

13. High Accuracy, Strong Reliability, and Test–Retest Stability in Identifying New Transverse Plane Modifiers of the SRS–Lenke–Aubin 3D Classification of AIS

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Hypothesis

The transverse-plane modifiers of the new SRS–Lenke–Aubin 3D classification can be identified with high accuracy and inter- and intra-assessor agreement.

Design

Test–retest usability and reliability study of AIS cases with standardized 2D and 3D displays and ground-truth comparison of the 2 transverse plane modifiers across two assessment sessions.

Introduction

The SRS–Lenke–Aubin 3D classification of AIS is recently published, but the ability to accurately recognize the new transverse plane modifiers is unknown.

Methods

Ten members of the SRS 3D Classification Task Force independently assessed 30 AIS cases (Lenke 1–6) across 2 sessions one week apart, with cases randomized per session. Cases were reviewed using radiographs with 2D measures, transverse views with key 3D measurements, and the standard Lenke classification. Participants assigned two transverse-plane modifiers of the new SRS–Lenke–Aubin 3D classification: ORPD (Orientation of the Regional Planes of Deformity: 1 <70°, 2 70–89°, 3 ≥90°) and AVR (Apical Vertebral Rotation: s <10°, m 10–19°, l ≥20°) for the proximal thoracic, main thoracic, and thoracolumbar/lumbar regions (6 values/case; 180 responses/participant/round). Accuracy was computed vs. a predefined ground truth. Within-round agreement was quantified using intraclass correlation coefficients (ICC; two-way random-effects, absolute agreement) and Fleiss' kappa. Test–retest stability was assessed using exact agreement, quadratic weighted kappa (kw), and ICC. Completion time was summarized, excluding outliers using the 1.5×IQR rule.

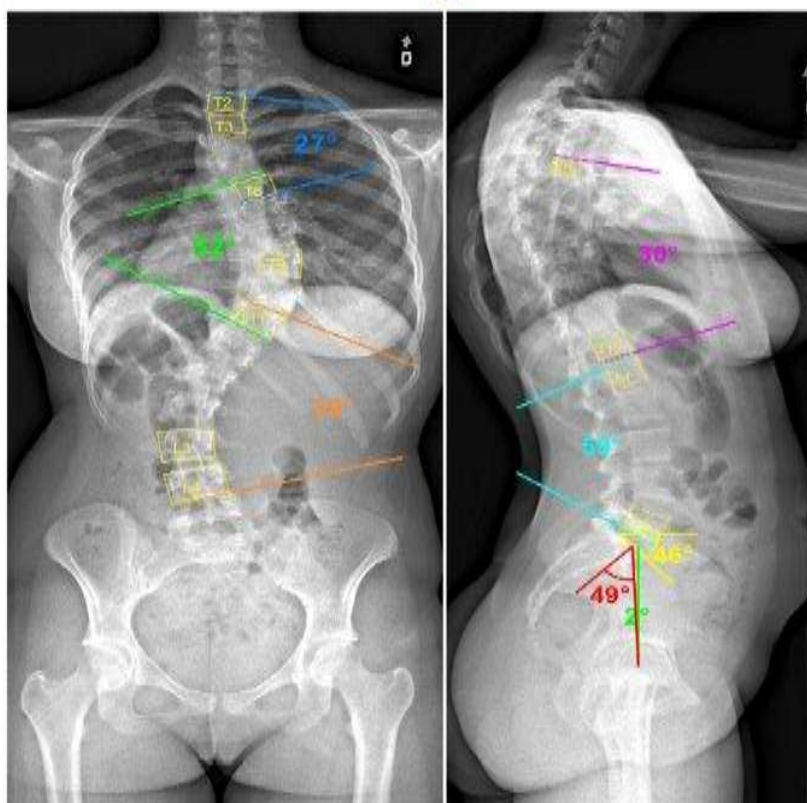
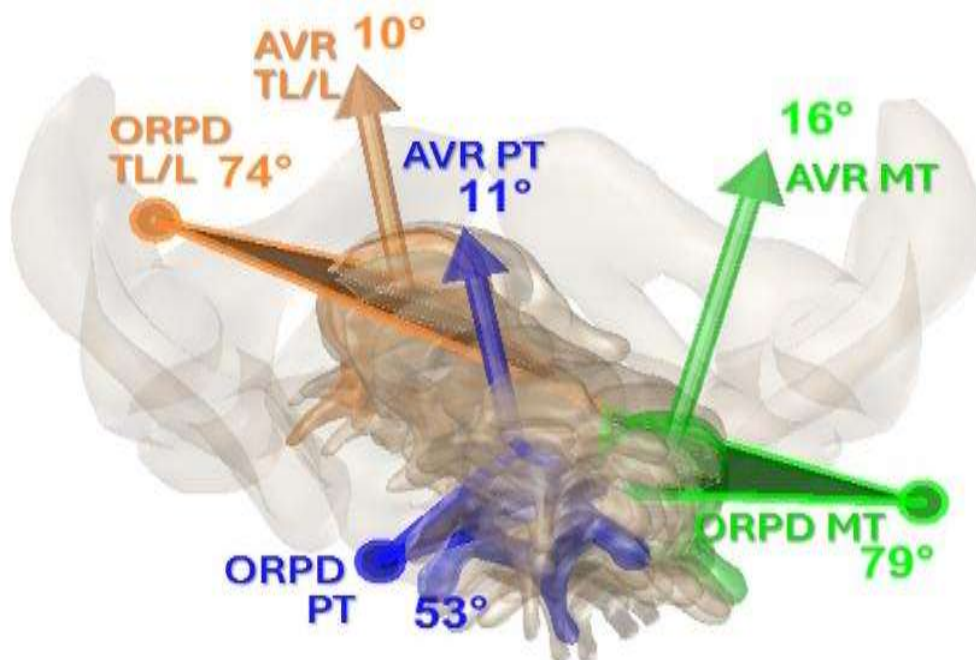
Results

Accuracy vs. ground truth was 98.33% in Round 1 and 98.39% in Round 2, with exact test–retest agreement of 97.83%. Test–retest consistency was very high for both modifiers (pooled kw =0.957 for ORPD; 0.982 for AVR). Test–retest ICC(2,1) was 0.957 for ORPD and 0.983 for AVR; complementary two-way mixed-effects ICC(3,1) yielded similar values, confirming excellent temporal stability of modifier identification. Mean completion time (one outlier excluded) decreased from 24.2±9.3 to 20.2±7.2 min.

Conclusion

Across a broad spectrum of AIS cases, participants consistently identified the transverse-plane modifiers with very high accuracy, strong within-round agreement, and robust test–retest stability, supporting the usability and reliability of the new SRS–Lenke–Aubin 3D Classification framework.

SRS-Lenke-Aubin 1BN P1m T2m L2m



Case example.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡ SRS Funded Research Grant

14. Beyond the 2D Lenke Classification: Clinically Relevant Insights from Transverse-Plane Descriptors of the SRS-Lenke-Aubin 3D Framework in Lenke 1 AIS

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Hypothesis

Transverse-plane descriptors of the SRS–Lenke–Aubin 3D classification capture clinically relevant features of Lenke 1 AIS not fully captured by 2D Lenke modifiers or radiographic measures.

Design

Retrospective analysis using transverse-plane descriptors derived from the SRS–Lenke–Aubin 3D classification.

Introduction

Lenke 1 is the most common AIS pattern, yet assessment relies mainly on radiographic 2D measures. This study examined whether transverse-plane descriptors—orientation of the regional plane of deformation (ORPD), apical vertebral rotation (AVR) and apical 3D distance to the end-vertebrae line (DAEVL)—provide clinically relevant information beyond standard 2D characterization.

Methods

101 Lenke 1 AIS cases were 3D reconstructed from preop radiographs. ORPD, AVR, and DAEVL were analyzed in proximal thoracic (PT), main thoracic (MT), and thoracolumbar/lumbar (TL/L) regions and compared with 2D measures: Cobb, thoracic kyphosis (TK), lumbar lordosis (LL). Associations between Lenke modifiers and transverse-plane modifiers were assessed using contingency tables (χ^2 , Cramér's V). Pearson correlations and multivariate regression evaluated regional coupling and independent coronal and sagittal contributions to ORPD. Subgroup analyses compared Lenke 1A, 1B, and 1C curves.

Results

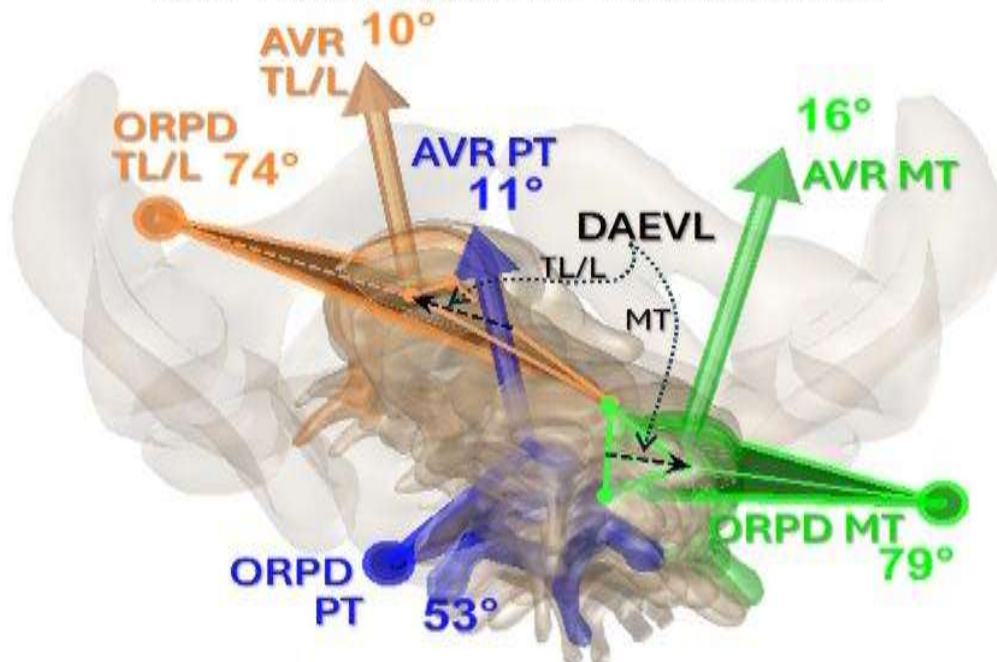
ORPD showed no association with Cobb magnitude in thoracic regions, but a moderate association in TL/L. Cobb–AVR correlations were weak to moderate across regions. ORPD and AVR were independent in the thoracic spine yet moderately coupled in TL/L. Lower TK correlated with increased MT ORPD. LL was unrelated to TL/L ORPD. DAEVL was moderately associated with Cobb magnitude and selectively with ORPD and AVR, mainly in TL/L. Strong associations emerged between Lenke lumbar modifier and TL/L ORPD, and between thoracic sagittal profile modifier and MT ORPD ($p < 0.01$). Multivariate analyses confirmed region-specific patterns, with MT ORPD driven by sagittal alignment and TL/L ORPD by coronal severity. 3D involvement increased from Lenke 1A to 1C.

Conclusion

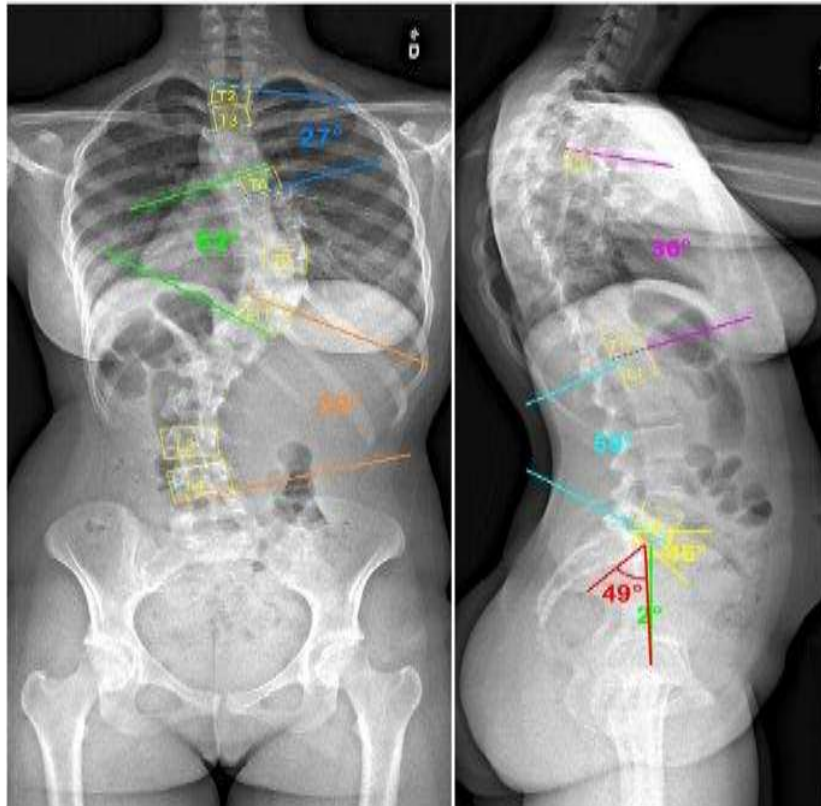
In Lenke 1 AIS, substantial 3D heterogeneity was noted, with similar Cobb angles corresponding to markedly different transverse-plane patterns. ORPD, AVR and DAEVL therefore provide complementary, region-specific characterization beyond conventional 2D assessment, supporting their integration within the SRS–Lenke–Aubin 3D classification.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

Transverse plane descriptors of the SRS-Lenke-Aubin 3D Classification



SRS-Lenke-Aubin 1BN P1m T2m L2m



§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡ SRS Funded Research Grant

15. A Quantitative CT-Based Analysis of Vertebral Rotational Asymmetry and Pulmonary Function in Scoliosis

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Hypothesis

We hypothesized that CT-derived global rotational asymmetry between the main and compensatory curves ($\Delta R(M-C)$) is most strongly associated with pulmonary function test outcomes, reflecting integrated thoracic torsional burden in scoliosis.

Design

Retrospective cross-sectional cohort study.

Introduction

Scoliosis is a 3D deformity; axial rotation can distort thoracic geometry and reduce ventilatory capacity. Two-dimensional measures and single-level apical rotation may not capture global torsional imbalance. We evaluated CT-derived rotation indices and their association with pulmonary function in an etiologically heterogeneous cohort.

Methods

We reviewed 250 patients with scoliosis who underwent full-spine CT and spirometry within 1 year (2013–2025). Vertebral rotation was measured on axial CT using the Aaro–Dahlborn method. Indices included apical rotation ($R(\text{Apex})$), 3-level mean apical rotation ($R(\text{Avg})$), and rotational asymmetry between main and compensatory curves ($\Delta R(M-C) = |RM - RC|$), where RM is the maximal main-curve rotation and RC is the maximal counter-rotation in the compensatory curve. Outcomes were FVC, FEV1, FVC%, and FEV1%. Pearson correlation and multivariable linear regression adjusted for age, sex, height, and weight were performed, with subgroup analyses by etiology.

Results

The cohort had a mean age of 15.6 ± 5.7 years; 49.6% were female. All rotation indices showed significant negative correlations with pulmonary function in the overall cohort. $\Delta R(M-C)$ showed strongest associations with FVC% ($r = -0.66$) and FEV1% ($r = -0.64$), as well as with absolute volumes (FVC, $r = -0.59$; FEV1, $r = -0.58$). In adjusted multivariate analyses, models incorporating $\Delta R(M-C)$ consistently demonstrated the highest explanatory performance compared with models based on $R(\text{Apex})$ or $R(\text{Avg})$. Subgroup analysis revealed the strongest associations in neurofibromatosis-related scoliosis ($r = -0.87$) and congenital scoliosis ($r = -0.71$). Associations were attenuated in neuromuscular subtypes and did not reach statistical significance in SMA.

Conclusion

CT-derived global rotational asymmetry between the main and compensatory curves is strongly associated with pulmonary function impairment in scoliosis and demonstrates superior explanatory performance to single-level rotation indices in adjusted models. Incorporating a CT-derived metric may complement traditional two-dimensional assessments for functional risk stratification.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

16. Adolescent Idiopathic Scoliosis with a Major Proximal Thoracic Curve: A Rare Type not Included in the Lenke Classification System - the Incidence, Radiographic Characteristics and Surgical Strategy

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Hypothesis

Adolescent idiopathic scoliosis (AIS) with a major proximal thoracic curve is rare and not included in the Lenke classification system. There are few literatures about this type of AIS.

Design

This is a retrospective study.

Introduction

Adolescent idiopathic scoliosis (AIS) with a major proximal thoracic curve is rare and not included in the Lenke classification system. There are few literatures about this type of AIS. The purpose of this study is to investigate the incidence, radiographic characteristics and surgical strategy for AIS with a major curve at the PT area.

Methods

AIS patients with a major curve at the PT spine treated surgically from January 2014 to January 2024 were included in our study. All the patients were corrected by posterior spinal fusion with pedicle screws and were followed at least two years after surgery. We evaluated the pre- and post-operative Cobb angles of the curve, curve range, location of the apex, sagittal parameters, and shoulder balance-related parameters.

Results

There are 43 patients out of 3103 AIS patients (1.39%) were included in this study. The average age of the patients was 14.8 years (range 11 to 18 years). There are 19 females and 24 males. The patients were classified to non-structural main thoracic group(NSMT) , in which the main thoracic curve was corrected to less than 25° on supine push-bending films, and structural main thoracic group (SMT), in which the MT curve was structural. There are 23 patients in NSMT group and 20 patients in the SMT group. The mean pre-operative cobb angle of proximal thoracic curve in NSMT and SMT group was $48.96^{\circ} \pm 6.1^{\circ}$ and $55.2^{\circ} \pm 12.36^{\circ}$ respectively. The mean pre-operative cobb angle of main thoracic curve in NSMT and SMT group was $39^{\circ} \pm 8.6^{\circ}$ and $48^{\circ} \pm 9.1^{\circ}$ respectively. The mean post-operative cobb angle of proximal thoracic curve in NSMT and SMT group was $18.78^{\circ} \pm 4.9^{\circ}$ and $23.8^{\circ} \pm 6.18^{\circ}$ respectively. The mean post-operative cobb angle of main thoracic curve in NSMT and SMT group was $12.0^{\circ} \pm 4.33^{\circ}$ and $15.35^{\circ} \pm 5.84^{\circ}$ respectively.

Conclusion

We reported a cohort of AIS with a major proximal thoracic curve, which is relatively rare curve type. Individualized surgical strategies are warranted for these patients based on different curve patterns to ensure a favorable clinical outcome.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

17. Proximal Thoracic-Predominant Lenke 2 Curves Have Important Surgical Differences

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Hypothesis

Correction of proximal thoracic–predominant (PTP) Lenke 2 curves is improved with constructs providing concave upward force rather than bilateral downward hooks.

Design

Retrospective multicenter cohort study.

Introduction

Lenke 2 adolescent idiopathic scoliosis (AIS) typically features a dominant main thoracic (MT) curve with a smaller proximal thoracic (PT) curve. Rarely, the PT curve equals or exceeds the MT curve. This PTP configuration is poorly characterized. This study characterized PTP Lenke 2 curves and evaluated the impact of proximal fixation strategy on alignment.

Methods

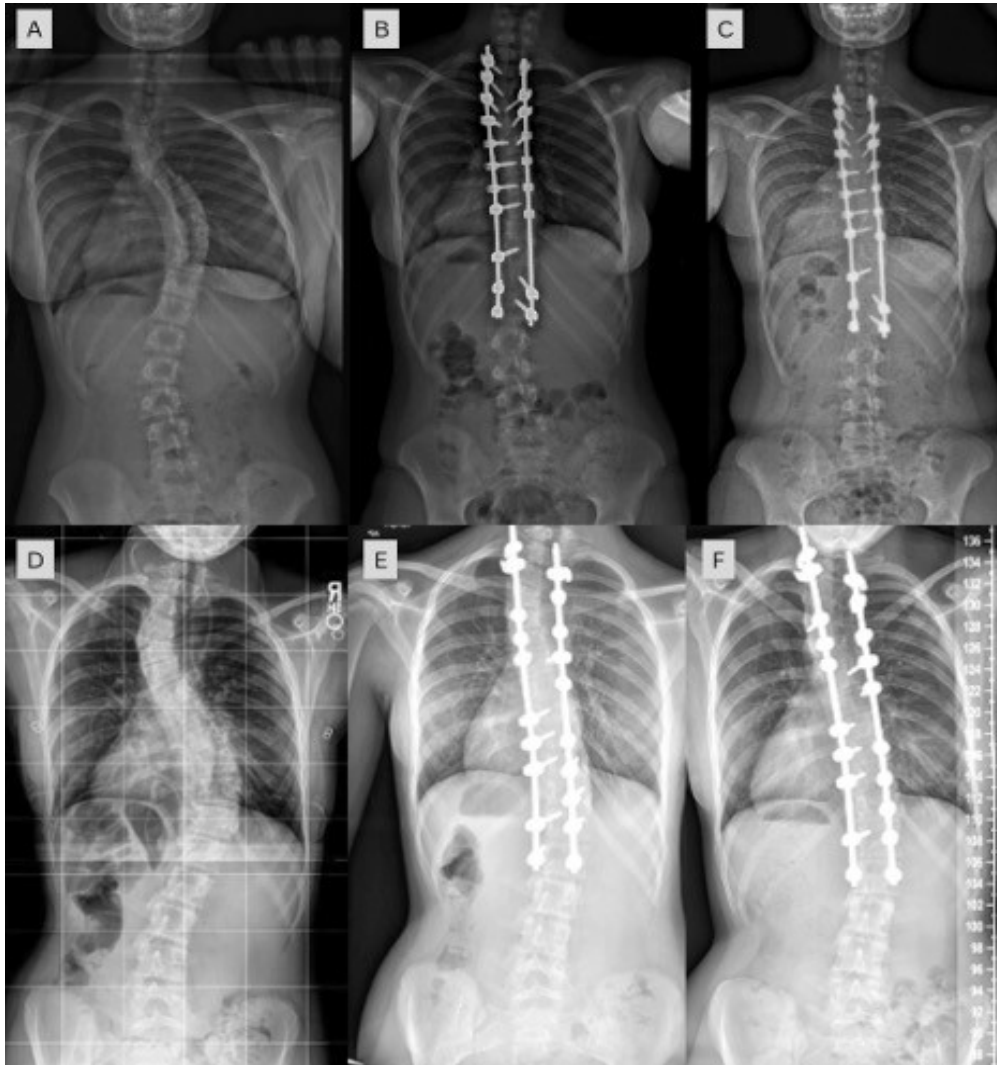
AIS patients with Lenke 2 curves undergoing posterior spinal fusion were identified. PTP curves were defined by PT Cobb angle $\geq$ MT Cobb angle and compared with MT-predominant (MTP) curves. Outcomes included PT and MT Cobb angles, deformity angular ratio (DAR), T1 tilt, shoulder balance, and SRS-22 self-image scores. Proximal fixation strategy and PT Ponte osteotomy use were analyzed.

Results

Of 915 Lenke 2 patients, 38 (3.1%) had PTP curves. Compared with MTP, PTP patients had larger PT curves (52° vs 37°), smaller MT curves (50° vs 60°), higher PT DAR (10.1 vs 6.0), and greater preoperative T1 tilt (15.3° vs 5.2° ; all $p < 0.01$). PTP patients achieved greater PT correction (59% vs 48%) but lower MT correction (63% vs 70%) and higher two-year postoperative T1 tilt (9.4° vs 7.5° , $p = 0.01$). SRS-22 self-image scores were higher in PTP patients pre- and postoperatively. Within the PTP cohort, concave upward UIV hook constructs achieved the lowest residual T1 tilt ($5.8^\circ \pm 4.3^\circ$) compared with pedicle screw–dominant ($7.2^\circ \pm 3.7^\circ$) and bilateral downward hook constructs ($9.0^\circ \pm 5.3^\circ$; $p = 0.041$), with lower rates of persistent left shoulder elevation (40% vs 62% vs 100%; $p = 0.028$). PT Ponte osteotomies increased PT correction in PTP curves (68% vs 35%, $p = 0.04$).

Conclusion

PTP Lenke 2 curves are a rare, distinct phenotype with high DAR, greater preoperative T1 tilt and different correction behavior than MTP curves. Successful management requires proximal thoracic mobilization, with concave upward pedicle hook fixation strategies and Ponte osteotomies in the PT curve, which are associated with improved cervicothoracic alignment.



Representative AP radiographs of PTP Lenke 2 curves showing improved T1 leveling with concave UIV pedicle hook fixation (A–C) compared with bilateral downward hooks (D–F).

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡SRS Funded Research Grant

18. Variation in Flexibility Imaging Techniques in Adolescent Idiopathic Scoliosis (AIS): A Multicenter Study

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Hypothesis

We hypothesize there will be significant variations in radiographic bending technique usage and measurements between and within sites.

Design

Retrospective cohort review of a prospective registry.

Introduction

Curve flexibility in AIS posterior fusion surgery is critical for preoperative planning to help predict achievable correction, inform fusion level selection, and identify the need for adjudicative procedures. There are many variations of radiographic bending assessment (e.g., supine, standing, fulcrum, traction). However, there is no consensus on the optimal method. This study aims to evaluate the variation of radiographic flexibility techniques used within and between sites of a multicenter registry.

Methods

Surgical patients enrolled in a multicenter AIS registry between 2009 - 2025 were included. Demographic, thoracic and lumbar bending methods, and radiographic data were collected. Patients were matched into cohorts (N=57) by Lenke curve type (1-6), skeletal maturity (Risser 0-3 or 4-5), and Cobb angle (5° increments from 40-70°). Curve flexibility was measured using: $100 * (\text{Cobb} - \text{Bending Cobb}) / \text{Cobb}$. The spread of variance across cohorts within each technique was assessed using the Brown-Forsythe test. Within each cohort, the lowest-variance technique (“winner”) was compared to the next-ranked techniques using paired variance ratio tests.

Results

2704 patients (15.2 ± 2.3 years old; 81% female at 24 sites) were included. Supine bending was the most common thoracic (49%) and lumbar (57%) flexibility assessment method. 23/24 sites utilized the same bending method >95% of the time for thoracic and lumbar flexibility assessments. Brown-Forsythe testing demonstrated stable variability across cohorts within supine ($p=0.137$), standing ($p=0.175$), and fulcrum ($p=0.752$) bending. Most variance-based rankings across cohorts were not statistically significant (91%). However, supine bending accounted for 61% of all variance-based “wins” and was the winning technique in all statistically significant comparisons.

Conclusion

Supine bending was the most utilized curve flexibility assessment method, and sites were internally consistent with bending film methodology. Supine films demonstrated the lowest variance across matched patient cohorts, suggesting the highest reproducibility among current practices. These findings support the use of supine bending as the current standard flexibility assessment method.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

Example of a matched cohort rank for patients with a Lenke 1 curve, Risser 0-3, and Cobb 50-55°

Matched Group (Lenke, Risser, Cobb)	First Place	N	Variance	Second Place	N	Variance	Third Place	N	Variance
1 0-3 (50.0, 55.0]	supine bending	52	176.2	standing	41	356.7	fulcrum	8	570.3

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡SRS Funded Research Grant

19. Accuracy of IS-GROWTH Predictions of the Risk of Reaching the Clinically Significant Thresholds of 30°, 45° And 50° in Idiopathic Scoliosis Patients.

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Hypothesis

IS-GROWTH can accurately predict the risk of reaching clinically significant scoliosis thresholds by the end of growth: 30° for probable stability in adulthood; 45° and 50° for surgical indications.

Design

Secondary analysis of a retrospective study on prospectively collected data.

Introduction

IS-GROWTH has recently been developed to predict the progression of curves in patients with Idiopathic Scoliosis (IS) of all ages, with curves up to 70° at first observation. While it provides a graphical representation of the wide range of possible evolutions, IS-GROWTH does not offer a risk percentage or thresholds, unlike the previously developed BrAIST-Calc. The latter, however, applies only to adolescents with IS and curves between 20° and 40°, with Risser 0-2 at first observation.

Methods

We analyzed the development and temporal validation groups from the previously published IS-GROWTH cohort, including all children with pre-treatment X-rays. Predicted curve ranges were examined in the validation group, and a square-root transformation was applied to approximate normality, assessed via Asymmetry and Kurtosis tests. Prediction models were developed for the 30°, 45°, and 50° thresholds, and temporal validation was performed on all radiograph pairs. Model performance was evaluated using discrimination (AUC), accuracy of risk estimates (Brier Scores with 95% CI), and calibration by comparing predicted probabilities with observed outcomes across risk deciles.

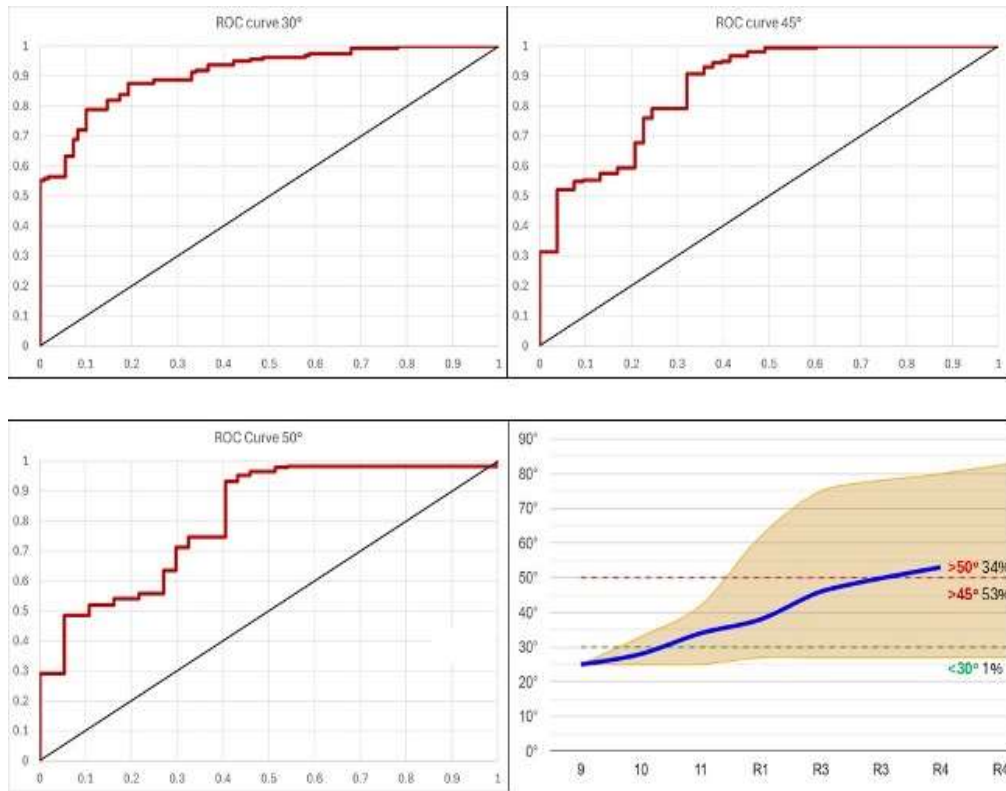
Results

We evaluated IS-GROWTH predictions for 552 patients (74% female, 12.4±2.0 to 14.7±1.7 years, 19±9° to 26±11°). A square-root transformation approximated normality (asymmetry 0.01, kurtosis 0.72). Temporal validation included 270 radiograph pairs (187 patients, 87% female). At growth end, 109 radiographs were <30°, 53>45°, and 37>50°. AUCs were 0.91, 0.86, and 0.81 for 30°, 45°, and 50° thresholds; Brier Scores 0.19, 0.15, and 0.14, respectively. Calibration showed strong agreement between predicted and observed risks across all thresholds, including extremes.

Conclusion

IS-GROWTH provides validated probabilities for reaching clinically significant scoliosis thresholds, complementing graphical trajectories with quantitative risk estimates. This enables personalized counselling and shared decision-making, allowing clinicians to quantify individual risk of progression or surgery and optimize treatment timing.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant



§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡SRS Funded Research Grant

20. The Closing Triradiate Cartilage Stage Identifies Accelerated Curve Progression in Idiopathic Scoliosis

Hong Zhang, MD; Judy-Mae Lima, BS; Chan-Hee Jo, PhD; Daniel J. Sucato, MD, MS

Hypothesis

A distinct transitional phase exists between the open and closed triradiate cartilage (TRC) that represents a biologically critical window for accelerated curve progression.

Design

Retrospective cohort study

Introduction

TRC status is commonly used to assess skeletal maturity and progression risk in scoliosis, however, its traditional binary classification as open or closed may inadequately capture critical transitional growth periods. This study aimed to re-evaluate TRC maturation, with particular emphasis on this transitional period, and to investigate scoliosis progression and growth patterns during the transitional phases.

Methods

A retrospective longitudinal study was conducted of 179 patients with idiopathic scoliosis (126 girls, 53 boys, mean age 9.7 ± 1.5 years) who were followed from childhood through early adolescence. Inclusion criteria were age >6 years with an open TRC at baseline, initial major Cobb angle between 10° and 45° , and documented curve progression to $\geq 50^\circ$ requiring surgical treatment during adolescence. TRC status was classified as open, closing, initial-closed, or fully closed based on radiographic appearance. Cobb progression rate (CPR), total spine height increase rate (TSHIR), and patient standing height increase rate (PSHIR) were measured and calculated for each TRC stages.

Results

In both sexes, CPR peaked during the closing-TRC stage, increasing approximately fivefold in girls and more than thirtyfold in boys compared with the open-TRC stage ($p < 0.0001$). Elevated CPR persisted into the initial-closed-TRC stage. TSHIR did not peak during closing-TRC and showed a significant inverse correlation with CPR in girls, whereas PSHIR remained relatively stable and did not correlate with CPR in either sex. The closing-TRC stage had a mean duration of 0.8 ± 0.3 years, occurring between 11.1 ± 0.9 and 12.0 ± 0.9 years of age in girls. In boys, the closing-TRC lasted 1.0 ± 0.5 years, occurring between 13.0 ± 1.1 and 13.9 ± 1.2 years, approximately 1.9 years later than in girls.

Conclusion

Redefining TRC maturation into four distinct stages identifies the closing-TRC stage as a critical window for accelerated scoliosis progression. This readily obtainable radiographic marker may enhance early risk stratification, inform surveillance timing, and support more proactive clinical decision-making in skeletally immature patients with idiopathic scoliosis.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

21. Deep Learning of Apical Intervertebral Disc MRI Predicts Scoliosis Progression Independent of Radiographic Parameters

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Hypothesis

Apical intervertebral disc morphology on MRI independently predicts scoliosis progression to surgery in adolescents with idiopathic scoliosis.

Design

Retrospective cohort study with deep learning–based imaging analysis.

Introduction

Current models for predicting adolescent idiopathic scoliosis (AIS) progression rely largely on radiographic spinal geometry, despite growing evidence that intervertebral disc changes may precede structural deformity. This study evaluated whether deep learning (DL) applied to apical intervertebral disc slices on MRI can independently predict progression to surgery, and assessed the incremental value of additional clinical variables.

Methods

Axial MRI regions of interest of apical intervertebral discs were extracted from 477 AIS patients. Images were standardised and augmented prior to analysis. A custom convolutional neural network (CNN) was trained to predict progression to surgical intervention within 5 years using the morphological appearance of the disc images alone. Numerical clinical variables (Cobb angle, age at imaging, and apical disc level) were subsequently integrated with CNN-derived features using a boosting-based classifier. The model was internally validated and performance evaluated on held-out validation data using accuracy, area under the receiver operating characteristic curve (AUC), and binary cross-entropy.

Results

DL analysis of disc images alone demonstrated strong predictive performance, achieving 81.3% accuracy with an AUC of 0.81. Incorporation of numerical clinical variables produced a modest improvement, with the combined model reaching 83.3% accuracy and an AUC of 0.82, alongside improved probability calibration. This is compared to an accuracy of 77.1% (AUC 0.87) when using Cobb angle alone as a predictor.

Conclusion

Apical intervertebral disc deformation on MRI is a strong independent predictor of AIS progression, supporting a disc-centred driver of disease evolution. While additional numerical clinical variables provide incremental benefit, deep learning of disc images alone achieves robust discrimination. Additionally, this MRI-based approach aligns with a growing focus on radiation-free care, offering a safer framework for early risk stratification. These findings reinforce disc-level imaging biomarkers as efficacious, non-ionising alternatives and offer a scalable framework for predictive modelling in scoliosis.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

22. Can Machine Learning Optimize Fusion Selection in Thoracic Adolescent Idiopathic Scoliosis? – a Dual-center Cohort Study with External Validation

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Hypothesis

Fusion shorter than the last touched vertebra (LTV) can be safely performed in selected patients with main thoracic adolescent idiopathic scoliosis (AIS)

Design

Retrospective dual-center cohort study.

Introduction

The optimal selection of the lowest instrumented vertebra (LIV) remains a critical challenge in the surgical management of AIS. Traditional strategies rely on the LTV, but this approach may not fully account for three-dimensional curve- and flexibility characteristics. We aimed to evaluate whether the use of a machine learning algorithm could improve patient-specific selection of the LIV and decrease the risk of distal adding-on in patients with thoracic AIS.

Methods

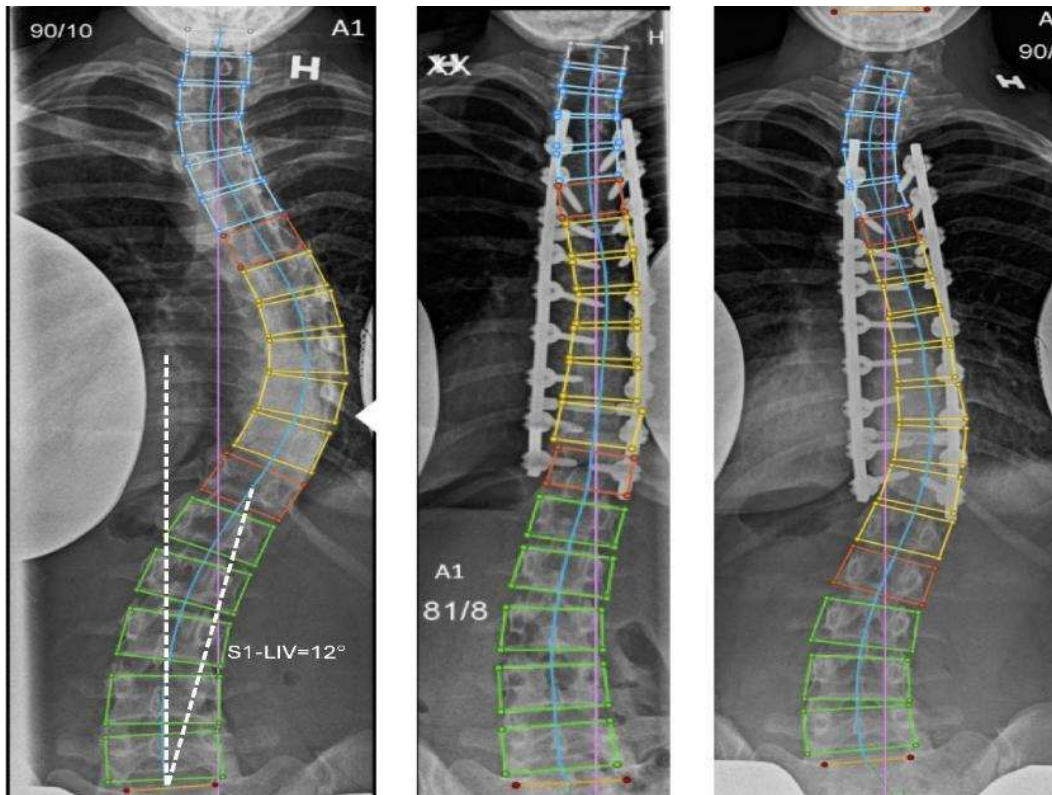
The derivation cohort included 177 AIS patients (Lenke type 1 or 2, lumbar modifier A/B) treated with selective posterior fusion. Radiographic analysis included a wide variety of parameters from coronal, sagittal and bending x-rays. After identifying the five most predictive preoperative parameters using random forest modeling and ROC analysis, the algorithm was externally validated in a cohort of 289 patients where LIV selection followed a standardized protocol. The primary outcome was distal adding-on at minimum two-year follow-up.

Results

Adding-on was observed in 33% and 21% of patients in the derivation and validation cohorts, respectively. Of the variables tested, only the S1-LIV angle - a measure of vertebral deviation from the midline - remained a significant predictor in multivariate analysis. An S1-LIV angle above 9.5° was associated with fourfold increased odds of adding-on. Machine learning-selected axial and sagittal parameters did not yield improvement over the S1-LIV angle alone when validated externally. Notably, selection of the LIV based on the S1-LIV angle saved lumbar motion segments in approximately 20% of patients without increasing the risk of adding-on.

Conclusion

The S1-LIV angle offers a quantitative tool for individualized LIV selection in AIS, and its use may facilitate level-sparing strategies in surgical planning without compromising patient outcomes.



A 55-degree Lenke 1A curve with an S1-LIV angle of 12 degrees. The last touched vertebra was L1. The patient was operated with a Th4-Th12 fusion with good immediate correction (middle). Two-year postoperative x-ray (right) showed adding-on with progression of the main curve and distalisation of the end vertebra.

23. Updated Guidance on Lower Instrumented Vertebra Horizontalization in Lenke C Curves after Selective Thoracic Fusion: The Concept of Dynamic Lumbar Curve Behavior

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Hypothesis

In AIS, a dynamic lumbar C modifier (C to B on supine films) in structural lumbar curves is associated with tolerance of a more horizontal LIV and improved radiographic outcomes compared with a fixed Lenke C modifier.

Design

Retrospective Review

Introduction

Selective thoracic fusion (STF) can be performed in select AIS pts with structural lumbar curves; however, optimal lower instrumented vertebra (LIV) alignment in Lenke C curves remains controversial. While a tilted LIV has traditionally been recommended to maintain coronal balance, LIV horizontalization may facilitate spontaneous lumbar curve correction at the risk of shoulder or coronal imbalance. “Dynamic alignment”, defined as a Lenke C modifier on upright XRs but Lenke B on supine XR, is a means of reliably quantitating lumbar curve flexibility. We hypothesize that this concept will be useful in guiding treatment strategies in Type C curves.

Methods

Review of AIS pts with a Lenke C modifier on upright XRs who underwent STF (LIV T11–L2) with ≥ 2 -year f/u. Pts were stratified by dynamic lumbar behavior (C to B vs C to C on supine XRs) and postop LIV orientation (horizontal vs tilted), yielding four groups (CBH, CBT, CCH, CCT). Outcomes included sagittal/coronal alignment (C7CSVL, C7SVA), LIV tilt, thoracolumbar (TL) cobb, and shoulder balance (T1 tilt).

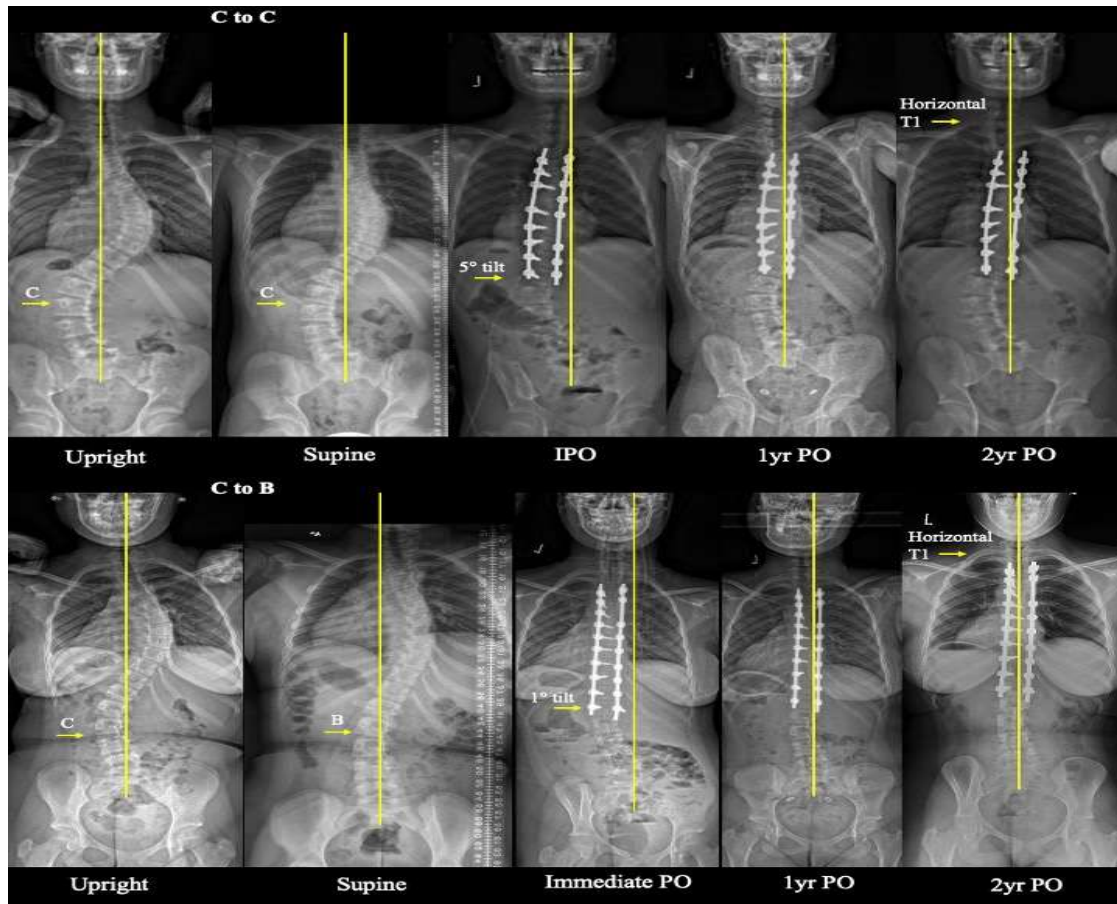
Results

30 AIS pts were identified. In C to C curves, pts with a tilted LIV (CCT; mean immediate postop [IPO] LIV tilt 7°) had significantly better 2-year alignment than those with horizontal LIVs (CCH; IPO tilt 2°), including lower T1 tilt (0.6° vs 11°, $p < 0.001$), reduced C7CSVL (0.4 vs 6cm, $p = 0.003$), lower CSVL–LIV distance (0.6 vs 2.1cm, $p = 0.03$), and improved C7SVA (1.6 vs 5.8cm, $p = 0.01$). In contrast, CCH pts had progressive LIV tilt to 13° with left shoulder imbalance. For C to B pts, CBH LIV tilt was 2° IPO and remained stable at 2yrs. Compared CBT, IPO tilt 9°, CBH pts had better shoulder balance (T1 tilt 0.8° vs 5.8°, $p < 0.001$), reduced C7CSVL (0.5 vs 3.8cm, $p = 0.007$), and smaller CSVL–LIV (0.6 vs 1.3cm, $p = 0.01$), with no difference in C7SVA (1.5 vs 2.1cm, $p = 0.10$).

Conclusion

In AIS pts undergoing STF, LIV tilt should be guided by dynamic lumbar behavior. Curves that convert from Lenke C to B supine tolerate LIV horizontalization with favorable coronal and shoulder balance, whereas curves that remain C require a tilted LIV to maintain balance.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant



CCT vs CBH

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡SRS Funded Research Grant

24. Long-Term Clinical and Radiographic Outcomes of Stopping Fusion at L3 in Structural Lumbar Curves Despite Standing and Bending X-rays Indicated to Stop at L4: A Minimum 20-Year Follow Up

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Hypothesis

Distal fusion can be safely stopped at L3 based on traction radiographs under general anesthesia (TrUGA), with durable and satisfactory long-term outcomes.

Design

Retrospective

Introduction

Selection of the LIV remains challenging in pts with structural lumbar curves particularly when choosing between L3 and L4. Stopping at L3 may help to maintain lumbar motion and limit degeneration in the unfused lumbar spine. The long-term consequences of stopping at L3 instead of L4 remains unclear. The aim of this study was to assess the clinical and radiographic outcomes, and evaluate disc degeneration (DD) and facet joint degeneration (FJD) of unfused lumbar spine, at minimum 20-year f/up.

Methods

34 pts (28F/6M) with structural lumbar curves were included. In all pts, standing CSVL did not touch L3, and conventional standing and bending x-rays indicated L4 as LIV; however, fusion was stopped at L3 based on TrUGA. Radiographic assessment included coronal, sagittal alignment, spinopelvic and vertebral pelvic angles (L1PA, T4PA, and T4–L1PA mismatch). Lumbar DD and FJD were evaluated on MRI using Pfirrmann and Fujiwara class. Clinical outcomes were assessed with SRS-22r.

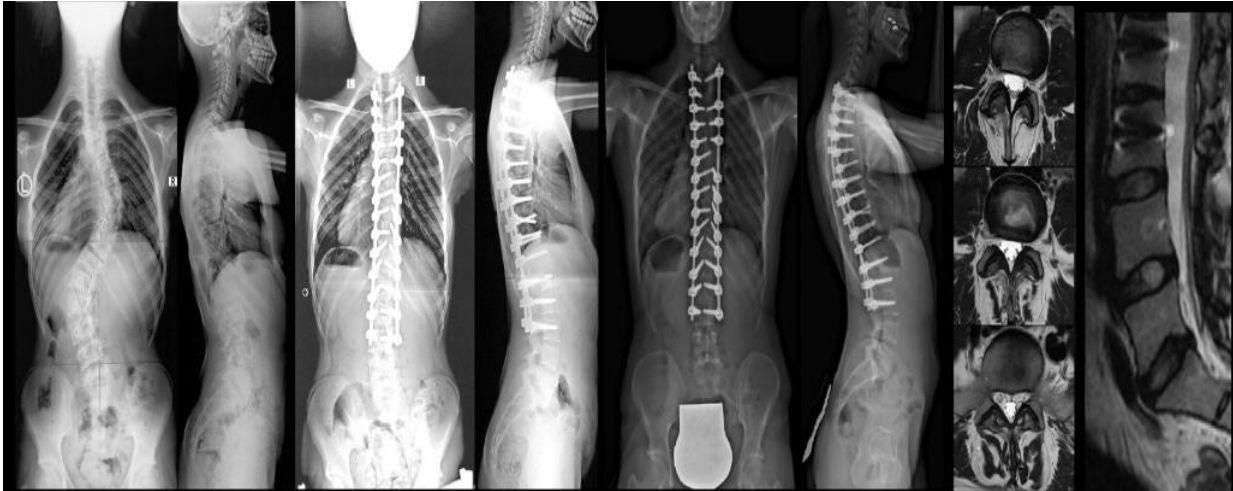
Results

Mean f/up was 22.5 yrs (range, 20–30), mean age at final f/up was 34 yrs (32–43). Mean lumbar curve correction was 78%, with no significant loss of correction. Disc wedging below LIV (early: $0.4^{\circ} \pm 3.8^{\circ}$; final: $2.4^{\circ} \pm 3.2^{\circ}$) and residual curve below L3 (early: $3.1^{\circ} \pm 2.7^{\circ}$; final: $3.0^{\circ} \pm 2.2^{\circ}$) remained stable over f/up. Sagittal parameters showed no significant changes including L1PA, T4PA, and T4–L1PA mismatch. Mild degeneration was observed below L3, with mean DD grade of 3.12 (range, 2–5) and FJD grade of 2.58 (range 1–4). Ten pts (33%) with sacral slanting $>10^{\circ}$ demonstrated one higher grade of DD and FJD at L5–S1 level compared with pts with $<10^{\circ}$. SRS-22r total score at final f/up was 4.54 ± 0.23 , and increased DD and FJD grades were not correlated with final SRS scores (all $p > 0.05$).

Conclusion

According to our study with min 20-year f/up, distal fusion could be safely stopped at L3 based on TrUGA, even when conventional radiographs suggested L4. Coronal and sagittal alignment parameters remained stable, and degenerative changes below L3 didn't correlate with final SRS scores. However, sacral slanting $>10^{\circ}$ was associated with increased L5–S1 DD and FJD over 20-year f/up

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant



§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡SRS Funded Research Grant

25. Rate and Risk of Curve Progression in Moderate AIS following Skeletal Maturity

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Hypothesis

Skeletally mature patients with moderate scoliosis do not have risk of curve progression into adulthood with no change in SRS outcome scores

Design

Multicenter,prospective

Introduction

Natural history of moderate AIS($\geq 30^\circ$) in skeletally mature patients is poorly defined.Studies reporting rates/risk factors for progression in AIS are predominantly of large curves in immature patients.Our aim was to determine the rate of curve progression in AIS following skeletal maturity and any associated changes in SRS-22 outcome scores;we also aimed to identify potential predictors of curve progression.

Methods

All patients had min 5yr f/u,AIS $\geq 30^\circ$,and were skeletally mature(Risser ≥ 4 ;females >14 and 2yrs post-menarche; boys >16 with no height change over 6mo).SRS-22 outcome scores and radiographic data were compared at baseline and 5yr f/u.Patients were divided into 2 grps based on curve size:Grp1=30-39° and Grp2 $\geq 40^\circ$.Curve progression was defined a priori as change in curve magnitude $\geq 5^\circ$ at f/u.Univariate and multivariate regression explored the association between curve progression and variables of interest to identify predictors of progression.

Results

There were 116 patients with mean age of 16.6 $\pm$ 1.5yrs;majority were females(91.4%).Mean major cobb at baseline was 39.9 $\pm$ 7.3°and 5yr f/u was 42.5 $\pm$ 8.6°.Mean change in Cobb was 2.6 $\pm$ 5.9°.Curve progression was noted in 27.6% of patients.24.7% of thoracic curves progressed compared to 32.6% thoracolumbar/lumbar curves.33.3% of Grp1 patients progressed compared to 22% in Grp2(p=0.3).Progressors had a significantly larger avg major Cobb at 5yr f/u compared to non-progressors (48.3 $\pm$ 6.9°vs40.2 $\pm$ 8.1°;p<0.001).Progressed curves on avg had a change in Cobb of 9.5 $\pm$ 4.6° with Grp1 trending to a greater rate of progression compared to Grp2(11.1 $\pm$ 5.4°vs7.2 $\pm$ 1.6°;p=0.015).SRS-22 scores on avg declined significantly over 5yrs(4.07 to 3.82;p<0.001).There was a significant decline in SRS general function(p<0.001),satisfaction(p=0.04),and total scores(p=0.02)in those that did not progressed.In progressed curves, there was a significant decline in all SRS domain scores.Univariate and multivariate analysis did not identify any predictors of curve progression.

Conclusion

Skeletally mature patients with moderate AIS($\geq 30^\circ$) may have a risk of progression at a mean rate of 1.9°/yr.Curve progression may lead to significant decline in SRS-22 outcome scores;in particular general function,pain and satisfaction.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

Table

Patient Demographics	Baseline	5 yr f/u	
Mean age(yrs)	16.6+/-1.5	-	
Gender (%)	M=91.4 F=8.6	-	
Mean Major Cobb (°)	39.9°+/-7.3°	42.5°+/-8.6°	
% Curves progressed (≥5°)	-	27.6	
Mean Change of Progressed Curves(°)	-	9.5°+/-4.6°	
% Progressed curves - MT	-	24.7	
% Progressed curves – ThL/L	-	32.6	
Curve Size at Baseline	Grp 1 (N=57)	Grp 2 (N=59)	P-value
Mean Baseline Major Cobb (°)	33.9	45.6	<0.001*
% Curves Progressed	33.3	22	0.17
Mean Change of Progressed Curves (°)	11.1	7.2	0.02 *
SRS-22 Scores of Progressed curves (n=32)	Baseline	5 year	P-value
Pain	4.2	3.9	<0.001*
Self- Image	3.8	3.6	0.012 *
General Function	4.4	4.1	<0.001*
Mental Health	3.9	3.5	<0.001*
Satisfaction	4.0	3.7	0.02*
Total	4.1	3.8	<0.001*
SRS-22 Scores of Non-Progressed curves (n=84)	Baseline	5 year	P-value
Pain	4.2	4.1	0.2
Self- Image	3.9	3.8	0.43
General Function	4.6	4.2	<0.001*
Mental Health	4.0	3.7	0.09
Satisfaction	3.9	3.6	0.04*
Total	4.1	3.9	0.02*
Multivariate Regression Variables	P-value		
Age	0.72		
Major Cobb	0.32		
Thoracic T2 to T12	0.8		
Thoracic Translation	0.98		
Lumbar Translation	0.9		
Pelvic Incidence	0.83		
Pelvic Tilt	0.72		
Sacral Slope	0.64		

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper,
‡SRS Funded Research Grant

26. Later Menarche Tracks with AIS Curve Severity—Clinical Association and Genetic Causality in 5,891 Patients

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Hypothesis

Later age at menarche (AAM) and stronger family-history (FH) burden are positively associated with greater AIS curve severity. We hypothesized that AAM shows stronger genetic and causal links to curve severity than to AIS susceptibility.

Design

Retrospective cohort with integrative genetic analyses.

Introduction

AIS progression accelerates during puberty, making prediction of ultimate curve severity central to clinical management. Although later AAM and stronger FH burden correlate with curve severity, whether they relate specifically to severity rather than susceptibility and whether genetics supports causality remains unclear.

Methods

AIS patients (N=5,891) were analyzed. The outcome was Cobb angle at last follow-up. FH categorized by affected relative count (0, 1, ≥ 2). AAM analyzed continuously and ordinaly (≤ 11 , 12–15, ≥ 16 years). Associations were tested using linear regression adjusted for age and BMI. Using GWAS (genome-wide association study) summary statistics, bivariate LD (linkage disequilibrium) score regression assessed genetic correlation between AAM and AIS phenotypes (Cobb angle; susceptibility). Two-sample MR (Mendelian randomization) tested causal effects of AAM on Cobb angle severity and AIS susceptibility, and AIS susceptibility on Cobb angle severity.

Results

FH was associated with higher Cobb angle at last follow-up ($\beta=1.26$, $P=0.02$). Later AAM was associated with higher Cobb angle ($\beta=1.95$ degrees/year, $P=3.7 \times 10^{-23}$), with a monotonic trend across ordinal AAM categories ($\beta=3.50$ per category, $P=4.0 \times 10^{-11}$). Genetic correlation was significant between AAM and Cobb angle severity ($r_g=0.25$, $P=0.04$) but not between AAM and AIS susceptibility ($r_g=0.04$, $P=0.33$). MR supported a causal effect of genetically later AAM on Cobb angle severity (IVW=2.35, $P=0.04$) but not on AIS susceptibility (IVW=0.03, $P=0.77$). Genetically increased AIS susceptibility also causally increased Cobb angle severity (IVW=1.79, $P=0.005$).

Conclusion

Greater FH burden and later AAM track with higher Cobb angle, and genetic correlation plus MR support a biologic relationship between pubertal timing and ultimate Cobb angle rather than AIS susceptibility alone. While the absolute per-year AAM effect size is modest, the consistency across clinical and genetic analyses provides objective support for a widely held clinical impression and motivates further work on pubertal-timing pathways in AIS severity and progression.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant

27. Sacral Slanting Predicts Residual Disc Wedging After Fusion to L3 in AIS

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Hypothesis

Preoperative sacral slanting (SS) angle has the greatest impact on postoperative L3–4 disc wedging angle (DWA) in adolescent idiopathic scoliosis (AIS) patients whose fusion stops at L3.

Design

Retrospective cohort study.

Introduction

Previous studies have reported that fusion to L4 in patients with a high SS angle may lead to coronal decompensation, whereas stopping at L3 may increase residual DWA below the lowest instrumented vertebra (LIV); however, the relative contribution of SS compared with other coronal alignment parameters is unclear.

Methods

AIS patients with a structural thoracolumbar (TL) curve (Lenke types 3–6) who underwent posterior spinal fusion with L3 as the LIV and had ≥ 2 -year follow-up were included. Patients with leg length discrepancy were excluded. SS was defined as the angle between the S1 superior endplate and the horizontal. DWA was measured at the L3–4 disc. Radiographic parameters measured on baseline, side-bending, and first-erect radiographs were used as candidate predictors, including TL Cobb angle, SS angle, LIV tilt, C7 plumb line to central sacral vertical line (C7-CSVL), LIV-CSVL, DWA, the angle between the construct axis and the LIV endplate, and the Cobb angle between the upper instrumented vertebra and LIV. The primary outcome was DWA at 2 years postoperatively. Candidate predictors were selected using least absolute shrinkage and selection operator (LASSO) regression to address potential collinearity, followed by multivariable linear regression.

Results

Forty-four patients were included (91% female; mean age 15.2 years; mean follow-up 2.7 years), with 61% Lenke type 5. Mean baseline TL Cobb angle, SS angle, and C7-CSVL were 50°, 3.4°, and 21 mm, improving to 15°, 2.7°, and 11 mm at 2 years, respectively. Mean DWA shifted from 2.7° toward TL convexity preoperatively to 5.0° toward concavity at 2 years. LASSO regression identified multiple candidate predictors; however, baseline SS angle was the only variable consistently selected across the overall cohort, Lenke type 5 subgroup, and non-type 5 subgroup. Greater baseline SS angle was independently associated with increased 2-year postoperative DWA ($\beta = 0.37$ per degree; 95% CI, 0.14–0.60; $P = 0.003$).

Conclusion

Preoperative SS angle was the most consistent predictor of residual DWA following fusion to L3 in AIS patients with structural TL curves and may aid patient counseling regarding a theoretically higher risk of future disc degeneration.

§ Hibbs Award Nominee – Best Clinical Paper, † Hibbs Award Nominee – Best Basic Science/Translational Science Paper, ‡SRS Funded Research Grant