

## 58. The Evolution of Sagittal Alignment in Pediatric Population: A Study of 500 Typically Developing Children

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### Hypothesis

The T4-L1-Hip Axis represent a normal sagittal alignment in pediatric population

### Design

Cross-sectional

### Introduction

Restoring sagittal parameters is essential to improve functional outcomes in deformity correction. The VPA, especially for L1 (L1PA), correlates well with global sagittal alignment, & T4-L1-hip forms a straight axis in normal adults. However, there is no data for the pediatric population.

### Methods

Patients from a single institution's database were recruited. These (up to 18 years) had whole spine radiographs for screening of scoliosis. Patients with curves  $>10^\circ$ , spondylolisthesis, pelvis or lower limb pathology, or significant back pain were excluded. Sagittal measurements recorded were pelvic parameters (PI, SS, PT), L1PA, T4PA, lumbar lordosis (LL: L1-S1, proximal LL: L1-L4, distal LL: L4-S1), and thoracic kyphosis (TK: T1-T12, upper TK: T1-T5, middle TK: T5-T9, lower TK: T9-L1). Change was assessed between the groups divided based on skeletal maturation (pre-pubertal, early puberty, pubertal peak, and late/post-puberty).

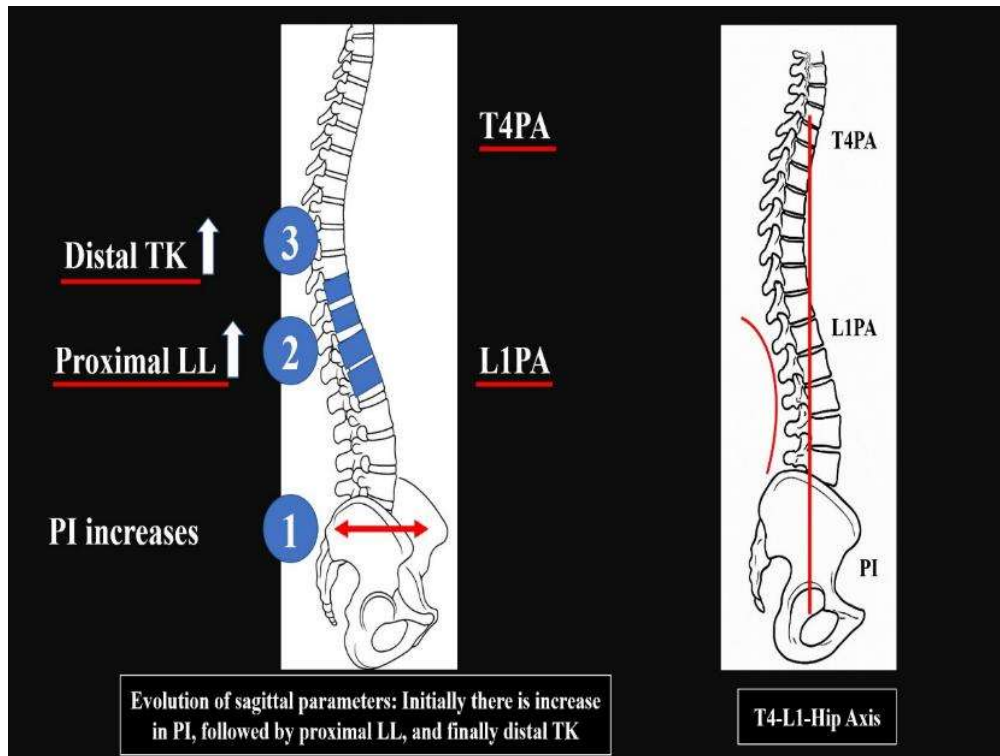
### Results

500 children (293F) with mean age 12.9 years (pre-pubertal= 134, early puberty= 67, pubertal peak= 47, post-puberty= 252) were included. PI ( $44^\circ \pm 10^\circ$ ) & PT ( $6^\circ \pm 8^\circ$ ) increased significantly with age ( $p < 0.001$ ). On post-hoc analysis, increase was significant at early puberty. SS ( $38.1^\circ \pm 8.8^\circ$ ) was consistent at all age groups ( $p = 0.07$ ). LL ( $55.4^\circ \pm 11.4^\circ$ ) increased significantly with age ( $p = 0.003$ ), particularly in early puberty &, increase was due to proximal LL ( $p < 0.001$ ), not distal LL ( $p = 0.59$ ). Similarly, there was an increase in TK ( $p < 0.001$ ) at post-puberty, significantly contributed by distal TK ( $p = 0.001$ ). The change in L1PA (median  $0.7^\circ$ , IQR  $8.6^\circ$ ) and T4PA (median  $-1.4^\circ$ , IQR  $9.8^\circ$ ) corresponds with LL and TK, respectively. On multivariable regression analysis, PI & L1PA combined have a strong correlation with LL, especially in the post-puberty group ( $R^2 = 0.7$ ). T4PA values have a strong correlation with L1PA & are within  $5^\circ$  of L1PA, for 80% prediction.

### Conclusion

This study reports the normal values of various sagittal parameters in pediatric population. PI exhibits a significant correlation with lumbar alignment; &, this correlation improves when combined with L1PA across all age groups. Sagittal alignment evolves during growth: an increase in proximal LL followed by distal TK. The T4-L1-hip axis holds true for the pediatric population, especially older children.

§ 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

## 59. Defining Whole Spine Sagittal Alignment Parameters in Normal Population: Prospective Analysis of 50000 Patients

Sung Hyeon Noh, MD, PhD

### Hypothesis

The purpose of this study is to present the normal whole spine sagittal alignment parameters in normal population

### Design

Retrospective study

### Introduction

Defining normative values of these clinically relevant sagittal parameters are essential as they provide objective surgical indications when planning treatment and serve as optimal target values for surgical correction. Insufficient incorporation of spino-pelvic parameters can result in detrimental outcomes such as spinal misalignment, decompensation, and failure of treatment.

### Methods

Fifty thousand patients aged more than 20 years old who had mild disability (MD, ODI of  $\leq 20$  score) and who met the inclusion criteria were included in this study. Patients were stratified into age cohorts: 20s, 30s, 40s, 50s, 60s, 70s or older. Radiographic evaluation, including C0C2 angle, C0C7 angle, C2C7 angle, odontoid hip axis (OH), SVA, TK, LL, L4S1 angle, PT, TPA, PI-LL, sacral slope (SS), spino-sacral angle (SSA) were conducted on the whole spine standing radiographs. Clinical scales (ODI, 36-item Short Form Health Survey [SF-36], and visual analogue scale [VAS] for back pain) were completed.

### Results

Among 50000 patients, there were 5805 people in their 20s, 5845 people in their 30s, 7875 people in their 40s, 10625 people in their 50s, 10750 people in their 60s, and 9100 people in their 70s or older. The average C0C2 angle, C0C7 angle, C2C7 angle, OH, SVA, TK, LL, L4S1 angle, PT, TPA, PI-LL, SS and SSA for 20s were  $23.5 \pm 12.42$ ,  $34.72 \pm 17.41$ ,  $14.05 \pm 12.29$ ,  $9.22 \pm 14.98$  degrees,  $25.22 \pm 24.25$  mm,  $28.31 \pm 15.07$ ,  $54.22 \pm 17.21$ ,  $34.31 \pm 16.66$ ,  $41.49 \pm 33.58$ ,  $26.63 \pm 39.97$ ,  $-12.35 \pm 36.74$ ,  $41.03 \pm 9.75$ ,  $132.71 \pm 9.75$  degrees.

### Conclusion

Through this study, whole spine sagittal alignment parameters according to age in a normal population were presented. C0C7 angle, C2C7 angle, SVA, TK, PT, and PI-LL increased statistically significantly with age. OH, LL, L4S1 angle, TPA, SS, and SSA decreased statistically significantly with age. These parameters will be very helpful to doctors and patients performing spinal surgery.

## 60. Does everyone with a given PI have the same L1PA? The importance of L4S1 in Sagittal Alignment

*Stephen J. Lewis, MD, FRCS(C); Fatemeh Alavi, PhD; Christopher J. Nielsen, MD; Fred H. Nicholls, MD*

### Hypothesis

Individuals with similar pelvic incidence (PI) do not necessarily exhibit the same L1–pelvic angle (L1PA). We hypothesize that L4S1 better impacts variability in sagittal alignment than PI alone.

### Design

Cross-sectional analysis

### Introduction

The L1PA as a critical measure for describing lumbar sagittal alignment has been proposed to be a function of PI:  $L1PA = 0.5 \times PI - 21^\circ$ . The T4 pelvic angle also reported to be nearly equivalent (within 4°) to the L1PA. However, patients with similar PI often demonstrate different L1PAs. This suggests that segmental lumbar distribution may play a critical role. This study evaluates the magnitude of L4S1 and variability in L1PA in individuals with comparable PI.

### Methods

A retrospective analysis was conducted on standing full-spine EOS radiographs of 410 asymptomatic adult volunteers (55.8% female; age 20–39 years). Spinopelvic parameters including PI, SS, L1PA, L1S1, and L4S1 were measured. Three groups with low (<45°), moderate (45°–55°), and high (>55°) PIs were considered. Each group was then divided into two groups with high and low L4S1 ( $p < 0.0001$ ) and non-significant difference between PI, PT, L1S1 from 242 individuals in total. The variability in L1PA and T4L1PA within same PI subgroups were assessed. Multivariable regression analyses on whole cohort determined the contribution of L4S1 versus PI to L1PA variability.

### Results

The groups with similar PI, PT, and L1S1, but different L4S1 ( $p < 0.0001$ ) demonstrated substantial inter-individual variability in L1PA ( $p < 0.0001$ ) and T4L1PA ( $p < 0.001$ ). L1PA was strongly associated with PI ( $\beta = 0.59$ ;  $P < 0.001$ ) and L4S1 ( $\beta = -0.49$ ;  $P < 0.001$ ). Predicted L1PA based on PI alone was compared with actual L1PA and contrasted with predictions derived from  $L1PA = 0.5 \times (PI - L4S1)$  model. The magnitude of L4S1 lordosis plays a critical role in shaping global sagittal alignment.

### Conclusion

Patients with the same PI do not necessarily share the same L1PA. While L1PA approximates the distribution of the lumbar lordosis, L4S1 lordosis is a critical driver of the L1PA variability and may provide more clinically meaningful guidance than PI alone. Incorporating the distal lordosis as measured by the L4S1 provides a more reliable measure of the L1PA ( $R^2 = 0.94$ ). These results support incorporating distal lumbar distribution into alignment assessment and planning rather than relying solely on PI.

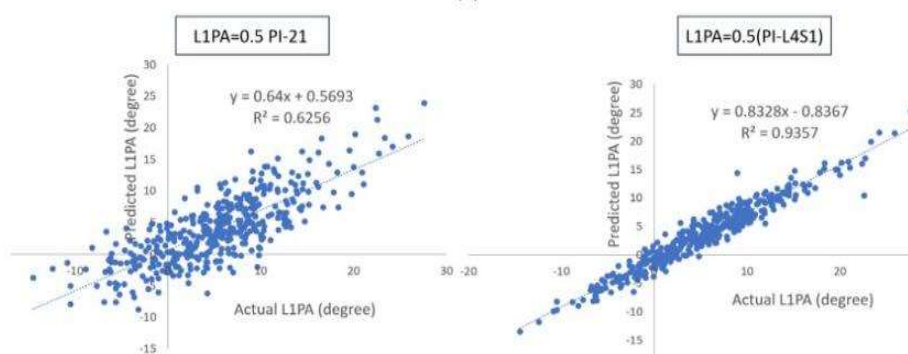
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| Group 1 |        | N  | PI    | PT   | SS    | L4S1     | L1S1  | L1PA     | T4PA   | T4L1PA |
|---------|--------|----|-------|------|-------|----------|-------|----------|--------|--------|
|         | mean   | 24 | 39.96 | 7.77 | 32.20 | 31.09    | 46.81 | 4.39     | 2.88   | -1.50  |
|         | mean   | 50 | 39.41 | 6.28 | 33.13 | 42.10    | 49.23 | -0.64    | 0.08   | 0.72   |
|         | T-test | 74 | 0.55  | 0.07 | 0.20  | 1.16E-21 | 0.09  | 8.44E-11 | 0.0005 | 0.0004 |

| Group 2 |        | N  | PI    | PT    | SS    | L4S1     | L1S1  | L1PA     | T4PA | T4L1PA  |
|---------|--------|----|-------|-------|-------|----------|-------|----------|------|---------|
|         | mean   | 52 | 50.04 | 13.13 | 36.91 | 35.49    | 53.26 | 8.87     | 6.82 | -2.05   |
|         | mean   | 43 | 49.52 | 12.04 | 37.48 | 44.13    | 54.69 | 5.07     | 5.26 | 0.19    |
|         | T-test | 95 | 0.34  | 0.07  | 0.37  | 1.51E-21 | 0.332 | 3.81E-11 | 0.01 | 1.1E-05 |

| Group 3 |        | N  | PI    | PT    | SS    | L4S1     | L1S1  | L1PA     | T4PA  | T4L1PA  |
|---------|--------|----|-------|-------|-------|----------|-------|----------|-------|---------|
|         | mean   | 36 | 61.81 | 17.59 | 44.22 | 39.30    | 60.79 | 13.99    | 11.11 | -2.88   |
|         | mean   | 37 | 61.68 | 15.72 | 45.96 | 49.74    | 63.12 | 9.07     | 8.49  | -0.58   |
|         | T-test | 73 | 0.929 | 0.10  | 0.13  | 3.66E-16 | 0.17  | 9.97E-07 | 0.012 | 0.00024 |

(a)



(b)

(a) Spinopelvic parameters of groups (b) Predicted versus actual L1PA

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

## 61. Establishing Lumbar Apex Pelvic Angle (LaPA) as the Rosetta Stone of Spinal Shape

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### Hypothesis

Dynamic regional landmarks especially lumbar apex predict PI-concordant sagittal shape more reliably than fixed vertebrae, acting as a "Rosetta Stone" to translate pelvic morphology into global sagittal shape

### Design

Multicenter radiographic analysis of normative volunteers

### Introduction

Pelvic incidence (PI) governs sagittal morphology, yet translating this constant into patient-specific targets remains difficult. Models anchored to fixed vertebrae (e.g. L1, T4) do not capture inter-individual variation in curve apices and inflection points. We tested whether the lumbar apex pelvic angle (LaPA) is the key PI-dependent landmark linking pelvic morphology to global spinal shape, while separating PI-driven variables from PI-independent geometric constraints

### Methods

We analyzed 236 asymptomatic volunteers (age 20–50; PI 21.8–103.2°) with standardized standing full-spine xrays. Pelvic Angles (PA) of regional landmarks were measured: LaPA, LiPA (thoracolumbar inflection), TaPA (thoracic apex) and TiPA (cervicothoracic inflection) contrasting them with fixed parameters (L1PA, T4PA, C2PA). PI dependency was assessed via Pearson correlation( $r$ ) and effect size( $\eta^2$ ). Heteroscedasticity was evaluated to quantify variability across the PI spectrum. Inter-parameter relationships mapped a stepwise predictive chain from pelvis to regional landmarks

### Results

LaPA showed the strongest dependency on PI and enabled continuous prediction ( $\text{LaPA} = -10.26 + 0.39 \times \text{PI}$ ;  $r=0.852$ ,  $\eta^2=0.59$ ,  $p<0.001$ ), outperforming L1PA ( $r=0.784$ ;  $\eta^2=0.47$ ). Mean LaPA increased from 5.0 degrees (low PI) to 17.4 degrees (high PI) with stable correlation across the full PI spectrum, including distribution extremes where fixed-vertebra angles were less reliable. A robust cascade was identified: LaPA predicted LiPA( $r^2=0.94$ ), which sequentially predicted TaPA ( $r^2=0.97$ ), TiPA ( $r^2=0.98$ ), and C2PA ( $r^2=0.99$ ). Composite indices (TiLiPA & TaLaPA) were PI-independent ( $r<0.10$ ,  $\eta^2<0.001$ ) suggesting universal alignment "rules". Variability increased with PI magnitude, supporting wider acceptable ranges for high PI individuals

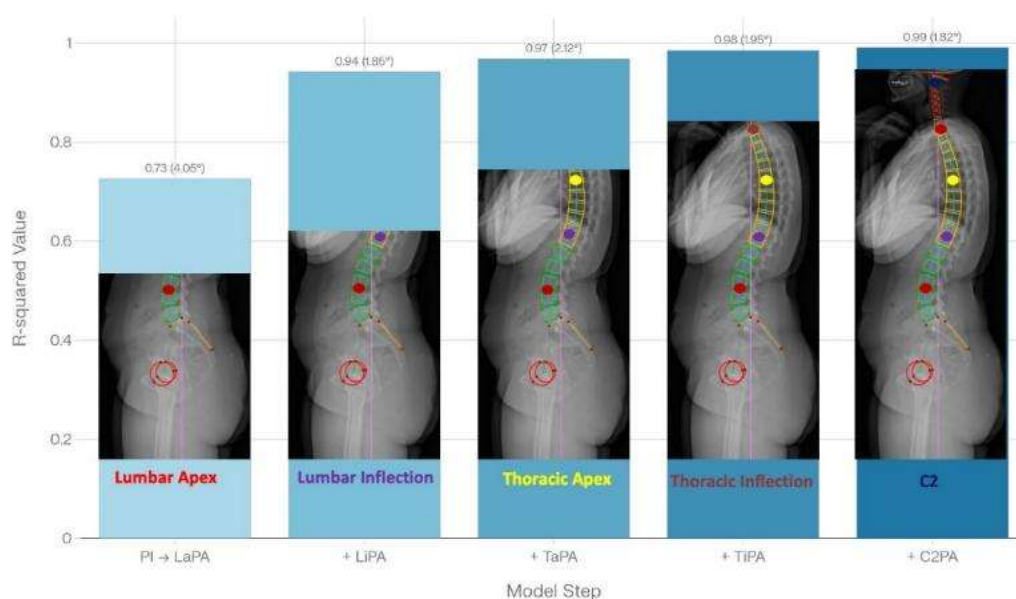
### Conclusion

LaPA functions as the optimal Rosetta Stone for PI-concordant shape reconstruction offering greater accuracy than fixed points. Calculating target LaPA from PI allows reliable sequential derivation of ideal regional landmarks via a strong correlation chain - while PI-independent parameters (TiLiPa & TaLaPa) provide universal bounds. Surgical validation is needed

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

## Predictive Power of the Spinal Cascade: Stepwise R<sup>2</sup> and Prediction Error

Each step adds a spinal parameter, improving model accuracy



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

## 62. Using Artificial Intelligence to Capture CT Films with Smartphones for Automatic Recognition of Osteoporosis

Junyu Li, MD; Da Zou, MD; Liangyuan Wang; Yongqiang Wang, MD; Zhuoran Sun, MD; Miao Yu, MD; Weishi Li, MD

### Hypothesis

A deep learning model (AIPOS) using smartphone-captured CT film or screen images can accurately screen for osteoporosis, offering a portable and accessible alternative to traditional methods.

### Design

Retrospective diagnostic study developing and validating an AI model. Included 204 patients (149 with CT film photos, 55 with screen-captured images) for osteoporosis classification.

### Introduction

Osteoporosis is a major public health challenge with high rates of missed diagnosis. Current gold-standard screening (DXA, QCT) is limited by cost and accessibility. While AI models show promise, they typically rely on original DICOM data within hospital networks, hindering point-of-care use. This study aims to develop a portable system using smartphone photos of CT images for accessible screening.

### Methods

CT images from 204 inpatients were captured via smartphone (films or computer screens). Two orthopedic physicians provided reference diagnoses based on bone density. The AIPOS model was built on ResNet-50 with a triple-attention mechanism. Performance was evaluated using 5-fold cross-validation, assessing accuracy, sensitivity, specificity, F1-score, and AUC.

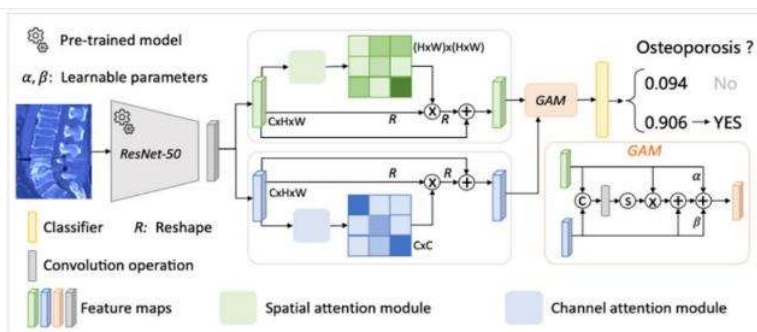
### Results

In 5-fold cross-validation, AIPOS achieved an average accuracy of 89.2%, sensitivity 92.6%, specificity 86.9%, F1-score 87.4, and AUC 0.951. Performance was better on CT film images than on screen-captured images (F1: 0.891 vs. 0.753). Cross-testing showed better generalization from film-trained to screen-test data (AUC 0.963) than the reverse (AUC 0.880). Window settings and scan orientation affected model performance

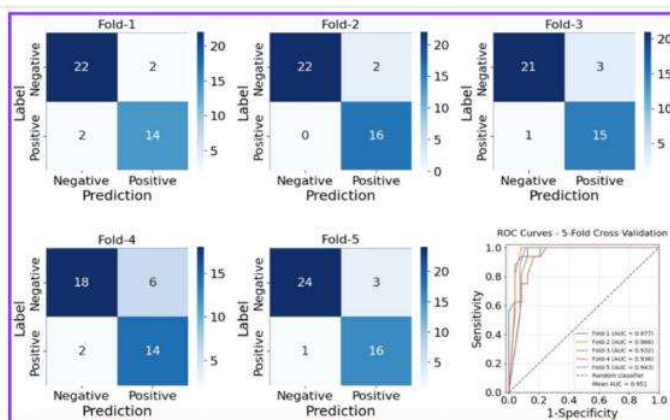
### Conclusion

The AIPOS system enables accurate, portable osteoporosis screening using smartphone-captured CT images, potentially increasing accessibility in community and home settings and reducing missed diagnoses

1



2



AIPOS Model Structure Diagram and Confusion matrix and ROC curve of the model in five-fold cross-validation on the mixed dataset.

### 63. Utilizing a Supervised Machine Learning Strategy to Automate Detection of Bony Fusion Using X-Rays in Lumbar Fusion Surgery ‡

Rushikesh S. Joshi, MD; Edward S. Harake, BS; Todd C. Hollon, MD; Paul Park, MD

#### Hypothesis

With a combination of self-supervised and supervised learning strategies, we aim to develop a computational tool that can learn radiographic features inherent to X-rays to predict bony fusion comparable to CTs, and outperform our ability as humans to predict fusion on spine X-rays.

#### Design

1,403 patients who underwent one- or two-level lumbar fusion surgery at a single institution between 2005-2023 were identified, yielding a total of 1,395 associated CT scans. CT scans were provided to fellowship-trained spine surgeons and a neuroradiologist for annotation. Every lumbar segment containing instrumentation was labeled as “fused” or “not fused” at three distinct anatomic sites. A total of 3,140 lumbar and scoliosis X-rays taken at various postoperative time points were paired with the extracted CTs and their level-specific labels.

#### Introduction

Bony fusion is one of the primary outcomes of spinal fusion surgery. CT scans remain the gold-standard for assessing bony fusion postoperatively, and can be difficult to obtain, are costly, and subject to surgeon bias. In this study, we sought to build an artificial intelligence (AI) tool to accurately predict bony fusion on X-rays.

#### Methods

A convolutional neural network (CNN) was developed to isolated instrumented segments from X-rays, and a twin neural network architecture was built to simultaneously evaluate individual cropped segments in both coronal and sagittal planes to predict bony fusion.

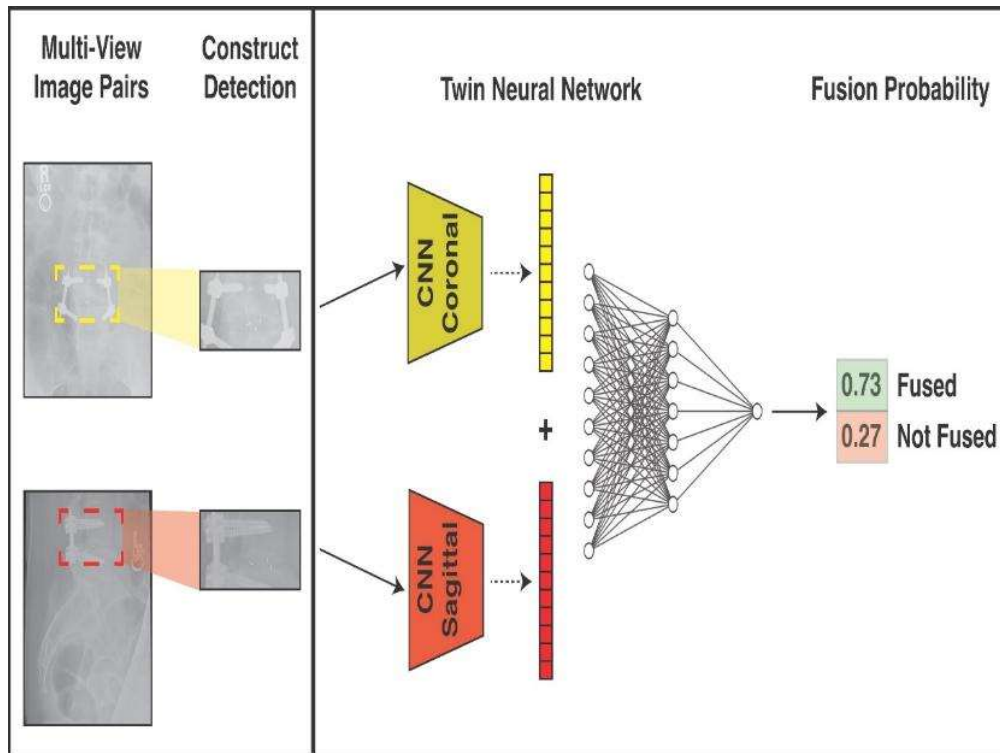
#### Results

Approximately 180 CTs were carefully annotated by our expert spine surgeons, corresponding to 367 unique x-ray studies. Individual instrumented levels were isolated from these studies using our CNN-based object detector and fed into our twin neural network model for training, with the dataset being split 85% training/15% testing. On an independent validation set, our model was able to predict bony fusion in relation to ground truth CT labels with 88% accuracy. This was compared to human performance of a board-certified neurosurgeon, who was able to predict bony fusion on x-rays in only 64% of cases by eye.

#### Conclusion

Using a combination of machine learning techniques, we were able to develop an AI-based model that could accurately predict bony fusion on X-rays. Future studies will continue to incorporate larger datasets to further train our model and enhance predictive capabilities to assist surgeons.

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



Twin neural network architecture

#### 64. Development and Validation of the Three-dimensional Depth Sensor Imaging System for Non-invasive Scoliosis Screening

Chen Liu, MD; Yingsen Pan, MD; Shao Chen, MD; Xiao-min Chen, MD; Yin-ling Sun, MD; Kai-qi Wang, MD; Honggen Du, MD

##### Hypothesis

We hypothesize that the developed three-dimensional depth sensor imaging system, integrated with adaptive correction and deep learning-based feature fusion, will demonstrate non-inferiority and potentially superiority in accuracy, sensitivity, and specificity compared to manual Angle of Trunk Rotation (ATR) assessment for the non-invasive screening of adolescent idiopathic scoliosis (AIS).

##### Design

Multicenter cross-sectional study

##### Introduction

To mitigate the high costs and radiation risks associated with X-ray examinations, numerous countries have implemented School Scoliosis Screening programs that utilize measurements of the ATR to screen large adolescent populations, despite the methods being time-consuming and subject to interpretative variability. We developed and validated a novel AIS screening system using a three-dimensional depth sensor, which incorporates adaptive correction techniques, deep learning algorithms and feature fusion method for objective, non-invasive, and automated detection of scoliosis.

##### Methods

Participants were based on suspected cases of adolescent idiopathic scoliosis. Utilizes a consumer-grade 3D depth sensor and a laptop, both integrated into the ROS framework. To identify whether patients with suspected adolescent idiopathic scoliosis were scoliosis by scanning the anterior flexion position. The data analysis framework presented in this article is methodically divided into two principal phases: the collection and preprocessing of human back point cloud data, and the development of deep learning classification models. And utilizing the Swin-Transformer model and the Feature-level feature fusion method. Accuracy, sensitivity and specificity were used to evaluate the system.

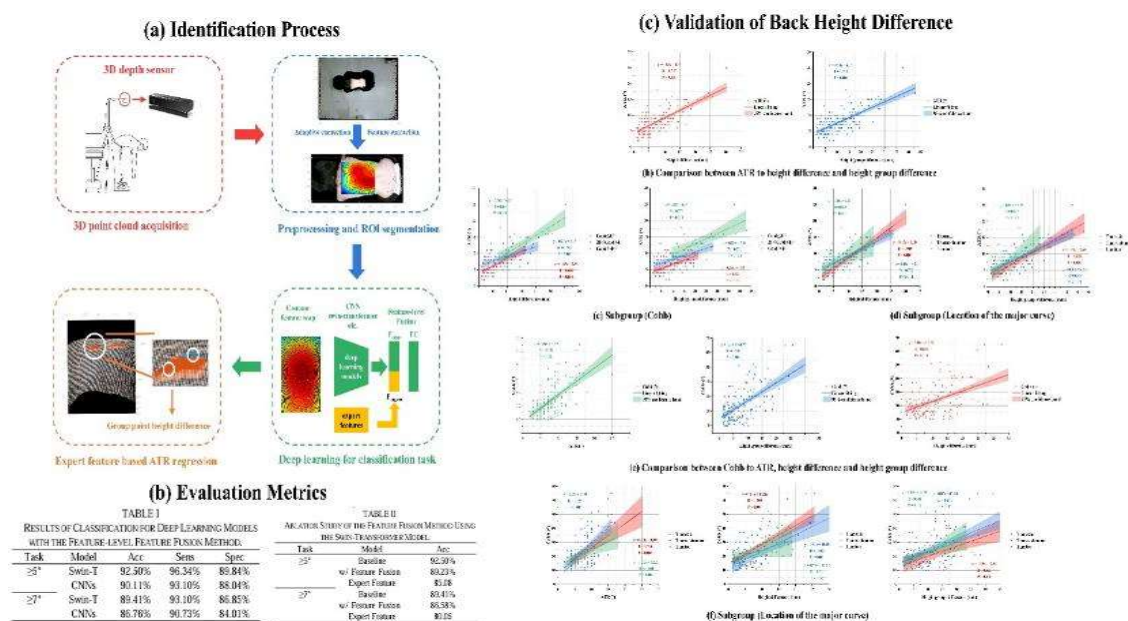
##### Results

This study included 869 subjects with documented ATR data across multiple centers. The system remarkably demonstrated an accuracy, sensitivity, and specificity of 93.0%, 96.4%, and 88.7% for predicting ATR equal to or greater than 5°, and 90.4%, 94.5%, and 85.2% for ATR equal to or greater than 7°, respectively. The introduction of the adaptive correction method enhanced accuracy by at least 1% (all  $P < 0.001$ ).

##### Conclusion

Our system exhibits great promise for highly accurate and readily accessible scoliosis screening, presenting a potential alternative to manual ATR measurements in large-scale screening initiatives.

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



## Methods and Results

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

## 65. Machine Learning Prediction of Cobb Angle from 3D Surface Topography in Adolescent Idiopathic Scoliosis: A Radiation-Free Alternative

Jose Maria Gonzalez Ruiz, PhD; Stephan Rothstock, PhD; Javier Pizones, MD, PhD

### Hypothesis

A machine learning model applied to 3D surface topography (3D-ST) data predicts the Cobb angle with a mean absolute error (MAE)  $<5^\circ$ , meeting clinical accuracy for detecting significant scoliotic changes.

### Design

Retrospective, observational, and analytical study.

### Introduction

Diagnosis, classification, and evaluation of adolescent idiopathic scoliosis (AIS) rely on the Cobb angle measured on radiographs with radiation risks. Tools combining 3D-ST and artificial intelligence have been developed, but most fail to meet the  $5^\circ$  clinical threshold for minimal significant change. Unlike conventional marker-less approaches, our model uses precise landmark-based extraction of 3D-ST coordinates for superior feature engineering that captures spinal curvature geometry.

### Methods

174 AIS patients (10-18 years, Cobb  $10^\circ$ - $60^\circ$ ) had their trunk surfaces analyzed by geometric morphometry, and the first 10 principal components of shape were extracted for Cobb prediction. These components were used to train and test the Cobb angle estimation model. The cohort was stratified by severity (mild  $<25^\circ$ , moderate  $25$ - $40^\circ$ , and severe  $>40^\circ$ ) to ensure equal representation of classes in the training and test sets. 140 patients were used for training and 34 for testing. Root Mean square error (RMSE), mean absolute error (MAE), and R2 were calculated comparing predictions and radiographic Cobb. The percentage of predictions below clinical threshold was calculated for the test set.

### Results

In the training set, the RMSE, MAE, and R2 were  $3.93^\circ$ ,  $3.15^\circ$ , and 0.86, respectively. In the test set, the RMSE was  $5.39^\circ$  [CI95%:4.15-6.74], the MAE was  $4.33^\circ$  [CI95%:3.29-5.50], and the R2 was 0.81 [CI95%:0.72-0.87]. 70.6% of patients were predicted below the clinical threshold ( $5^\circ$ ). Figure 1 shows the plot of predicted versus radiographic Cobb.

### Conclusion

Our model predicts Cobb angle from 3D-ST with an MAE below the clinical threshold of  $5^\circ$ , allowing detection of relevant curve changes while reducing reliance on radiographs. This radiation-free tool supports follow-up by flagging progression and quantifying changes in trunk asymmetry associated with radiographic progression.

## 66. XR-GAN Enables Radiation-Free Radiograph Synthesis After Posterior Spinal Fusion in Adolescent Idiopathic Scoliosis: Toward Remote Follow-Up

Nan Wu, MD; Jingxi Su, ME; Aoran Maheshati, MD; Baitao Liu, MD; Kexin Xu, MS; Xiangjie Yin, MD; Jianguo T. Zhang, MD

### Hypothesis

A generative adversarial network (GAN) framework can accurately synthesize high-fidelity postoperative spinal radiographs from standardized 2D-RGB back photographs, providing a radiation-free alternative for monitoring spinal alignment and instrumentation.

### Design

This was a multi-center retrospective diagnostic study utilizing a large cohort of clinical and imaging data for model development and external validation.

### Introduction

Adolescent idiopathic scoliosis (AIS) management requires frequent postoperative radiographic follow-up to monitor spinal alignment and implant integrity. However, repeated ionizing radiation exposure and limited access to full-spine imaging in primary care or resource-limited settings complicate long-term care. While artificial intelligence has advanced scoliosis screening, high-fidelity generative solutions for postoperative assessment, which must account for complex surgical hardware, remain scarce. We proposed a radiation-free, deep-learning framework to bridge this gap.

### Methods

A total of 1,229 paired postoperative back photographs and radiographs from 1,059 AIS patients who underwent posterior spinal fusion were collected. A GAN-based model, XR-GAN, was trained on 992 image pairs. The model was evaluated on 110 internal and 127 external test pairs from three independent centers. Performance was measured by Cobb angle prediction accuracy (R2, MAE), scoliosis severity grading, and image quality metrics, including Fréchet Inception Distance (FID) and Structural Similarity Index (SSIM).

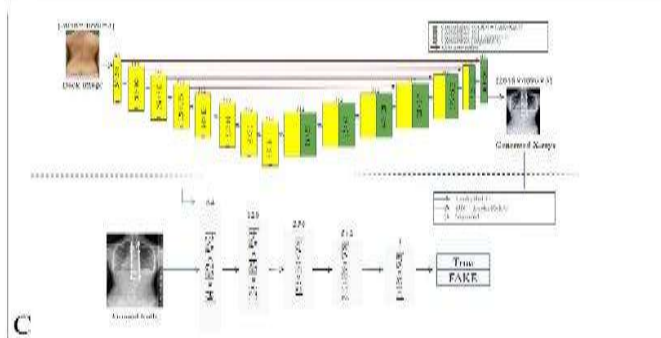
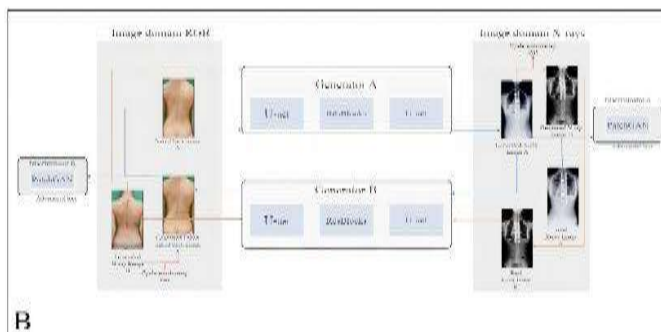
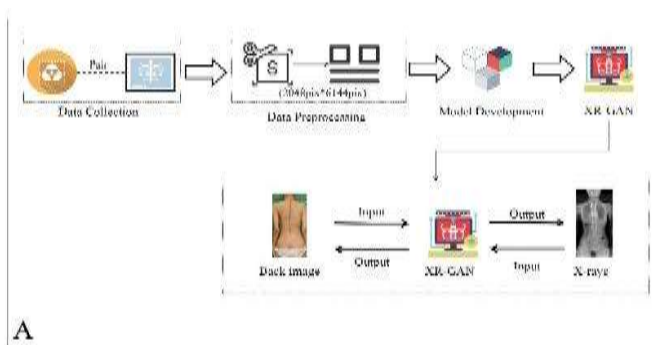
### Results

XR-GAN achieved superior Cobb angle prediction in the internal test set (R2=0.964, MAE=1.54°) and maintained robustness in external validation (R2=0.873, MAE=2.16°). Compared to baseline models, XR-GAN demonstrated significantly higher image quality (FID=12.275, SSIM=0.920) and expert ratings (90.3/100). The model accurately preserved anatomical fidelity in fusion segments and successfully reconstructed pedicle screw-rod instrumentation at both immediate postoperative and one-year follow-up stages.

### Conclusion

XR-GAN enables the accurate synthesis of postoperative radiographs from simple back photographs. This low-cost, radiation-free methodology provides a practical solution for remote AIS monitoring, potentially reducing the need for clinical visits and radiation exposure while improving access to care in underserved regions.

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



## 67. Impaired Laminin-Dystroglycan/Integrin Signaling from Fibro-Adipogenic Progenitor Drives Deep Paravertebral Muscle Strength Imbalance in Adolescent Idiopathic Scoliosis

Xuan Huang, MD; Jiafeng Dai, MD; Zhen Wang, MD; Junduo Zhao, MD; Haoyu Cai, MD; Hongyi Zhou, MD; Yutian Niu, MD; Yizhen Huang, MD; Heng Sun, MD; Yong Zhang, PhD; Jianxiong Shen, MD

### Hypothesis

Deep paravertebral muscle strength imbalance induces adolescent idiopathic scoliosis. Impaired Laminin-Dystroglycan/Integrin signaling contributes to deep paravertebral muscle strength imbalance in AIS.

### Design

Basic research

### Introduction

Adolescent idiopathic scoliosis (AIS) is a prevalent spinal deformity with a largely elusive etiology. While genetic, hormonal, and neurological factors have been implicated, the precise pathogenesis remains unclear. Deep paravertebral muscle (DPM) includes multifidus, rotatores, and semispinalis. This study investigates the role of DPM strength imbalance and its underlying cellular and molecular mechanisms in AIS development.

### Methods

A bipedal rat model was established, comprising a control (CON) group and a group with unilateral DPM excision (EX) to induce scoliosis. Spinal morphology was assessed via CT and MRI. Human DPM samples from controls and AIS patients were analyzed using histological staining (H.E., Oil Red O, NADH, myofiber typing) and MRI-based fat quantification. Single-cell (sc) and single-nucleus (sn) RNA sequencing of DPM were performed to characterize cellular heterogeneity and interactions. Immunofluorescence was performed to validate the result.

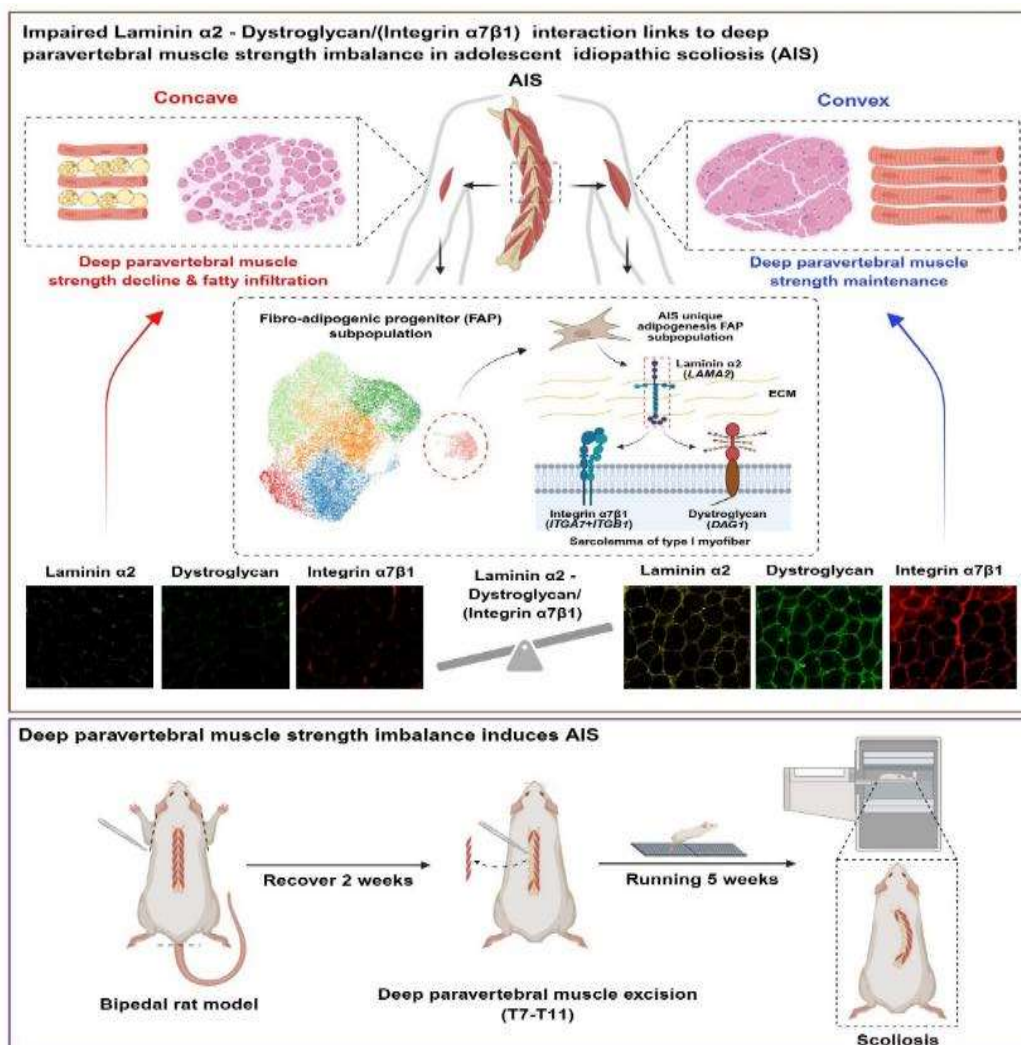
### Results

All EX rats (16/16) developed scoliosis with right-sided spinal curvature, whereas no deformity occurred in CON rats (0/10). In human AIS samples, the concave-side DPM exhibited a lower proportion of type I myofibers, a higher proportion of type IIx myofibers, and greater fatty infiltration compared to the convex side. snRNA-seq confirmed myofiber type imbalance and adipogenic changes in AIS. scRNA-seq identified a unique, imbalanced Fibro-Adipogenic Progenitor (FAP) subpopulation in AIS with an aberrant differentiation trajectory. Cell-cell communication analysis revealed a significantly weaker Laminin  $\alpha 2$ -Dystroglycan/Integrin  $\alpha 7 \beta 1$  interaction from this AIS-specific FAP subpopulation to type I myofibers on the concave side than on the convex side. This result was further validated by immunofluorescence of AIS DPM.

### Conclusion

Imbalanced DPM strength is a causative factor in AIS. This imbalance is associated with a pathological FAP subpopulation in AIS, whose impaired signaling via Laminin  $\alpha 2$ -Dystroglycan/Integrin  $\alpha 7 \beta 1$  pathway to type I myofibers contributes to the asymmetric muscle properties and the pathogenesis of AIS.

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



Graphical abstract

## 68. Unilateral Intradiscal Injection of Vosoritide-Loaded PLGA Microspheres Induces Asymmetric Spinal Growth in Juvenile Rabbits

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### Hypothesis

Asymmetric growth plate chondrocyte activity contributes to scoliosis progression. Locally promoting unilateral vertebral growth via sustained release could modulate spinal alignment.

### Design

Experimental study

### Introduction

Spinal growth imbalance drives scoliosis. While our team previously proved locally inhibiting growth through chondrocyte apoptosis could induce spinal curvature, a strategy to actively promote growth via sustained local drug delivery remains unexplored.

### Methods

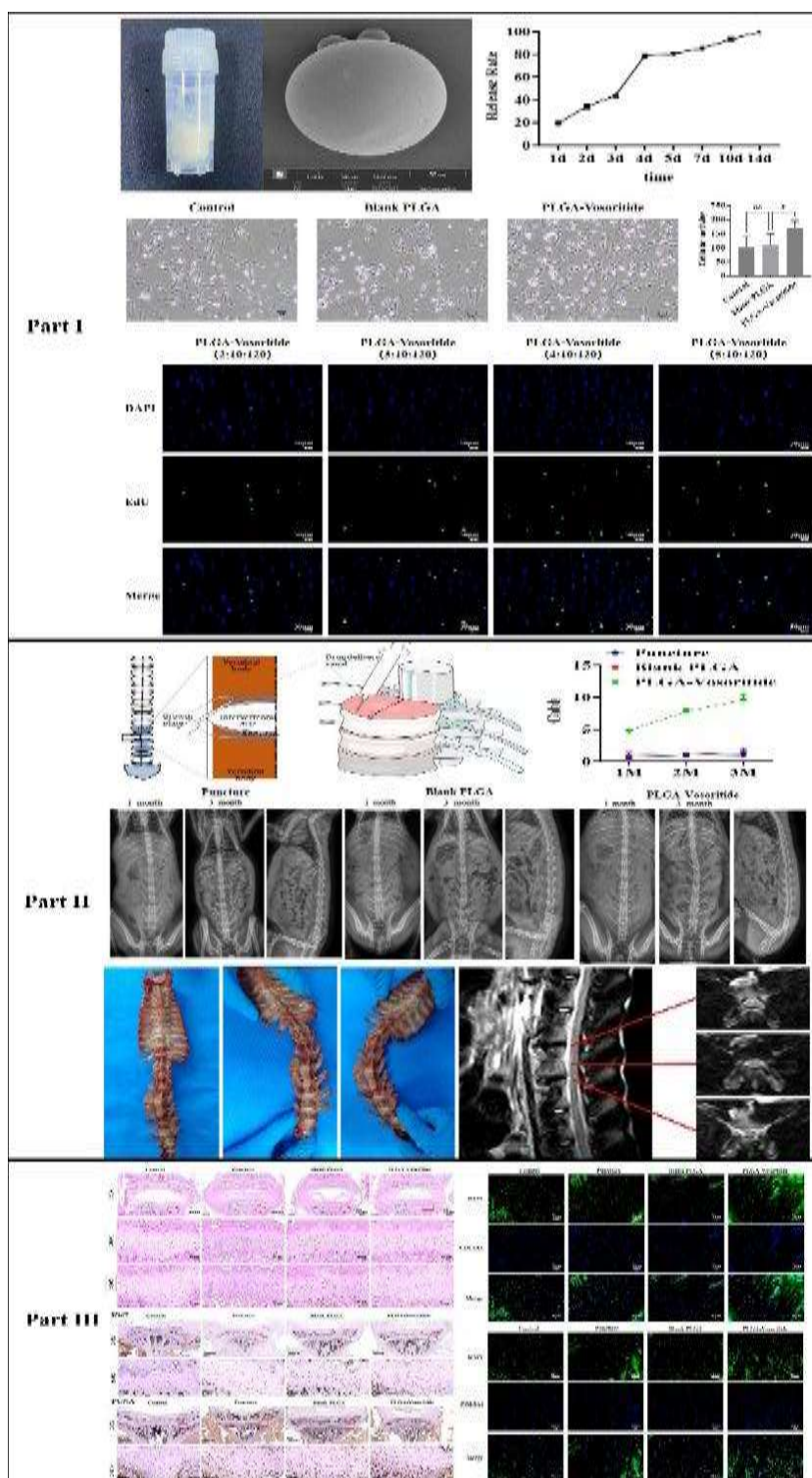
We fabricated vosoritide-loaded PLGA microspheres via S/O/W emulsification. After optimization in vitro, juvenile rabbits received unilateral intradiscal injections at two lumbar levels. Groups: control, puncture, blank PLGA, and PLGA-vosoritide. Cobb angles were tracked radiographically at 1, 2, and 3 months. Growth plate responses were evaluated via histology and immunofluorescence.

### Results

Part I: PLGA-vosoritide microspheres (optimal formulation: vosoritide:DEX:PLGA=4:10:120) demonstrated sustained release over 14 days with no cytotoxicity. Part II: Unilateral injection induced progressive spinal curvature, with Cobb angles measuring  $4.76^{\circ} \pm 0.27^{\circ}$ ,  $7.79^{\circ} \pm 0.49^{\circ}$ , and  $9.58^{\circ} \pm 0.95^{\circ}$  at 1, 2, and 3 months respectively, with no neurological impairment observed. Part III: The injected side exhibited thickened growth plates, increased chondrocyte proliferation, and enhanced collagen synthesis, as confirmed by histology and immunofluorescence showing upregulated expression of proliferation markers and extracellular matrix components. No such changes or spinal deformity were observed in the control, puncture, or blank microsphere groups.

### Conclusion

Local sustained release of vosoritide via PLGA microspheres effectively promotes unilateral vertebral growth and induces rigid asymmetric spinal curvature, introducing a novel biological approach with therapeutic potential for growth-related spine disorders.



Part I: PLGA-vosoritide microspheres demonstrated sustained release over 14 days. Part II: Unilateral injection induced progressive spinal curvature. Part III: The injected side showed enhanced growth plate thickness, chondrocyte proliferation, and collagen synthesis.

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

### 69. Increasing Opioid Dose Impairs Spinal Fusion in a Rat Model ‡

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#### Hypothesis

Increasing postoperative opioid dose is associated with impaired spinal fusion and fusion bone mass quality in a rat lumbar fusion model.

#### Design

Controlled animal study.

#### Introduction

Opioids are commonly administered postoperatively for spinal surgery and have been implicated as a potential cause for impaired bone formation. However, the outcomes of prolonged opioid exposure on spinal fusion outcomes remains poorly defined. This study evaluated the dose-dependent impact of morphine on spinal fusion using a rat model.

#### Methods

One hundred twenty rats underwent bilateral posterolateral lumbar fusion at L4-5 and were randomized to receive postoperative subcutaneous morphine at 4 doses (control, 1mg, 2mg, 4mg) for 6 weeks. Fusion was assessed using manual palpation with 2 graders (MP), plain radiographs (XR), and micro computed tomography (CT). Bone mineral density (BMD), tissue mineral density (TMD), bone volume (BV), total volume (TV), and bone volume fraction (BV/TV) was assessed on an 80-rat subset. Comparisons were performed using one-way ANOVA or chi square testing, with post-hoc analysis as needed. Significance was  $p < 0.05$ .

#### Results

XR and CT demonstrated decreased fusion rates with increasing opioid dose, with CT bilateral fusion rates declining from 83.3% in controls to 56.7% in the 1mg, 53.3% in the 2mg, and 40% in the 4mg morphine groups ( $p = 0.007$ ). MP demonstrated a similar dose-dependent reduction in mechanical fusion rates for both graders ( $p = 0.007$ ,  $p < 0.001$ ). Imaging analysis revealed a reduction in fusion mass area with 307.6mm<sup>2</sup> for controls, 268.1mm<sup>2</sup> for 1mg, 257.6mm<sup>2</sup> for 2mg, and 213.7mm<sup>2</sup> for 4mg ( $p < 0.001$ ). BV ( $p = 0.109$ ) and TV ( $p < 0.001$ ) also demonstrated a reduction in increasing opioid dose groups. TMD differed between groups, with a lower TMD observed at 1mg and 2mg than control, but without further dose-response at 4mg ( $p = 0.019$ ). BMD (Control: 236.8 mgHA/cm<sup>3</sup>, 1mg: 248.7, 2mg: 255.9, 4mg: 249.1,  $p = 0.508$ ) and BV/TV ( $p = 0.323$ ) were similar across groups.

#### Conclusion

Prolonged postoperative opioid administration is associated with impaired spinal fusion in a rat model, driven primarily by reduced fusion mass size as opposed to impaired bone mineralization. These findings suggest that postoperative opioid exposure may adversely affect fusion mass formation in a dose-dependent manner, with a greater effect on the quantity of bone formation rather than the quality. Further research is needed to quantify this effect in humans.

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

| Imaging Analysis of Fusion                     |                |            |            |            |         |
|------------------------------------------------|----------------|------------|------------|------------|---------|
|                                                | Control (n=30) | 1mg (n=30) | 2mg (n=30) | 4mg (n=30) | P-value |
| Plain Radiograph<br>Bilateral Fusion (%)       | 26 (86.7)      | 19 (63.3)  | 20 (66.7)  | 14 (46.7)  | 0.013   |
| Computed<br>Tomography Bilateral<br>Fusion (%) | 25 (83.3)      | 17 (56.7)  | 16 (53.3)  | 12 (40)    | 0.007   |
| Manual Palpation of Fusion                     |                |            |            |            |         |
| <b>Grader 1 (%)</b>                            |                |            |            |            | 0.007   |
| Unrestricted                                   | 0              | 2 (6.7)    | 2 (6.7)    | 2 (6.7)    |         |
| Restricted                                     | 1 (3.3)        | 9 (30)     | 7 (23.3)   | 11 (36.7)  |         |
| Fused                                          | 29 (96.7)      | 19 (63.3)  | 21 (70)    | 17 (56.7)  |         |
| <b>Grader 2 (%)</b>                            |                |            |            |            | <0.001  |
| Unrestricted                                   | 0              | 4 (13.3)   | 0          | 3 (10)     |         |
| Restricted                                     | 2 (6.7)        | 6 (20)     | 13 (43.3)  | 25 (83.3)  |         |
| Fused                                          | 28 (93.3)      | 20 (66.7)  | 17 (56.7)  | 2 (6.7)    |         |
| Imaging Results                                |                |            |            |            |         |
|                                                | Control (n=20) | 1mg (n=20) | 2mg (n=20) | 4mg (n=20) | P-value |
| Fusion mass (mm^2)                             | 307.6          | 268.1      | 257.6      | 213.7      | <0.001  |
| Bone Mineral Density<br>(mg HA/cm^3)           | 236.8          | 248.7      | 255.9      | 249.1      | 0.508   |
| Tissue Mineral Density<br>(mg HA/cm^3)         | 861.3          | 844.1      | 841.3      | 850.1      | 0.019   |
| Bone Volume (mm^3)                             | 30.3           | 26.5       | 25.8       | 23.9       | 0.109   |
| Total Volume (mm^3)                            | 204.1          | 155.1      | 151        | 146.4      | <0.001  |
| Bone Volume /Total<br>Volume (%)               | 15.3           | 17.1       | 17.3       | 16.3       | 0.323   |

Table 1

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