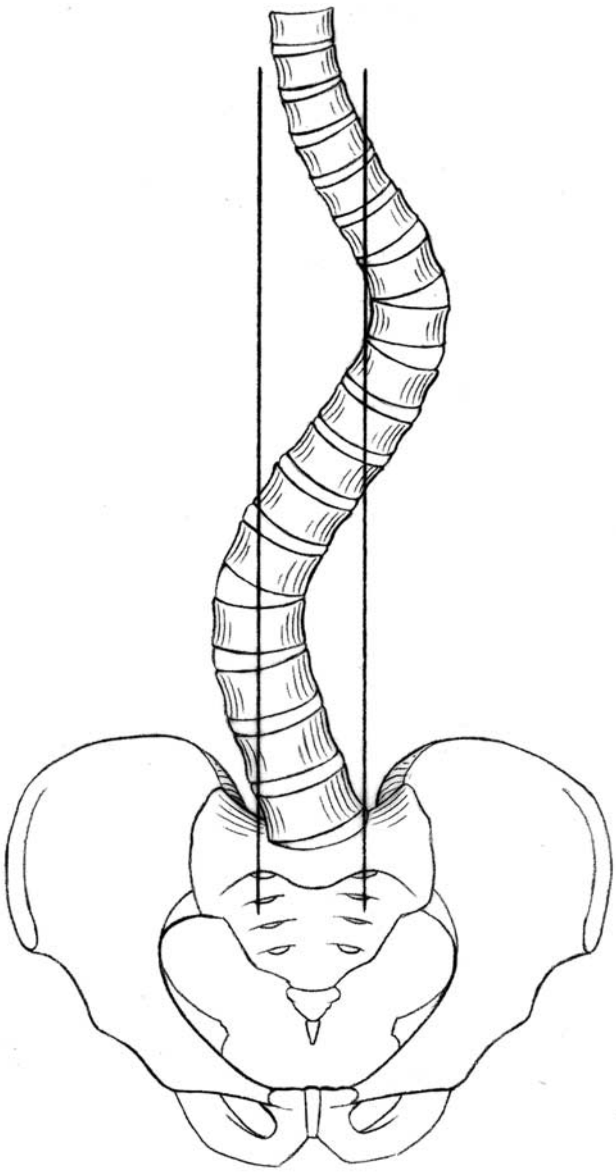
Fig. 1



Upper and lower end vertebrae. The end vertebra is defined as the vertebra that is most tilted into the curve.

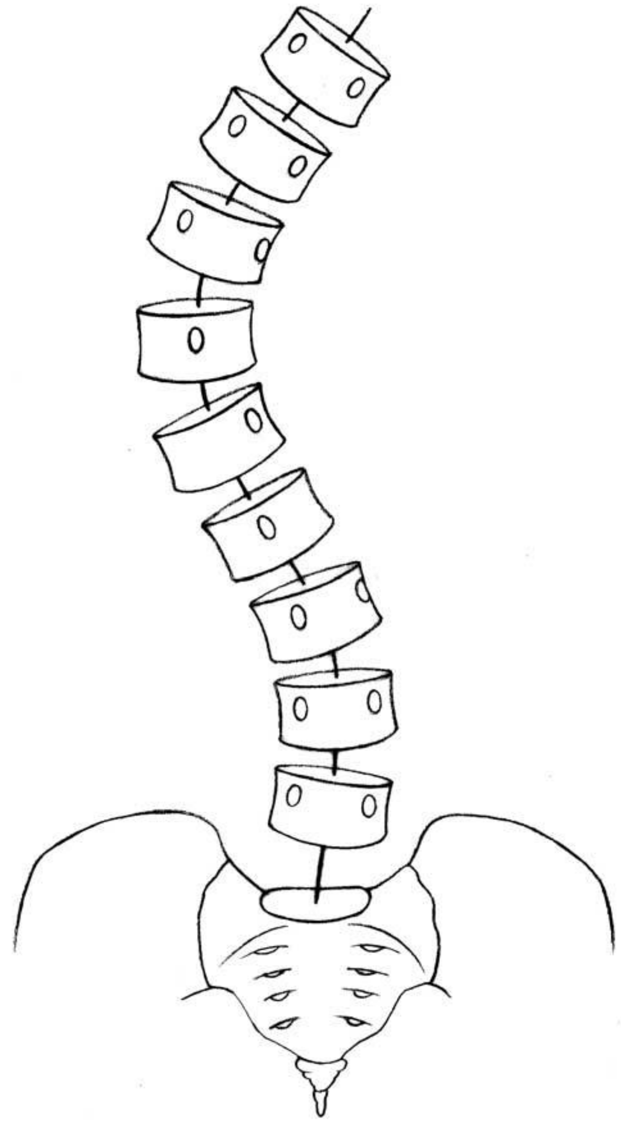
DOI: 10.1097/BPB.0b013e32833cb72d

Fig. 2



Stable zone of Harrington: defined by parallel lines that pass through the lumbosacral joints.

Fig. 3



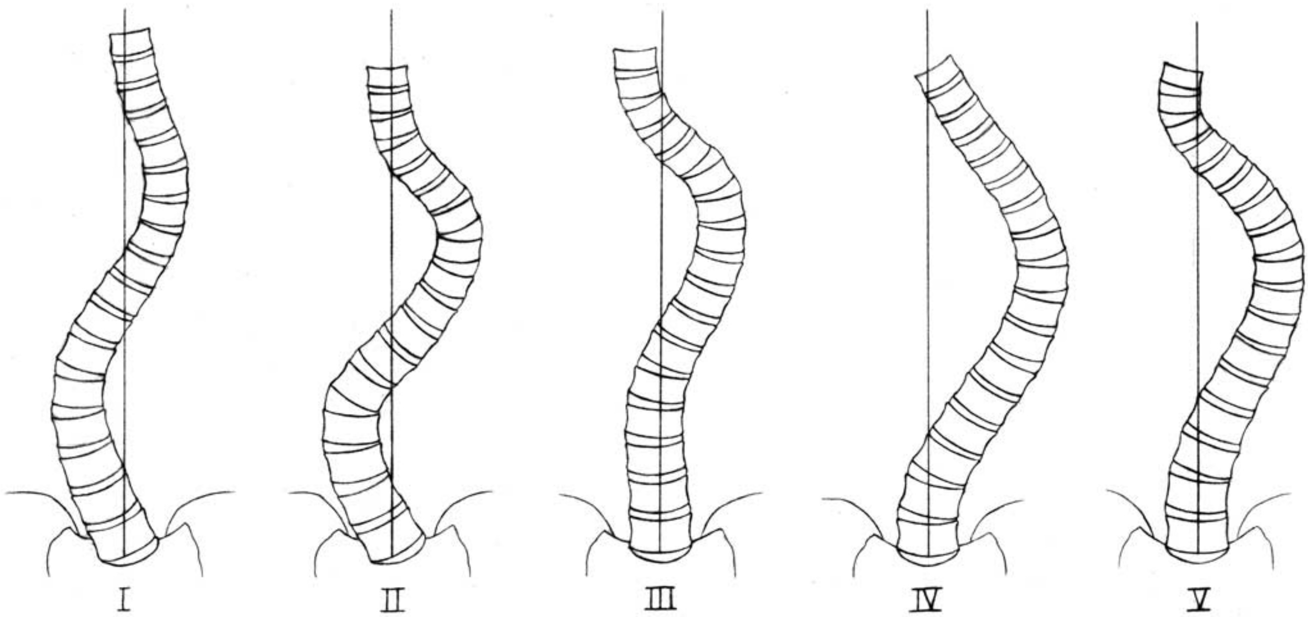
Neutral vertebra is defined as the vertebra without axial rotation. In the neutral vertebra, the two pedicles look equidistant from the lateral wall of the vertebra.

of fusion should extend from T4 to L4 to decrease the risk of postoperative decompensation [9].

In 1972, Moe [5] introduced the concept of selective thoracic fusion, stressing the importance of assessing the flexibility of each curve and recommending the fusion of only stiff curves. His concept was essentially to fuse the smallest number of levels that will result in a well-balanced spine. Cochran *et al.* [10] also recognized the importance of avoiding extension of the fusion level into the lumbar spine and preserving as many mobile segments as possible. These authors showed that the lower the level of fusion in the lumbar spine, the higher the chance that these patients will develop back pain in the future. The incidence of back pain was only 25% in patients who were fused down to L1 compared to 82% in patients who were fused down to L5. Based on these results, surgeons adopted the concept of selective thoracic fusion, saving as many mobile segments in the lumbar spine as possible.

The appropriate levels of fusion were then defined by King *et al.* [4] in a study that included 405 patients with AIS treated with posterior spine fusion using the Harrington instrumentation. In his article, King described five patterns of thoracic curves (Fig. 4). Types I and II are S-shaped curves in which both the thoracic and lumbar curves cross

Fig. 4



King's classification of the thoracic curves.

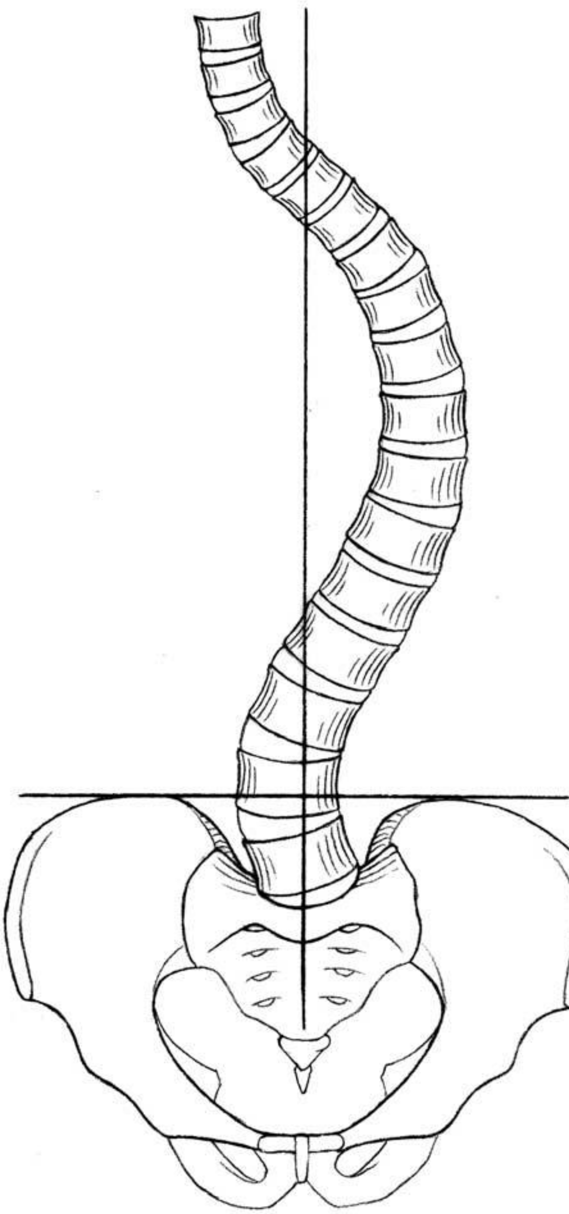
the midline. The differentiation between these two types is based mainly on the comparison of the Cobb angles of the thoracic and lumbar curves, as well as the flexibility index (FI). The FI is defined as the percentage of correction of the lumbar curve minus the percentage of correction of the thoracic curve. In Type I, the lumbar curve is larger than the thoracic curve and the FI is a negative value. In Type II, the thoracic curve is larger than the lumbar curve and the FI is a positive value. Type III is a single thoracic curve in which the lumbar curve does not cross the midline. Type IV is a long thoracic curve in which the L5 vertebra is centered over the sacrum, but the L4 vertebra is tilted into the long thoracic curve. Type V is a double thoracic curve with positive T1-tilt and structural upper thoracic curve on side bending view.

King *et al.* showed that whenever the lower level of fusion was the stable vertebra, the result was a well-balanced spine, but whenever the lower level of fusion was either cranial or caudal to the stable vertebra, a progression of the lumbar curve or lateral decompensation was a risk. The stable vertebra was defined as the first vertebra that is bisected, or most closely bisected by the central sacral line (Fig. 5). Based on these findings, they recommended that the lower level of fusion in AIS should be the stable vertebra. Experience of other surgeons with the Harrington instrumentation showed that these results were reproducible [11,12].

During the mid 1980s, a new instrumentation system, the Cotrel-Dubousset Instrumentation (CDI) [13], was introduced into the market and became popular, first in Europe, and then in the United States. This system is based on the segmental instrumentation of the spine using hooks and rods and, theoretically, allows the derotation and thus correction of the spine in the coronal, sagittal and axial planes. CDI also offered greater stability and eliminated the need for the 6–12 months postoperative cast/brace immobilization that was required with the Harrington instrumentation [14]. Interest in this system among surgeons led to a major shift in instrumentation from the traditional Harrington rods with only distraction forces to the CDI system with the concept of spine derotation.

Many surgeons around the world started using CDI while continuing to apply King's guidelines regarding the lower level of fusion. This was the case until the late 1980s when several reports appeared indicating a higher decompensation rate with CDI, primarily in Type II cases, than had been associated with the Harrington instrumentation [15–19]. Earlier, postoperative coronal spinal balance had been satisfactory using the Harrington instrumentation while applying King's guidelines of fusion down to the stable vertebra. Unfortunately, this did not prove to be the case with CDI. Mason *et al.* [16] reported a 4% decompensation rate using the Harrington rod instrumentation and its variants compared to 41% decompensation rate using CDI. Other authors also reported similar increased rates of coronal decompasation with CDI [15,20].

Fig. 5



Stable vertebra is defined as the vertebra that is bisected or most closely bisected by the central sacral line.

By this time, it had become apparent that the previous criteria of fusion to the stable vertebra were no longer applicable with the use of CDI. Surgeons reviewed their cases to identify factors related to the postoperative worsening of spinal balance. In addition to the choice of fusion level and type of instrumentation used, factors that have been cited include: (i) overcorrection of the thoracic curve [19,21], (ii) hook pattern [15,22], (iii) misclassification of the curve [23,24], and (iv) derotation of the curve [19].

Overcorrection of the thoracic curve

Several surgeons have suggested that the overcorrection of the thoracic curve contributed to postoperative spinal imbalance. Using the CDI and King's criteria for the selection of fusion level, Thompson *et al.* [19] evaluated the effect of the magnitude of correction on balance in 30 patients by measuring the preoperative flexibility of the major thoracic curve and the secondary lumbar curve and comparing the results to the postoperative correction of these cases. Preoperative flexibility of the major thoracic curve averaged 58% while the postoperative correction averaged 68%. In contrast, the preoperative flexibility of the secondary lumbar curve was 88% while the postoperative correction was only 58%. Therefore, when the major curve was overcorrected, the secondary curve was corrected to a lesser extent than the preoperative flexibility had suggested. The excessive derotation of the major curve or instrumentation extending into the lumbar curve had increased the rotational deformity of the secondary curve.

Thompson *et al.* hypothesized that these findings could be explained by the presence of 'transitional mobile segments' at the junction between the major and secondary curves and noted that these segments have greater mobility (larger changes in segmental rotation and the segmental Cobb angles). Inclusion of these mobile segments appeared to result in transmission of torsional forces to the uninstrumented lumbar segments beyond its capability for spontaneous correction leading to spinal decompensation. To achieve a well-balanced spine, the surgeons recommended avoiding correction in excess of preoperative flexibility and avoiding instrumentation within the 'transitional mobile segments'.

Other surgeons have stressed the importance of avoiding excessive correction of the thoracic spine, primarily when dealing with type II curves. Arlet *et al.* [21] believed that decompensation was the result of an imbalance between the thoracic and lumbar curves and that the surgeon has to decide either to limit the correction of the thoracic spine or extend the fusion to include the lumbar spine. Similarly, King [9,23] stated that more correction of the thoracic spine does not always mean better overall spinal balance nor better clinical results. It must be remembered that the aim of surgery is to achieve a well-balanced and compensated spine.

Hook pattern

The standard hook configuration originally described by Dubousset was to distract on the concave side and compress on the convex side. By reviewing the relationship between the hook pattern and decompensation in 82 AIS cases using CDI, Bridwell *et al.* [15] identified the following five different hook configurations: (i) Group A: fusion to the stable vertebra using standard hook pattern (the lowest hook on the concave side was placed in the distraction mode); (ii) Group B: fusion to one level short of the stable vertebra using standard hook pattern; (iii) Group B-RB (reverse bending): fusion to one level short of the stable vertebra with reversal of the rod bend and hook configuration between the last two vertebrae; (iv) Group C: fusion to the stable vertebra with reversal of the rod bend and hook configuration between the last two vertebrae; and (v) Group D: fusion extends beyond the stable vertebra with reversal of the rod bend and hook configuration between the last two vertebrae. The surgeons found that eight of 17 (47%) patients with Type II curves in Group A decompensated postoperatively, one of the one (100%) in Group B-RB and none in Groups B, C and D. They concluded that application of King's criteria while using CDI produces less predictable outcomes in providing a well-balanced spine. They recommended that to decrease the decompensation rate, Group B or C hook pattern should be used. The decision of which of these two patterns to use depends on the patient's preoperative sagittal contour at the thoracolumbar (TL) junction. If junctional kyphosis is less than 5°, fusion should be short of the stable vertebra using the standard hook configuration (Group B). However, if junctional kyphosis is greater than 5°, then the fusion should extend either down to the stable vertebra or beyond the stable vertebra with reversal of the hook configuration at the lower aspect of the curve (Group C or D, respectively). These findings were subsequently supported by Lenke *et al.* [24] who showed that spinal balance is best achieved by reversing the rod bend and hook configuration between the neutral and stable vertebra at the level where the orientation of the disc space starts to change.

Why does changing the hook configuration between T11 and L1 in King Type II curves yield good results while using standard hook configurations results in spine decompensation in some of the cases? King *et al.* [4] pointed out that 'not all right thoracic curves are the same'. Both Type II and Type III curves have the right thoracic curve as the major curve but they behave quite differently. A higher rate of decompensation was found in Type II curves compared to Type III curves using the same instrumentation, CDI.

Several unique characteristics of Type II curves appeared to predispose them to decompensation using the standard hook pattern. First, Type II typically have a higher apex compared with Type III. Second, the lumbar curve in Type II usually starts at T11 while the lumbar curve in Type III usually starts at L1. Finally, the direction of the axial rotation in Type II curves in the segment from T11 to L1 is opposite to that of the thoracic curve, while it is in the same direction in Type III. Therefore, in a Type II curve, applying a distractive force from T11-L1 may lead to imbalance. In the coronal plane, the distraction forces will open the disc spaces. In the axial plane, this will lead to an increase in the rotation of the lumbar curve beyond its capacity for spontaneous correction. In the sagittal plane, distraction at the TL junction will tend to increase the junctional kyphosis. Thus, the modified hook pattern, that is, the reversal of the hook pattern between T11 and L1 is appropriate for Type II curves and more predictably leads to a well-balanced spine.

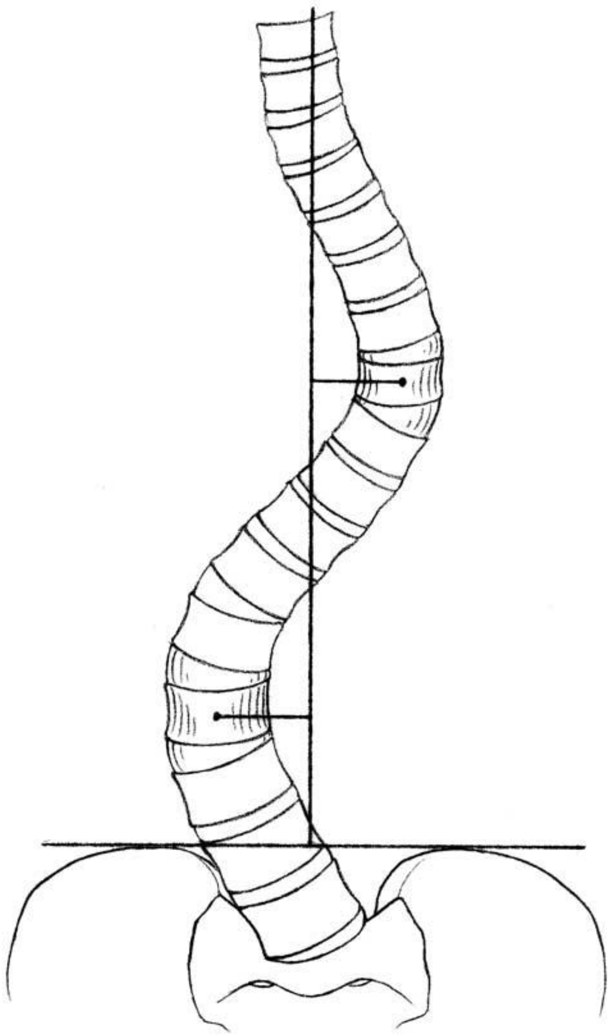
Misclassification of the curve

The purpose of classification systems of spinal curves is to assist in determining the most appropriate surgical procedure. Recently, some surgeons have questioned the ability of King's classification system to adequately identify the surgically important aspect of all spinal curves. Lenke *et al.* [25] believed that most of the decompensation problems with Type II curves were due to the inappropriate definitions of Type I and Type II. According to King *et al.* [9], the distinction between Type I and Type II depends on the magnitude of the thoracic and lumbar curves and/or the FI. In Type I, either the lumbar curve has a larger Cobb angle than the thoracic curve or the thoracic is larger than the lumbar curve, but there is a negative FI. In Type II, the thoracic curve has a larger Cobb angle than the lumbar curve with a positive FI. This classification seemed to work very well with the Harrington instrumentation, but not with CDI.

Lenke *et al.* [24] challenged the concept of differentiating between King Type I and Type II based on the FI. In their review of 52 patients (of which 25 had been classified as Type I and 27 as Type II), they found that 21 of the 25 that would have been defined as King Type I curves had a positive FI. They concluded that the lumbar curve was inherently more flexible than the thoracic curve and that positive FI by itself cannot differentiate between Type I and Type II. By studying the characteristic of each curve and assessing the factors that led to decompensation, Lenke *et al.* established criteria that improved the differentiation of Type I and Type II. Specifically, the Cobb angle ratio, the apical vertebral rotation (AVR) ratio and the apical vertebral translation (AVT) ratio of the thoracic to the lumbar curve may more precisely distinguish between Type I and Type II (Fig. 6). If these ratios are ≤ 1, the curve is a Type I and both the thoracic and lumbar curves should be fused. If the ratios are ≥ 1.2, the curve is a Type II and selective thoracic fusion is warranted. Following these criteria, Lenke *et al.* found that 100% of the patients had a well-balanced compensated spine at follow-up.

Similarly, Ibrahim *et al.* [26] believed that the major cause of decompensation lay in the definition and classification of Type II curves. They suggested that Type II curves can be divided into two subgroups, Type IIA and Type IIB. In Type IIA, the Cobb angle of the lumbar curve is less than 35° with at least 70% correction on side bending view, the LS fractional curve is less than 12° and the apical lumbar vertebra touches the central sacral line. In Type IIB, the lumbar curve is less than 35° with less than 70%

Fig. 6



Apical vertebral translation is the perpendicular distance from the center of the apical vertebra to the central sacral line.

correction on side bending view, the LS fractional curve is less than 12° and the apical lumbar vertebra extends beyond the central sacral line. Ibrahim *et al.* believed that selective thoracic fusion is warranted in Type IIA, but not in Type IIB. For Type IIB, the recommendation was that the fusion level should extend into the horizontal lumbar vertebra and the inferior hooks should be in the compression mode rather than the distraction mode, that is, reversal of the hook configuration.

As confusion was apparent among surgeons in the application of King's classification, other classification systems were developed in an effort to improve the selection of treatment method and predictability of outcome. In 2001, Lenke *et al.* [25] proposed a new classification system based on six different curve types with coronal (A, B, C) and sagittal (−, N, +) plane modifiers. This classification has been shown to have good intraobserver and interobserver reliability [27]. In addition, the Lenke's classification was considered a treatment-based system because of the fact that only curves designated to be structural should be instrumented and fused while the other minor curves should not. Lenke *et al.* [27] found that this classification correlated in 90% of cases with the recommended treatment. They stated that this system provides general guidelines to follow when assessing scoliosis and that for each curve, other parameters such as the ratios (Cobb, AVR, AVT), the appearance of the patient and the overall spinal balance should be considered before embarking on any type of treatment.

Spine derotation

The ability of different instrumentation to effectively derotate the spine in the axial plane has been investigated. Using the CDI, Wood *et al.* [28] compared the preoperative and postoperative vertebral rotation in reference to the sagittal plane and to the S1 vertebra. The average derotation of the apical vertebra was 13.8% relative to the sagittal plane and approximately 9% relative to the sacrum. They concluded that CDI does not consistently derotate the thoracic spine relative to the pelvis and that coronal plane correction may only be apparent.

King [23] also believed that CDI does not have a true derotation effect on the spine. He thought that decompensation of King Type II curves was due mainly to the derotation maneuver and overcorrection of the thoracic curve. To avoid the decompensation, he suggested that the lower level of fusion should still be the stable vertebra but with no derotation of the spine, only distraction on the concave side and compression on the convex side.

Using pedicle screws for instrumentation, Lee *et al.* [29] showed also that simple rod derotation has only a 'posteromedialization' effect on the spine with little true derotation. With simple derotation, the screws slide on the precontoured rod, producing only an apparent effect. However, applying direct derotational force on the screws will allow true derotation of the spine in the axial plane. The average derotation of the spine was only 2.4% with simple derotation compared to 42% with direct vertebral rotation. Their recommendation was to use pedicle screws as the instrumentation in scoliosis surgery with the neutral vertebra as the end point of fusion. Similarly, in a retrospective study to determine the distal fusion level in the treatment of single thoracic idiopathic scoliosis using pedicle screw instrumentation, Suk *et al.* [30] found that the neutral vertebra is an important factor for the determination of fusion level. They found that when the neutral vertebra was either the same or one level distal to the end vertebra, fusion to the neutral vertebra yielded satisfactory results. When the neutral vertebra was more than two levels distal to the end vertebra, satisfactory results were obtained by fusing down to one level shorter than the neutral vertebra.

According to the surgeons, this strategy can save one or two motion segments as compared with fusion extending to the stable vertebra.

Apparently, the variable effect of the different instrumentation systems on spinal derotation has a direct impact on the selection of fusion level. King, using the CDI, recommended the stable vertebra as the lower level of fusion while Lee *et al.* and Suk *et al.* recommended the neutral vertebra as the lower level of fusion. All these techniques resulted in a well-balanced compensated spine in the majority of the cases.

The type of instrumentation system plays an even more important role in the selection of fusion levels when dealing with the King Type V curves. The major issue with these curves is to decide whether or not to include the upper thoracic curve in the fusion. Using the Harrington instrumentation, Lee *et al.* [31] found that fusion of the upper thoracic curve depends on the preoperative shoulder balance. If the patient has left shoulder elevation preoperatively, the upper thoracic curve should be included in the fusion mass, while if there is right shoulder elevation, fusion may be limited to the primary thoracic curve. In the case of balanced shoulders preoperatively, fusion of the upper curve depends on its flexibility. If the upper curve is more rigid than the main thoracic curve, both curves should be fused, while if the upper curve is more flexible, then fusion of the main thoracic curve is sufficient to yield good results.

Using CDI, Lenke *et al.* [32] proposed different criteria to determine when the upper thoracic curve should be instrumented. These criteria include:

(1) An upper curve $>30^\circ$ that does not bend out to less than 20° on side bending view
(2) AVR >1 or AVT >1 cm
(3) Left shoulder elevation or positive T1 tilt
(4) Transitional vertebra located at or below T6

They believed that whenever the majority of these criteria are met, the upper thoracic curve should be considered structural and should be included in the fusion along with the main thoracic curve.

Using pedicle screw fixation, Suk *et al.* [33] found that some patients with a double thoracic curve pattern in whom the upper thoracic curve was not fused in accordance with Lenke's recommendations ended up with an elevated left shoulder because of the relative overcorrection of the major (lower) thoracic curve. A direct correlation was seen between the preoperative and postoperative shoulder height difference. They proposed a formula to predict the postoperative shoulder height difference based on the preoperative shoulder height difference. Specifically, using pedicle screw fixation, the upper thoracic curve should always be fused except when the right shoulder is 12 mm or more higher than the left shoulder. The use of pedicle screw fixation in King Type V curves has resulted in an increased frequency of the inclusion of the proximal curve compared with other types of instrumentation. This is because of the fact that pedicle screw fixation allows better correction of the right main thoracic curve which, in the case of isolated fusion of the main thoracic curve, leaves the left upper thoracic curve unbalanced and thus unmasks the left shoulder elevation produced by that curve.

Sagittal plane considerations

Traditionally, treatment of AIS was focused on correcting the coronal plane balance with little attention given to the sagittal and axial planes. After the introduction of the new instrumentation systems which allowed three-dimensional correction of the spinal deformities, it has become evident that restoration of the normal sagittal contour of the spine is equally important for the long term outcome of the surgical management.

In the era of Harrington instrumentation back in the 1960s and 1970s, correction of the coronal plane deformity was based on distraction rods applied between the end vertebrae of a curve. This technique has yielded 'acceptable' results regarding coronal plane deformities but the distractive forces applied to the posterior column of the spine have created a 'lordosing effect' on the spine and thus flatback deformity, a condition very poorly tolerated by the patients.

Although surgeons have attempted to avoid this deformity by contouring the Harrington rods, their endeavors have only resulted in partial correction with the net result still less than optimal restoration of the sagittal balance of the spine. The later use of luque instrumentation was not more encouraging regarding sagittal balance. Reports on luque instrumentation have shown sagittal realignment as good as with the Harrington instrumentation combined with sublaminar wiring [34].

With the use of the new instrumentation systems (hooks and screws), it became evident that achieving proper sagittal balance is critical to the surgical management of AIS. Two general rules were followed concerning the sagittal plane deformity. First, fusion should not be stopped at the TL junction and second, fusion should not be stopped at the apex of a kyphosis. Some surgeons expressed their concern regarding stopping a fusion at the TL junction, stating that this might be associated with increased risk of postoperative 'junction kyphosis' and thus decompensation in the sagittal plane [18,22]. However, several reports have shown that this is not a problem [23,35,36]. Idiopathic right thoracic scoliosis is not characteristically accompanied by a segmental postoperative junctional kyphosis and therefore it is safe to stop a fusion in this region. However, should this segment be included in the fusion, either because of the presence of long thoracic curve or because of preoperative junctional kyphosis at the TL junction, reversal of the rod bend and reversal of the hook pattern on the left side (concave side) of the curve between T12 and L2 as showed by Bridwell *et al.* [15] does help maintain lordosis at this segment of the spine and thus avoids post-operative junctional kyphosis.

Based on these observations, one can say that obtaining proper sagittal balance is becoming more recognized as critical to the surgical management of AIS. Any pre-operative sagittal deformity should be certainly considered during the preoperative surgical planning. A general rule to follow regarding the sagittal plane correction in thoracic AIS is to start and end a fusion at a neutral vertebra.

Summary

We now have a clearer idea where to start and where to end our fusion level in AIS. Still, we cannot always define the best lower level of fusion to be the stable vertebra, the neutral vertebra or the end vertebra. Our final decision should be based on many factors including the clinical appearance of the patient, the type of the curve and its flexibility, the surgical technique and the instrumentation used. Changing one or more of these factors will change the appropriate lower level of fusion. Finally, advancement in surgical techniques and development of newer and stronger instrumentation systems has led to changes in the assessments of the best lower level of fusion which will probably continue to fluctuate between the end vertebra, the stable vertebra and the neutral vertebra.

Acknowledgements

No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

References

1 Goldstein LA. Surgical management of scoliosis. *J Bone Joint Surg Am* 1966; **48**:167–196.
2 Goldstein LA. The surgical management of scoliosis. *Clin Orthop* 1971; **77**:32–56.
3 Harrington PR. Technical details to the successful use of instrumentation in scoliosis. *Orthop Clin North Am* 1972; **3**:49–67.
4 King HA, Moe JH, Bradford DS, Winter RB. The selection of fusion level in thoracic idiopathic scoliosis. *J Bone Joint Surg Am* 1983; **65**:1302–1313.
5 Moe JH. Methods of correction and surgical techniques in scoliosis. *Orthop Clin North Am* 1972; **3**:17–48.
6 Woodward HR, Chan DPK, Goldstein LA, Devany JR, Haake PW. Selection of fusion area in thoracolumbar and lumbar curve pattern: a follow-up report. *Orthop Trans* 1980; **4**:38–39.
7 Ferguson HB. The study and treatment of scoliosis. *South Med J* 1930; **23**:116–120.
8 Risser JC. Scoliosis: past and present. *J Bone Joint Surg Am* 1964; **46**:167–199.
9 King HA. Selection of fusion levels for posterior instrumentation and fusion in idiopathic scoliosis. *Orthop Clin North Am* 1988; **19**:247–255.
10 Cochran T, Irstam L, Nachemson A. Long term anatomic and functional changes in patients with adolescent idiopathic scoliosis treated by Harrington rod fusion. *Spine* 1983; **8**:576–583.
11 Kalen V, Conklin M. The behavior the unfused lumbar spine following selective thoracic fusion for idiopathic scoliosis. *Spine* 1990; **15**:271–274.
12 Knapp DR, Price CT, Jones ET, Coonrad RW, Flynn JC. Choosing fusion level in progressive thoracic idiopathic scoliosis. *Spine* 1992; **17**:1159–1165.
13 Cotrel Y, Dubousset J, Guillaumat M. New universal instrumentation in spinal surgery. *Clin Orthop* 1988; **227**:10–23.
14 Richards BS, Johnston CE III. Cotrel-Dubousset instrumentation for adolescent idiopathic scoliosis. *Orthopedics* 1987; **10**:649–654.
15 Bridwell KH, McAllister JW, Betz RR, Huss G, Clancy M, Schonecker PL. Coronal decompensation produced by Cotrel-Dubousset derotation maneuver for idiopathic right thoracic scoliosis. *Spine* 1991; **16**:769–777.
16 Mason DE, Crango BS. Spinal decompensation in Cotrel-Dubousset instrumentation. *Spine* 1991; **16**:S394–S403.
17 Puno RM, Grossfeld SL, Johnson JR, Holt RT. Cotrel-Dubousset instrumentation in idiopathic scoliosis. *Spine* 1992; **17**:S258–S262.
18 Richards BS, Birch JG, Herring JA, Johnston CE, Roach JW. Frontal plane and sagittal plane balance following Cotrel-Dubousset instrumentation for idiopathic scoliosis. *Spine* 1989; **14**:733–737.
19 Thompson JP, Transfeldt EE, Bradford DS, Ogilvie JW, Boachie-Adjei O. Decompensation after Cotrel-Dubousset instrumentation of idiopathic scoliosis. *Spine* 1990; **15**:927–931.
20 Moore MR, Baynham GC, Brown CW, Donaldson DH, Odom JA. Analysis of factors related to truncal decompensation following Cotrel-Dubousset instrumentation. *J Spinal Disorder* 1991; **4**:188–192.
21 Arlet V, Marchesi D, Papin P, Aebi M. Decompensation following scoliosis surgery: treatment by decreasing the correction of the main thoracic curve or letting the spine go. *Eur Spine J* 2000; **9**:156–160.
22 Shufflebarger HL, Clark CE. Fusion levels and hook patterns in thoracic scoliosis with Cotrel-Dubousset instrumentation (CDI). *Spine* 1990; **15**:916–920.
23 King HA. Analysis and treatment of Type II idiopathic scoliosis. *Orthop Clin North Am* 1994; **25**:225–237.
24 Lenke LG, Bridwell KH, Baldus C, Blanke K. Preventing decompensation in King Type II curves treated with Cotrel-Dubousset instrumentation. *Spine* 1992; **17**:S274–S281.
25 Lenke LG, Betz RR, Harms J, Bridwell KH, Clements DH, Lowe TG, Blanke K. Adolescent idiopathic scoliosis: a new classification to determine the extent of spinal arthrodesis. *J Bone Joint Surg Am* 2001; **83**:1169–1181.
26 Ibrahim K, Benson L. Cotrel-Dubousset instrumentation for double major right thoracic left lumbar scoliosis, the relation between frontal balance, hook configuration, and fusion levels. *Orthop Trans* 1991; **15**:114.
27 Lenke LG, Betz RR, Clements D, Merola A, Haher T, Lowe T, *et al.* Curve prevalence of a new classification of operative adolescent idiopathic scoliosis. *Spine* 2002; **27**:604–611.
28 Wood KB, Transfeldt EE, Ogilvie JW, Schendel MJ, Bradford DS. Rotational changes of the vertebral-pelvic axis following Cotrel-Dubousset instrumentation. *Spine* 1991; **16**:S404–S408.
29 Lee SM, Suk S, Chung ER. Direct vertebral rotation: a new technique of three-dimensional deformity correction with segmental pedicle screw fixation in adolescent idiopathic scoliosis. *Spine* 2004; **29**:343–349.
30 Suk S, Lee SM, Chung ER, Kim JH, Kim WJ, Sohn HM. Determination of distal fusion level with segmental pedicle screw fixation in single thoracic idiopathic scoliosis. *Spine* 2003; **28**:484–491.
31 Lee CK, Denis F, Winter RB, Lonstein JE. Analysis of the upper thoracic curve in surgically treated idiopathic scoliosis. *Spine* 1993; **18**:1599–1608.
32 Lenke LG, Bridwell KH, O'Brien MF, Baldus C, Blanke K. Recognition and treatment of the proximal thoracic curve in adolescent idiopathic scoliosis treated with Cotrel-Dubousset instrumentation. *Spine* 1994; **19**:1589–1597.
33 Suk S, Kim WJ, Lee CS, Lee SM, Kim JH, Chung ER, Lee JH. Indications of proximal thoracic curve fusion in thoracic adolescent idiopathic scoliosis. *Spine* 2000; **25**:2342–2349.
34 Crawford AH, Macke J, Caudle R. Sagittal plane correction by contoured Harrington rods and interspinous segmental instrumentation. Proceedings of the Annual Meeting of the Scoliosis Research Society, Vancouver, Canada, 1987, 45.
35 Bridwell KH, Betz R, Capelli AM, Huss G, Harvey C. Sagittal plane analysis in idiopathic scoliosis patients treated with Cotrel-Dubousset instrumentation. *Spine* 1990; **15**:644–649.
36 Mielke CH, Lonstein JE, Denis F, Vanderbrink K, Winter RB. Surgical treatment of adolescent idiopathic scoliosis. *J Bone Joint Surg (Am)* 1989; **71**:1170–1177.