SYSTEMATIC REVIEW

Shoulder Imbalance in Adolescent Idiopathic Scoliosis: A Systematic Review of the Current State of the Art

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Abstract

Background: Shoulder imbalance (SI) is among the most rated manifestations of adolescent idiopathic scoliosis (AIS) pointed to by patients and spine surgeons. It serves as a criterion to assess the outcome of scoliosis surgery and is also a cause of dissatisfaction for the patients postoperatively. Despite the availability of multiple studies on this issue, a comprehensive survey of the risk factors and preventive measures has yet to be elucidated. The present study aimed to highlight the most recent approach to the evaluation and management of SI, as well as medical counseling about the expectations and limitations of the surgery.

Methods: A systematic literature review using electric databases was conducted, including PubMed, Embase, the Cochrane Library, and Google Scholar, with a well-defined search strategy on SI definition, risk factors, and preventive and surgical recommendations.

Results: A total of 69 articles were identified; SI > 2 cm was the most used cut-off, and its risk factors included the main thoracic Cobb angle > 80˚, preoperative level shoulder, high left shoulder, and higher Risser grade. The most stated strategies to preclude SI were the sufficient correction of the proximal thoracic curve, and moderate correction of the main thoracic and lumbar curve (LC).

Conclusion: Shoulder imbalance should be prevented not only for appearance or satisfaction but also for possible complications such as distal adding-on, new LC progression, or trunk shift postoperatively in AIS patients.

Level of evidence: V

Keywords: Elevated shoulder, High shoulder, Scoliosis, Shoulder asymmetry, Shoulder balance

Introduction

Adolescent idiopathic scoliosis (AIS) is a complex body disfigurement with a three-dimensional deformity of the spine that distorts the trunk in the form of causing rib hump, waste line asymmetry, neck tilt (NT), and shoulder imbalance (SI) [Table 1]. The primary goal of AIS surgery is to halt the progression of scoliosis and correct the deformities through stable arthrodesis.[1] The success of scoliosis surgery can be judged through a series of clinical (i.e., shoulder level, clinical rib, and lumbar hump) and radiographic parameters. Furthermore, patient-reported outcome measures (PROM) questionnaires such as SRS 22, SRS 30, and Short Form 36 would numerically quantify patient satisfaction with the surgery. Adolescent idiopathic scoliosis patients ideally expect a straightened spine and the loss of hump deformity accompanying balanced shoulders from the scoliosis surgery. Of all, achieving shoulder balance (SB) is relatively unpredictable. Although several recommendations exist regarding restoring SB in scoliosis surgery, none proved a sustainable outcome.

Shoulder imbalance lowers the results of PROM and causes patient dissatisfaction.[2,3] More recent classifications for AIS have tried to incorporate SB in the

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Table 1. Table of abbreviations

Abbreviation	Meaning	Abbreviation	Meaning
AIS	Adolescent idiopathic scoliosis	MT	Main thoracic
AVT	Apical vertebral rotation	NT	Neck tilt
CA	Clavicle angle	PROM	Patient-reported outcome measures
CHD	Coracoid height difference	PSI	Postoperative shoulder imbalance
CRID	Clavicle-rib intersection difference	PT	Proximal thoracic
FRA	First rib angle	RSH	Radiographic shoulder height
LC	Lumbar curve	SB	Shoulder balance
LIV	Lower instrumented vertebra	SI	Shoulder imbalance
LSI	Lateral shoulder imbalance	UEV	Upper end vertebra
MSI	Medial shoulder imbalance	UIV	Upper instrumented vertebra

preoperative evaluation of patients; however, they have yet to gain widespread use.[4,5]

The incidence of preoperative SI in AIS patients was reported at 23%, 32%, and 50% for Lenke 1, Lenke 2, and Lenke 5, respectively; and postoperative shoulder imbalance (PSI) is observed at

20% of Lenke 1, 26% of Lenke 2, and 8-31% of Lenke 5 AIS patients in two years postoperatively.[6,7] This little difference implies the challenge of obtaining a balanced shoulder via surgery and exposes issues regarding torso and shoulder symmetry that are less well understood. The incidence of PSI is the lowest in Lenke 1 AIS compared to Lenke 2 and Lenke 5AIS, which may be due to the experience of surgeons with this common type of scoliosis.

Historically, incorrect selection of upper instrumented vertebra (UIV) was held responsible for PSI; however, several studies demonstrated that a combination of factors led to PSI.[8,9] Postoperative shoulder imbalance could indicate surgical decompensation and the need for possible reoperation. Other complications could follow PSI, such as distal adding-on phenomenon, new lumbar curve (LC) progression, and trunk shift.[10-12] Therefore, spine surgeons should be aware of the risk factors and measures to avoid PSI.

In this review, we go through this common problem encountered in AIS surgery by definition, risk factors, strategies to decrease the chance of PSI, and the subsequent complications of PSI.

Materials and Methods

A systematic literature search was conducted using electric databases, including PubMed, Embase, the Cochrane Library, and Google Scholar for studies written in English available with full-text from January 2000 to December 2021.

The search terms used for databases were “shoulder balance” OR “balanced shoulder” OR “shoulder imbalance” OR “shoulder level” OR “unbalanced shoulder” OR “shoulder height” OR “shoulder tilting”, AND “scoliosis”; the first phrase was substituted sequentially with another; however, “scoliosis” was constant in every search time. Secondary searches were conducted by searching the reference lists of the selected studies; then, further screening was performed according to the inclusion and exclusion criteria.

Inclusion and exclusion criteria

The inclusion criteria of the present study were as follows: all English language studies regarding shoulder imbalance in scoliosis (including case-control study, cohort study, reviews, case series, case reports, and comments). The exclusion criteria consisted of duplicated reports and shoulder imbalance studies in fields other than spine surgery (e.g., sports medicine, physical medicine, and rehabilitation).

Results

A total of 69 articles were identified using the keywords above. Four papers were removed after a review of titles and abstracts, which were neither relevant to the topic nor in the context of scoliosis. All the reviewed studies are depicted in the flowchart, including retrospective studies (n=39), prospective studies (n=15), cross-sectional studies (n=6), review articles (n=3), case report (n=1), and meta-analysis (n=1) [Figure 1; Table 2].

Discussion

Shoulder balance in a healthy population

Recently, normal measures of shoulder height difference and spine alignment have gained growing attention among spine surgeons for preoperative planning and outcome assessment. The shoulder height difference is mainly affected by the rib cage, shoulder girdle, and spine. Shoulder assessment in scoliosis is based on three regions; the neck, shoulder, and axillary region. Therefore, the measurement of the shoulder level alone is less representative of SI.

Kuklo et al.[13] were the first to use numerical value as the cut-off for SI in AIS patients. They designated SI to be present when the difference between radiographic soft tissue shadow over the acromioclavicular joints exceeds

1 cm on either side.

Akel et al.[14] later evaluated 91 asymptomatic adolescent patients through photographs and radiographs taken simultaneously to standardize normative values of SB. They observed that radiological parameters such as coracoid height difference (CHD), clavicle angle (CA), and clavicle-rib intersection difference (CRID) had a high correlation with clinical pictures. The digital photographs revealed that only 19% of adolescents had absolutely level shoulders; if they stepped up the threshold to 1 cm, this number would rise to 72%. The average height difference between shoulders was 1.7 to 13.3 mm; healthy adolescents did not recognize up to 27 mm difference between their shoulders. They concluded that SB in healthy adolescents often does not exist, contrary to the popular belief.

Shoulder balance is thought to be taken for granted because there is symmetry in other parts of human anatomy. In a sample of 273 healthy adolescents, Clement et al.[15] indicated that the average radiographic shoulder height (RSH) difference in the normal population is 0.9 cm (varying from − 1.5 to 2.4 cm, with 95% confidence interval).

Given the normal values, a cut-off of 20 mm difference in shoulder height seems a reasonable threshold to raise suspicion for further evaluations even though 10 mm and 15 mm shoulder height differences have also been used in previous studies as the limit for SI.[16-29]

The growing use of the EOS system (EOS Imaging, Paris, France) has replaced traditional 72-inch-long cassette posteroanterior radiographs, and measures of SB in both techniques did not prove significant differences. Therefore, meta-analysis and pooled data could be retrieved from studies using either technique.[15]

Measurement of shoulder imbalance

No standard clinical or radiologic criteria exist for the SI diagnosis. However, SI is routinely measured in three ways: radiographically, clinically, and cosmetically. The correlation between clinical, radiographical, and patient impressions of SI has been investigated in previous studies.[13-15,30]

The radiographic balanced shoulder has always been regarded as equivalent to having a level shoulder height. Nevertheless, Qiu et al.[31] noted there is a discrepancy between radiographic SB and cosmetic SB; the latter emphasizes more on areal balance and symmetry. They found radiographic parameters could only partially reflect the shoulder cosmetic appearance (correlation coefficient≤0.8). However, higher inter- and intra-observer reliability analysis of radiographic SB measures compared to clinical and cosmetic measures proved its helpfulness in practice.[14,30]

Clinical evaluation of shoulder imbalance

The one that is visible to the patient should be considered the most important reference; it can be carried out anteriorly or mostly posteriorly; however, no strong correlation between anterior and posterior clinical SB was observed, and surgeons should evaluate both sides in planning deformity correction.[32,33] The most commonly used parameters for clinical assessment of SI are reviewed here [Figure 2].

1-Shoulder level angle (biacromial angle/clinical clavicle angle) is the angle formed between the line that touches both the acromion and the horizontal plane. It is measured anteriorly or posteriorly, and a different value is not surprising. A shoulder level angle of more than 2° is considered the cut-off for having SI [Figure 2A].[34]

2-Anterior/Posterior axillary angle is the angle between the line touching both the axillary fold and the horizontal plane, with the patient being observed ventrally or dorsally [Figure 2A].

3-Scapular prominence and scapular angle, Scapular

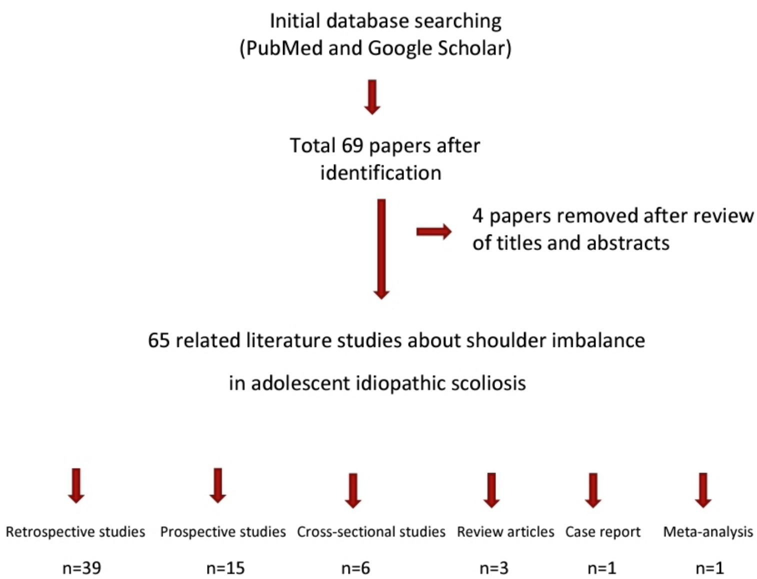

Figure 1. Flowchart outlining data retrieval and analysis.

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Table 2. Highlights of studies on shoulder imbalance

Year of publication	Author(REF NO) (study type)	Lenke Type	No. of patients (mean follow up year)	Purpose of study	Conclusion of study
2021	Isogai (24) (Retrospective cohort)	Lenke 2	72(2y)	To investigate the risk factors of PSI in patients with Lenke 2 including the position of preoperative upper end vertebra.	Upper end vertebra at T1 and Risser grade ≥3 at the time of surgery are significant risk factors of PSI
2021	Bram (52) (retrospective cohort)	Lenke 1-4	407(2y)	To examine the impact of preoperative left shoulder elevation and choice of UIV on PSI.	Preoperative Left shoulder elevation is less likely to achieve shoulder balance postoperatively. Choice of higher UIV did not affect PSI. A PTC > 34.5° was predictive of severe PSI in patients with preoperative LSE
2020	Okada (18) (Retrospective cohort)	Lenke 5C	100 (3y)	To evaluate the risk factors of PSI in patients with Lenke type 5C curves.	Excessive correction of the lumbar curve of >73% and preoperative T1 tilt of >4° can be risk factors for PSI in patients with Lenke type 5C curve.
2016	Lee (23) (Retrospective Cohort)	Lenke 2	80 (2.5y)	To identify the radiographic factors related to PSI	PSI correlates with a higher Risser grade, a larger postoperative PWA, and a higher postoperative PTC/MTC ratio.
2017	Gotfryd (34) (Prospective cohort)	Lenke 1	52 (2y)	To determine the predictors of the shoulder balance after MTC fusion in Lenke 1	Correction of the main right thoracic curve could be enough to balance the shoulders. Preoperative level shoulder is predictive of a deformity reversal after MTC fusion.
2018	Zhang (6) (Meta-analysis)	All types	26 studies Variable follow up	To detect the incidence and risk factors for PSI in AIS	Pooled incidence of PSI is 26% ; risk factors for PSI: Risser sign, Preoperative LC, Postoperative positive RSH, Correction rates of PTC, MTC, and LC at follow-up. Adding-on associates with PSI.
2019	Yang (25) (Retrospective Cohort)	All types	114 (2y)	To explore the risk factors of PSI and determine whether PSI could be predicted	Adding-on and AVT of PTC were the risk factors. Thus, sufficient correction of AVT of PTC and prevention of adding-on is necessary.
2019	Sielatycki (59) (Retrospective Cohort, multicenter)	Lenke 1&2	145 (5y)	To assess how ''overcorrection'' of the MTC without control of the proximal curve increases the risk for shoulder imbalance in Lenke type 1 Adolescent Idiopathic Scoliosis	Significant correction of MTC (>54%) with simultaneous ''under-correction'' (<52%) of PTC resulted in PSI in 59% of patients, regardless of the UIV. Hence the PTC must be carefully scrutinized in order to optimize shoulder balance, especially when larger correction of the MT curve is performed.
2016	Amir (9) (Retrospective cohort)	Lenke 1&2	84 (2y)	To determine if surgically leveling the upper thoracic spine in patients with AIS results in level shoulders	Leveling the upper thoracic spine does not guarantee clinically balanced shoulders or clavicles. Trapezial prominence was impacted by leveling T1 and the first rib and by minimizing the upper thoracic curve.
2013	Yaszay (7) (Prospective cohort multicenter)	Lenke 5	104 (2y)	To identify the frequency of an opposite high shoulder in Lenke 5 patients and evaluate factors that influence preoperative and postoperative shoulder balance	Half of all Lenke 5 curves have a high opposite shoulder that is influenced by the size of the compensatory thoracic curve. Postoperatively, most patients had level shoulders. Inclusion of the thoracic spine did not influence postoperative shoulder balance.
2016	Luhmann (8) (retrospective cohort)	All Types	619 (2y)	To determine whether T1 tilt could be used as an intraoperative proxy for shoulder balance determination	Lenke 3 and 6 curve patterns demonstrated preoperative to postoperative correlation with T1 tilt, but in other Lenke types T1 tilt cannot be used as an intraoperative proxy for shoulder balance.
2019	Jiang (11) (retrospective cohort)	Lenke type 2B/C	25 (2y)	To evaluate the association between postoperative lumbar curve progression and the shoulder height in AIS patients with Lenke type 2B/C	Postoperative lumbar curve progression is a risk factor for deterioration of shoulder imbalance in patients with Lenke 2B/C AIS during the follow-up period, because the lumbar curve progressed to the left side, the left shoulder would be further elevated.

*AIS: Adolescent idiopathic scoliosis. AVT: Apical vertebral translation. CA: Clavicle angle. CHD: Coracoid height difference.
CRID: Clavicle rib intersection difference. MTC: Main thoracic curve. LC: Lumbar curve. PSI: Postoperative shoulder imbalance.
PTC: Proximal thoracic curve. PWA: Proximal wedge angle. UIV: Upper instrumented vertebra.

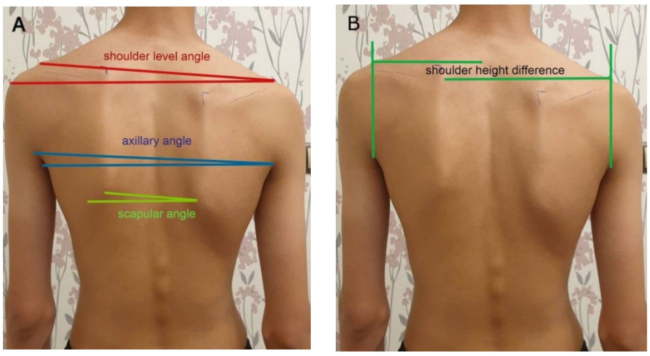

Figure 2. Clinical shoulder evaluation A, Shoulder level angle, axillary angle, and scapular angle. B, Shoulder height level.

prominence is recorded as yes or no; and the scapular angle is formed by the line joining the inferior poles of the scapulae and the horizontal line, a scapular angle > 9° is the single best indicator of SI with a 100% sensitivity and specificity [Figure 2A].[35]

4-Shoulder height difference, Vertical lines are drawn through the posterior axillary folds. The height difference between the intersection of these lines and horizontal lines on shoulders is measured to reflect the clinical SB [Figure 2B].

5-Trapezial angle is the angle between the horizontal line and the line connecting the intersection of sternocleidomastoid muscle and trapezius muscle profiles [Figure 3A].

6-Trapezial area is enclosed by the following borders: a line connecting the top margin of acromial processes, a perpendicular line to it through the intersection of the sternocleidomastoid muscle and the trapezius muscle, and the superior margin of the trapezius muscle [Figure 3B].

Ono et al. [36] further subdivided SI into two distinct regions of medial and lateral SI. Medial SI is reflected in trapezial prominence resulting from a tilted T1 vertebra or proximal ribs and lateral SI depends on CA. He also proved that lateral SI is weakly correlated with T1 tilt, first rib angle, and the upper thoracic curve size.

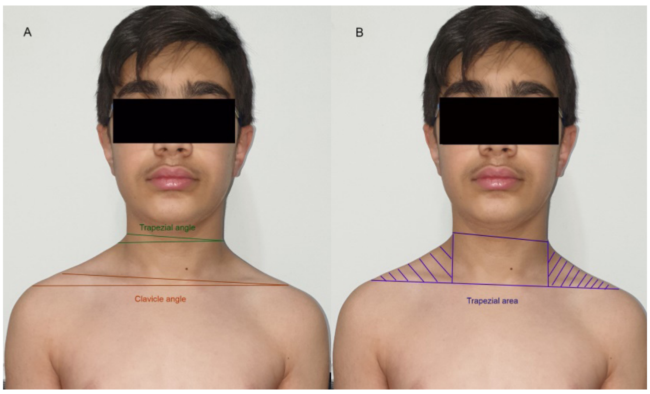

Figure 3. Clinical shoulder evaluation A, Trapezial and clavicle angle. B, Trapezial area.

Briefly, a balanced shoulder exists medially when the height difference of the right and left trapezial angle tip is less than 1 cm; accordingly, a difference of less than 2 cm for lateral shoulder height represents a laterally balanced shoulder.[3]

Radiographical evaluation of shoulder imbalance

Although some studies[14,30] found a strong correlation between radiographic and clinical evaluation for SI, Yang et al.32 could not get more than a moderate correlation (r=0.4) in Lenke 1 and even lower in Lenke 2 AIS patients.

1- Lateral shoulder imbalance (LSI) radiographic parameters

Coracoid height difference (CHD) measures the height difference in millimeters between the coracoid processes by drawing a horizontal line at the upper margin of each. Moreover, CHD > 9 mm indicates SI. In addition, CHD, along with CA, shows the highest correlation coefficient with clinical pictures [Figure 4A].[14]

Clavicle angle (CA) denotes the angle between a line connecting the highest points of both clavicles and the horizontal plane. Moreover, CA > 2° is regarded as having SI and a high preoperative CA predicts a probable PSI.[13] Hong et al.[30], in their reliability analysis of SB measures, indicated that CA and CHD are reliable parameters and

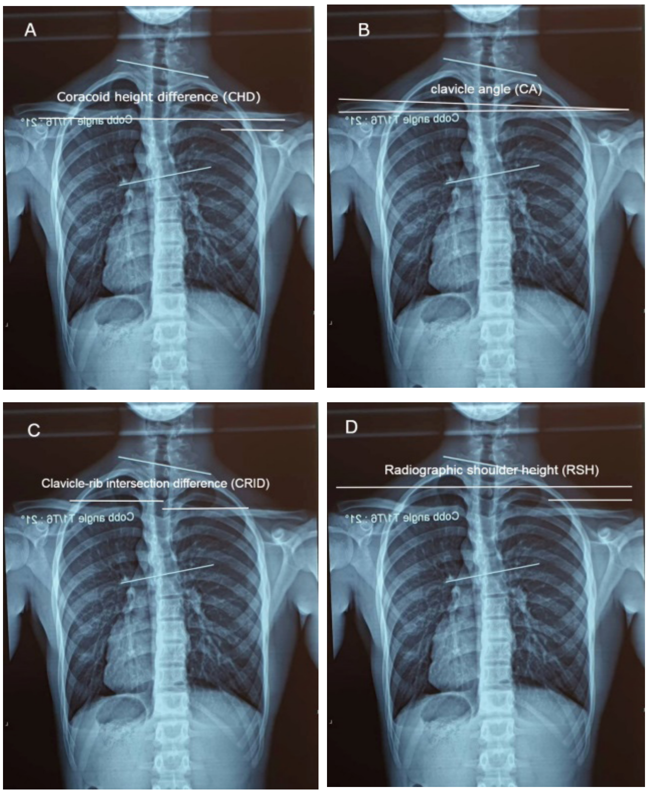

Figure 4. Lateral shoulder imbalance radiographic parameters. A, Coracoid height difference (CHD). B, Clavicle angle (CA). C, Clavicle-rib intersection difference (CRID). D, Radiographic shoulder height (RSH).

useful clinical methods for SI evaluation [Figure 4B].

Clavicle-rib intersection difference (CRID) represents the height difference between the horizontal lines passing through the intersection point of the superior border of the clavicle with the outer edge of the second rib. Bagó et al.[37] outlined CRID and CHD as reliable indirect references with high correlation coefficients (r=0.93 and r=0.96, respectively) to estimate actual SB [Figure 4C].

Radiographic shoulder height is the height difference of soft tissue shadows directly superior to acromioclavicular joints in millimeters. Radiographic shoulder height is the most commonly used parameter to assess SI in the literature and is regarded as an alternative to clinical shoulder evaluation in most studies [Figure 4D]. Currently, the most reliable measures of shoulder level are CA difference, CRID, and CHD.[13,14,30,38]

2- Medial shoulder imbalance (MSI) radiographic parameters

T1 tilt is outlined as the angle between the horizontal line and the line through the upper endplate of T1 [Figure 5A]. The T1 tilt has been initially utilized to estimate clinical SI; however, further studies could not find a strong correlation between T1 tilt and SB (mild correlation, r=0.54).[13,23,37,39] Akel et al.[14] revealed that T1 tilt could not differentiate between normal and abnormal clinical SB. Furthermore, Luhmann et al.[8] demonstrated that T1 tilt cannot be used as an intraoperative proxy to determine PSI.

The first rib angle (FRA) represented a tilt of a tangential line that connects both tops of the first ribs [Figure 5B]. The first rib angle is usually associated with the presence of a proximal thoracic (PT) curve. A positive value is adopted for T1 tilt and FRA when the highest side is left, and a negative value is assigned when the right side is more elevated.

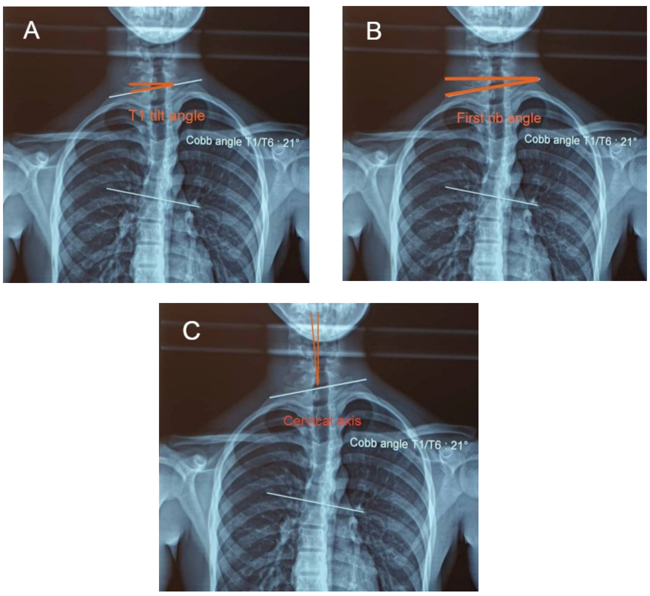

Figure 5. Medial shoulder imbalance and neck tilt radiographic parameters. A, T1 tilt angle. B, First rib angle. C, Cervical axis.

Neck tilt radiographic parameters

The cervical axis indicates NT and is the angle between the longitudinal axis of the cervical spine (line drawn from the center of the C2 odontoid process to the center of C7) and the vertical axis [Figure 5C]. Both medial SI and NT could predict the distal adding-on phenomenon.[40,41]

Cosmetic shoulder balance

Although AIS patients might have the same radiologic findings, they might have relatively different physical appearances. Qiu et al.[42] investigated the association between radiologic measurements and cosmetic appearance (trunk and waistline) in AIS patients and found that it was the apical vertebral translation, not the Cobb angle, that had the highest correlation coefficient with cosmetic appearance. Although perfect radiographic SB is being achieved, AIS patients often complain about the residual cosmetic deformity; this discrepancy between radiographic SB and what an AIS patient feels led to the concept of cosmetic SB.[31]

It has been debated that radiographic parameters might not be a good substitute for clinical shoulder evaluation.[43] Sharma et al.[44] emphasized the gap between radiographic indices and cosmetic deformity (r≤0.7) in Lenke 1C scoliosis and concluded that overreliance on radiographic indices could be misleading.

Cosmetic shoulder indices bring more accuracy to visual inspection. It is carried out by transferring photographs of patients back to a computer. Then, cosmetic parameters such as outer/inner shoulder height, shoulder area index, shoulder angle, and axilla angle are measured [Figure 6].

Neck tilt

Neck tilt occasionally accompanies SI and aggravates shoulder appearance. It is defined radiographically as the deviation of the cervical axis from the vertical plane and clinically described as the right and left trapezius muscle outline difference in front of a grid. Neck tilt correlates well with T1 tilt and occurs due to residual PT curve or overcorrection of the main thoracic (MT) curve. Neck tilt is distinct from SI, whereas a patient could simultaneously have both.[38] Although NT is not an indicator of SI, it damages the body symmetry concept and may induce the thought of shoulder height discrepancy. Furthermore, NT could affect postoperative outcomes.

In a study conducted by Chan et al.,[45] it was reported that preoperative “cervical axis” deviation increases the risk of distal adding-on by 5.4 times following surgery in Lenke 1 and Lenke 2 AIS patients. They postulated that head tilt follows NT; therefore, asymmetry in labyrinths and eyes forced the body to restore the horizontal gaze and ears by distal adding-on mechanism.

Additionally, immediate postoperative shoulder or neck imbalance is not a significant risk factor for the postoperative distal adding-on phenomenon. Postoperative NT is a compensatory mechanism to neutralize the newly imposed coronal imbalance if any. Sufficient correction of the PT curve and avoiding overcorrection of coronal malalignment should be taken into account and let the remaining MT curve and LC motion segments compensate for coronal balance when operating on Lenke 1 and 2 AIS patients.[46,47]

Jiang et al.[48] in a study revealed that Lenke type 2 AIS patients with right-elevated shoulder gained improved SB but deteriorated cervical tilt after partial/non-fusion of the PT curve. Therefore, they recommended complete fusion of the PT curve to prevent the residual cervical tilt in these patients.

Risk factors for postoperative shoulder imbalance

Demographic factors, including age, gender, and BMI, are not among the risk factors for PSI. However, Risser grade ≥ 3 is a known risk factor for PSI,[24] implying that skeletally mature patients are more likely to suffer from PSI at the time of surgery. This is primarily due to the lower ability of compensation in older age as well as the more rigid curve a surgeon might encounter.

Risser grade ≤ 3 is also an independent risk factor for distal adding-on, regardless of lumbar fusion level.[6]

Patients with rigid PT curves (Lenke 2 and 4) are at particular risk of PSI, even with proximal thoracic instrumentation.[49] Upper-end vertebra (UEV) of the PT curve mainly lies at T2; when a longer PT curve extends to T1 instead of the more frequent T2, the odds of SI significantly increase; thus UEV at T1 is regarded as a risk factor for PSI in Lenke 2 AIS.[24]

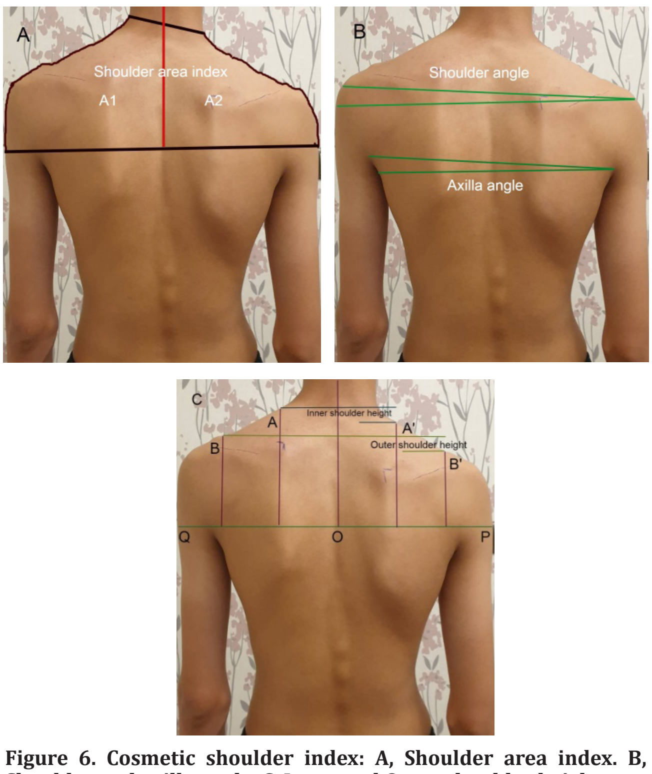

Figure 6. Cosmetic shoulder index: A, Shoulder area index. B, Shoulder and axilla angle. C, Inner and Outer shoulder height.

A level shoulder preoperatively in AIS patients indicates the spine is in a balanced state with compensation, and any change in this chain would probably decompensate it and risk SB. Of note, excessive correction increases the risk of SI in less severely affected patients.[50,51]

A high preoperative left shoulder also carries a much higher risk of PSI compared to a right-elevated shoulder since the PT curve is usually more rigid than the MT curve and less correctable.[52]

A low preoperative MT curve flexibility (<55%) is a significant predictor of PSI. A reasonable surgical strategy is to consider proximal fusion in the presence of low-flexibility MT curves and less aggressive MT curve correction. Achieving a level T1 in low flexibility curves should be a priority and may require fusion of the PT curve. Residual T1 tilt ≥ 9° intraoperatively increases the odds of PSI to 7.2 times.[16] Overcorrection of the MT curve using modern pedicle screws may be beyond the flexibility of the PT curve for spontaneous correction and leads to reversion of preoperative SI; the most commonly elevated shoulder postoperatively is the one that was depressed preoperatively.[26,53]

Ohrt-Nissen et al.[16] proposed that a sensible cut-off for MT curve correction may be a maximum of 20% "over correction" more than the fulcrum flexibility measure. Insufficient correction of the PT curve is associated with the occurrence of PSI, and the residual curve brings on shoulder height difference. Results on the degree of LC correction are not that straightforward; LC overcorrection is found in most PSI patients compared to balanced shoulder patients.[18]

Although shorter distal fusion and less correction of LC could lead to better SB through its compensatory mechanism, distal adding-on and new LC progression may lurk; therefore, the relationships between the PT curve, MT curve, and LC should be scrutinized meticulously by the surgeons. The abovementioned risk factors are applicable to moderate AIS (<80˚curve). In severe AIS and congenital scoliosis with complex pathogenesis, preoperative RSH and T1 tilt were found to be independently predictive of PSI.[54]

Dealing with a proximal thoracic curve

As a rule of thumb, a severe preoperative left-sided SI (≥2.0 cm) is less likely to gain balance postoperatively.[52] Fusion to T1 or T2 controls the PT curve, although it does not accurately predict a balanced shoulder[29]. Furthermore, the benefits of going such high should be weighed against the costs such as prolonged surgery time, more blood loss, more muscle dissection and denervation, scar visibility in the lower neck, and prominency of instrumentation. Suk et al.[1] proposed including a PT curve in the fusion when the preoperative shoulder asymmetry was ≤ 12 mm to minimize the risk of iatrogenic reversion of the shoulder deformity.

Amir et al.[9] prospectively analyzed 84 Lenke 1 and 2 AIS patients and observed that leveling the upper thoracic spine does not guarantee clinically balanced shoulders. In another research, Yang et al.[28] noticed lateral SB is not controlled by instrumentation to T2, although positive T1 tilt indicates fusing to T2 to improve medial SB. Brooks et al.[26] in a multicenter review of prospectively collected data on 626 all Lenke-type AIS patients, found the selection of T4 as a UIV resulted in more SB postoperatively than T2 or T3, irrespective of which shoulder was elevated preoperatively, and fusing to T2 only improved PT curve correction.

On the contrary, in another study, fusion to T2 compared to T3/T4 improved SB in Lenke 2 AIS patients with greater skeletal maturity (Risser grade≥4) and a more flexible MT curve.[55]

Although the choice of UIV has been much disputed, shoulder level could be a practical modifier for this dilemma. Proximal thoracic curve fusion (UIV at T1/T2) acts as a left shoulder depressor, and MT curve fusion (UIV at T4/T5) is a right shoulder depressor; hence a fine-tuning of the level and magnitude of the correction is a prerequisite for achieving a balanced shoulder.

In the AIS Lenke classification, the side bending PT curve ≤ 25° is regarded as non-structural and could be left unfused. However, recent studies demonstrated two subclasses with different prognoses in this group of patients. If a PT side bending value lies between 24° to 15°, poorer shoulder and neck balance is expected compared to when the PT curve is corrected to less than 15°, which in this subclass a better T1 tilt, CA, and subsequently better shoulder and neck balance emerge postoperatively.[56]

In another earlier study, the concept of selecting UIV based on shoulder level was explained and Ilharreborde et al.[57] recommended that PT curve fusion is better to be performed based on SB status and T1 tilt, not only based on curve rigidity.

Although SI is a distinct feature of Lenke 1 and 2 AIS patients, it may be seen in Lenke 3 or 5 AIS patients as well. In addition, different patterns of SI exist with each type. Menon et al.[58] discovered four patterns of SI according to shoulder directionality relative to T1 tilt which were subdivided into concordant (left shoulder up with positive T1 tilt or right shoulder up with negative T1 tilt) and discordant (left shoulder up with negative T1 tilt or right shoulder up with positive T1 tilt). He concluded that the relationship between the proximal spine and shoulder was independent of the PT curve structurality and proposed that fusion to T2 would be necessary for all the discordant patterns.

The T1 tilt is not a reliable intraoperative proxy to determine postoperative SB in Lenke 1 and 2, owing to inconsistent relation with RSH. However, T1 tilt positively correlated with RSH in Lenke 3 and 6 curve patterns.[8,9]

Inadequate correction of the PT curve or overcorrection of the MT curve sets a new coronal imbalance and leads to the occurrence of PSI or distal adding-on to compensate for this shift.

Sielatycki et al.[59] observed that if PT curve flexibility in Lenke 1 and 2 AIS patients was lower than 52%, significant correction of the MT curve (>54%) would result in PSI regardless of the UIV level. He also found that if PT curve flexibility exceeded 52%, a balanced shoulder would probably follow postoperatively, irrespective of the MT curve correction.

The scoliosis correction technique

Rod derotation technique for MT curve correction may worsen the vertebral rotation of the PT curve; however, its significance on SI is unclear.[60] A study performed by Chang et al.[5] demonstrated that the direct vertebral rotation method gained better PT curve correction than the rod derotation technique; however, no statistically significant difference was observed in SB at the final follow-up.

Moreover, using hooks at UIV acts as an autoregulator for SB and reduces the RSH in two years postoperatively without giving rise to distal adding-on[61]; supra-transverse hooks also help push down either shoulder effectively through the rib cage.

Terheyden et al.[49] recommended favoring derotation of the MT curve over the concave side distraction in AIS surgery to achieve better SB.

Selecting upper instrumented vertebra

The shoulder girdle is not directly connected to the spine. Thus, spine adjustment might be insufficient to get balanced shoulders in AIS patients. Although thoughtful UIV selection guarantees no SB, incorrect UIV selection would cause probable SI.

Recommendations for fusion levels have evolved from the time of King's classification to Lenke AIS classification, Ilharreborde,[57] and Trobisch.[62] Bjerke et al.[29] published a literature review on the UIV selection effect on SB and concluded that all three methods (Lenke, Ilharreborde, and Trobisch) ended up with the same result. Currently, the most commonly used guideline for obtaining postoperative SB is based on a paper published by Rose and Lenke in 2007,[63] and fusion to T2 is recommended if:

-PT Cobb angle > 30°
-PT apical vertebral rotation ≥ Grade 1
-PT apical translation ≥ 1 cm
-Preoperative left shoulder elevation
-T1 is tilted toward PT concavity
-PT/MT transitional vertebra at T6 or below
-Left shoulder elevation with a push-prone radiograph.

Trobisch, in his literature review in 2013, described a simplified algorithm for UIV selection using Lenke type and SB; in patients with Lenke 1, 3, and 6 with a high left shoulder, fuse to T2, neutral to T3, and high right shoulder to T4; and for Lenke 2 and 4, instrumentation to T2 is recommended, and for Lenke 5, fusion to the UEV of the thoracolumbar/LC is recommended. Ilharreborde UIV selection rule is based on T1 tilt and SB direction; when they are in the opposite direction, T2 is chosen; if T1 tilt and SB are in the same direction to the left (i.e., right shoulder up), T4 is recommended and by the time T1 tilt and SB are in the same direction to the right (i.e., left shoulder up), T2 is selected. Ilharreborde guideline only applies to the PT and MT curves that proportionately correct on the lateral bending radiographs toward the convex side (almost the same flexibility); in the presence of a rigid PT curve and flexible MT curve, T2 would be the ideal UIV. Practically, shoulder level takes priority over PTC rigidity when choosing UIV; partial or non-fusion of PT curve is advocated if patients with

Lenke 2 AIS have preoperative right-elevated shoulder because the correction of MT curve will elevate the left shoulder and restore SB.[57] Right-elevated shoulder occurs in Lenke 2 AIS patients if the apex of MT curve is proximal or MT Cobb angle is large.[59]

Scoliosis correction rate effect on shoulder imbalance

Gotfryd et al.[34] reported that the amount of MT curve correction did not negatively affect the SB. However, later studies proved otherwise and recommended proportionate curve correction to achieve better SB.[1,18] The amount of surgical correction of the MT curve is directly associated with SI; the greater the correction of the MT curve, the greater the chances of SI. Every 5 degrees of additional correction of the MT curve beyond the first 40° would increase the likelihood of SI by 21%. As a result, patients with higher preoperative MT Cobb angle are at higher risk for PSI.[64] The PT curve flexibility and correction rate is lower compared to the MT curve; therefore, the effect of left-shoulder elevation gained from MT curve correction is much stronger than the effect of right-shoulder elevation gained from PT curve correction. In Lenke 2 AIS patients, it would be no surprise that a selective thoracic fusion without including a PT curve might be all that is necessary to achieve a balanced shoulder.[62]

Spontaneous correction of shoulder imbalance

Mainly, a significant difference is observed in SB measured by RSH in the immediate postoperative period compared to the last follow-up; the early postoperative SB status might be affected by postoperative pain and malposture, which improves gradually.[65] The average time for spontaneous SB (CHD and CA) ranges from 7 to 12 months (in 90% of patients) and continues to improve during the first 24 months after the surgery.[66] The spontaneous development of cosmetic SB will also occur (about 1 cm) if UIV is selected appropriately. Left shoulder elevation is the frequent pattern of PSI and is less responsive to spontaneous correction.[6,67] Spontaneous correction of SI happens through a combination of mechanisms such as distal adding-on, wedging of the proximal disc to UIV (predominantly in patients with Risser grade≤3), visualization of a level shoulder in the mirror (muscle tone adjustment around scapula), and inner ear labyrinth role in maintaining a level head.

Postoperative shoulder imbalance consequences (distal adding-on)

Postoperative shoulder imbalance, as a deviation, forces the body to put things in order again, and this process could result in a new LC progression or a distal adding-on phenomenon. Wang et al.68 defined "distal adding-on" as a progressive increase in the number of vertebrae included within the distal curve after instrumentation, whether an increase of 5 mm in the deviation of the lower instrumented vertebra (LIV)+1 from the central sacral vertical line or an increase of 5° in the angulation of the first disc below the instrumentation. It could cause disc degeneration and correction loss, and reoperation. Incorrect selection of the LIV is typically the primary cause of distal adding-on after selective thoracic fusion, though postoperative T1 tilt is mentioned as another factor in other studies.[10,21,41]

The distal adding-on phenomenon is associated with PSI,[21,23,40] and a multicenter study by Cao et al.[21] revealed that this relation is weak (r=0.228), although significant (P≤0.05); It also acts as a compensatory mechanism for PSI and improvement of PSI after the occurrence of distal adding-on were reported in Lenke 2 AIS patients during the follow-up.

Chan et al.[45] showed that preoperative "cervical axis" deviation increases the risk of distal adding-on following surgery in Lenke 1 and 2 AIS patients.

Distinguishing distal adding-on from lumbar curve progression

Distal adding-on as an extension of a right MT curve usually elevates the right shoulder. Consequently, residual left-elevated SI could be neutralized by the progression of this phenomenon.[11]

This is mainly observed in patients with thoracic scoliosis with a lumbar modifier of A; while an inadequate selection of LIV in patients with a lumbar modifier of B C could result in new LC progression[55,69]; or even worse, it might cause trunk shift in some Lenke 1C patients who failed to grow a new compensatory LC.[12] New LC progression is frequently a left-sided curve that is the opposite of distal adding-on with a right-sided curve. The advent of new LC progression, unlike distal adding-on, could deteriorate an already balanced shoulder during follow-up.[11]

Postoperative shoulder imbalance indicates that the spine is not proportionately corrected during the AIS surgery and any new change in SB is confronted to some extent in the form of spontaneous correction or coronal decompensation (distal adding-on or new LC progression). We favor the concept of a "balanced shoulder" rather than a "level shoulder" focusing more on symmetry and clinical shoulder assessment. Risk factors for PSI consist of a high MT Cobb angle, preoperative level shoulder, high left shoulder, and higher Risser grade. Our strategies to prevent PSI include sufficient correction of the PT curve and moderate correction of the MT and LC curves, use of supra-transverse hooks at UIV and tilting UIV up or down depending on its station, correct LIV selection (in lumbar modifier B/C, LIV≥L3 is safe), achieving maximum SB intraoperatively for Risser grade ≥ 4 due to low potential for spontaneous correction, and offering final fusion to all growing rod graduates for a better SB.

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