Original Article

Preceding neurosurgery is not needed for presumed adolescent idiopathic scoliosis with syringomyelia: a 10-year longitudinal comparative study

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Background: One-stage scoliosis correction surgery is safe for adolescent idiopathic scoliosis (AIS), but it is not yet known whether it is safe for presumed AIS (PAIS). This study sought to investigate the safety and efficacy of one-stage scoliosis correction surgery for PAIS associated with syringomyelia from multiple perspectives by conducting an analysis of 10-year consecutive cases.

Methods: A retrospective study of all consecutive cases of patients diagnosed with PAIS associated with syringomyelia or AIS from January 2011 to January 2020 was performed. The main radiographic parameters and clinical function scores before, immediately after, and at the last follow-up were collected or measured. Three-dimensional (3D) models of spinal canal length were generated, refined, measured, and compared between the PAIS and AIS groups.

Results: In total, 318 patients with AIS and 47 patients with PAIS associated with syringomyelia were included in the study. There were no significant differences between the two groups in terms of changes in the Cobb angle of the main curve (MC), thoracic kyphosis (TK), coronal balance (CB), sagittal vertical axis (SVA), Oswestry disability index (ODI), Scoliosis Research Society-22 (SRS-22) score, cervical and thoracolumbar spinal canal length, and whole spinal canal length before and after the surgery ($P>0.05$). The changes in the thoracolumbar and whole spinal canal length were significantly positively correlated with the improvement rate of the MC ($P<0.05$), but were not significantly correlated with the improvement rate of TK, the SRS-22 score, and the ODI ($P>0.05$).

Conclusions: In relation to the main radiologic parameters, clinical function scores, and 3D biomechanics, one-stage posterior correction surgery was found to be safe and effective for patients with PAIS associated with syringomyelia.

Keywords: Presumed adolescent idiopathic scoliosis (PAIS); syringomyelia; surgery

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Introduction

Adolescent idiopathic scoliosis (AIS) is the most common type of scoliosis that occurs between the ages of 10 to 18 years (1). AIS occurs in 2–4% of the population and accounts for 70–90% of total scoliosis (2). The treatment guidelines for AIS are well established (3-8). In recent years, with the development of spinal magnetic resonance imaging (MRI), some intraspinal abnormalities have been detected, such as syringomyelia, Chiari malformation, tethered cord, and split cord malformation (9). Davids *et al.* (10) first studied AIS with intraspinal abnormalities and named it "presumed adolescent idiopathic scoliosis (PAIS)". Syringomyelia is the development of a fluid-filled cyst (syrinx) within the spinal cord, and is the most common intraspinal abnormality for PAIS patients (11).

The surgical strategy for patients with PAIS associated with syringomyelia remains controversial. Some spine surgeons have suggested that syringomyelia should be treated before scoliosis correction, as syringomyelia can increase the risk of neurological deterioration (12). However, other studies have suggested that neurosurgery may not be necessary for asymptomatic patients, as the neurosurgical intervention can lead to many complications, and second-stage corrections can increase the difficulty and risk of surgery (13-23).

The change in the spinal canal length after scoliosis correction surgery is crucial for surgical safety, but currently, there is no effective method for measuring the three-dimensional (3D) length change of the spinal cord. To date, only a few studies have measured changes in spinal canal lengths in patients with scoliosis before and after surgery using X-ray or computed tomography (CT) images, and the results of these studies have differed significantly due to factors related to the technical means and sample differences (24-26). In a previous study, we found that one-stage posterior scoliosis correction surgery was safe and effective for patients with PAIS (9). However, the length changes of the spinal cord at different locations during scoliosis correction surgery remain unknown. In this study, 3D scoliosis models were reconstructed using 3D CT images of the whole spine for patients with PAIS associated with syringomyelia and patients with AIS who underwent one-stage posterior surgery from January 2011 to January 2020.

This study sought to investigate the safety and efficacy of one-stage scoliosis correction surgery for PAIS associated with syringomyelia from multiple perspectives by analyzing 10-year consecutive cases. The changes in the main radiographic parameters, clinical function scores, and spinal canal lengths before and after surgery between patients with PAIS associated with syringomyelia and patients with AIS were compared. We present this article in accordance with the STROBE reporting checklist (available at https://tp.amegroups.com/article/view/10.21037/tp-22-658/rc).

Highlight box

Key findings

- One-stage posterior correction surgery is safe and effective for patients with presumed adolescent idiopathic scoliosis (PAIS) associated with syringomyelia.

What is known, and what is new?

- One-stage scoliosis correction surgery is safe for adolescent idiopathic scoliosis (AIS) patients.
- The effects of surgery are similar between AIS and PAIS patients.

What is the implication, and what should change now?

- For surgery, the main radiologic parameters, clinical function scores, and three-dimensional biomechanics were similar between AIS and PAIS patients. No preceding neurosurgery is needed for PAIS patients.

Methods

Patients

We conducted a 10-year longitudinal comparative study with a minimum 2-year follow-up period. This retrospective study examined the data of consecutive patients with a diagnosis of PAIS associated with syringomyelia or AIS, who underwent posterior scoliosis correction surgery from January 2011 to January 2020. To be eligible for inclusion in this study, patients had to meet the following inclusion criteria: (I) have pre- and post-operative anterior-posterior and lateral whole spine X-rays and whole spine CT scans (64-slice, 1 mm fault) available; (II) have undergone pre-operative MRI; (III) have no history of spinal surgery or neurosurgery; (IV) have no neurological symptoms before surgery; (V) have a thoracic curve in the right direction; and (VI) have been followed-up for a minimum of 2 years. Patients were excluded from the study if they met any of the following exclusion criteria: (I) had congenital scoliosis associated with syringomyelia; (II) had a history of spinal surgery; (III) had other internal diseases of the nervous system; and/or (IV) had MRI results showing intraspinal abnormalities other than syringomyelia. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Ethics

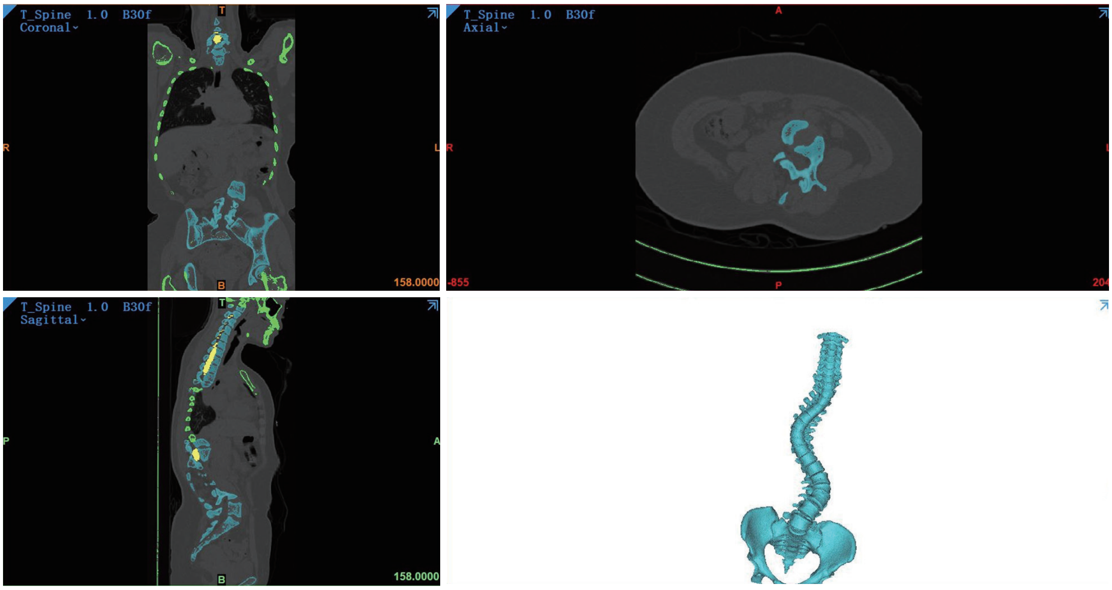

Figure 1 Three-dimensional model reconstruction using Mimics Medical 21.0 software. The vertebral bodies were stained by selecting the appropriate color threshold.

Board of Beijing Chao-Yang Hospital (No. 2019-02-1821), and the requirement of informed consent for this retrospective analysis was waived.

Data collection

Relevant radiographic data before and immediately after surgery, and at the last follow-up were collected or measured. All the radiographic parameter measurements were performed by two doctors (J.L. and Y.Z.), and average values were calculated to reduce errors.

Demographic data were collected for all patients, including age, gender, Risser sign, and syringomyelia location. Radiographic parameters, including the main coronal curve, coronal balance (CB, distance between the C7 plumb line and the central sacral vertical line), thoracic kyphosis (TK, Cobb angle from T5–T12), and the sagittal vertical axis (SVA), were measured pre-operatively, immediately post-operatively, and at a minimum of two years post-operatively. On the X-ray of the full spine in the standing position, the most inclined vertebras at the upper and lower ends of the spine were the end vertebras. The Cobb angle was defined as the angle between the upper endplate of the upper-end vertebra and the lower endplate of the lower-end vertebra, which was the main curve (MC) angle of scoliosis. The global CB was the horizontal distance from a vertical line extending from the center of the C7 vertebrae to the centre sacral vertical line (CSVL). The SVA was defined as the distance between the C7 plumb line and the posterior-superior corner of S1, and it was considered positive when the vertical plumb line laid anterior to the posterior-superior corner of S1. The Oswestry disability index (ODI) scores of the PAIS and AIS groups were also compared.

Surgical techniques

All the patients received jaw-occipital belt traction for 2 weeks. The posterior spinal correction and fusion with a pedicle screw (titanium; Weigo or RICH, China) instrumentation were performed by the same senior surgeon (Y.H.) for all patients. Somatosensory evoked potentials and motor evoked potentials, and the wake-up test were applied to all patients during surgery.

3D model data analysis

Model generation

First, the pre-operative and post-operative CT data were collected and the tomographic pictures of the whole spine of the patient were input into Mimics Medical 21.0 (Material NV, Leuven, Belgium) to create the 3D models with a threshold value of 226–3,071 HU (*Figure 1*). In general, the staining of the whole spine was completed when the

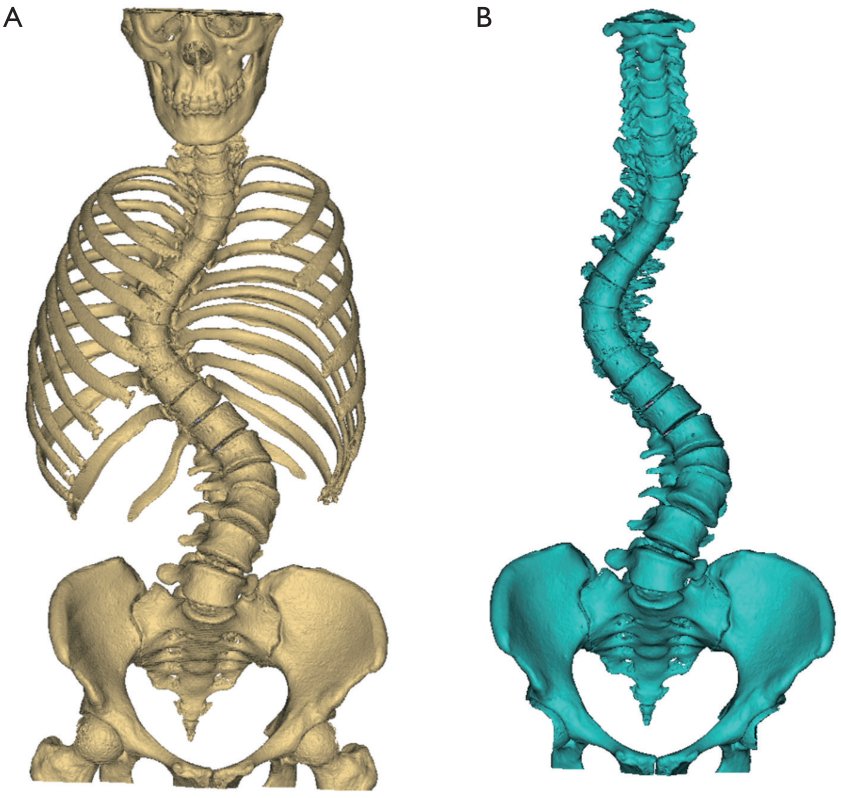

Figure 2 Model trimming and refinement.

staining threshold was around 200 HU.

Model trimming

After color removal, the skull, ribs, and pelvis were still visible. To facilitate the model reconstruction and 3D analysis, excess skulls, ribs, and pelvis were removed by trimming with the mask edit tool. At this time, a basic 3D model was generated (*Figure 2A*). For patients with AIS and PAIS associated with simple syringomyelia, as the fixed segment for surgical treatment was generally not higher than the T2 vertebral body, C1–C7 and T1–L5 segments were selected for the spine construction. Finally, on the coronal CT scan, the ribs were excised by about 1 cm along the side of the scoliosis with the cutting function. However, a small part of the ribs and the rib heads might remain after this operation. As this study sought to examine the reconstruction and analyze the internal wall of the spinal canal, no treatment could be performed that would affect the reconstruction of the spinal canal or the positioning of the marks. Otherwise, the ribs were erased at the thoracic rib joints when the vertebral body plane was trimmed. After that, the preliminary model generation was complete.

Model refinement

The internal defects and extra parts of the bone tissue were trimmed one by one. Three-plane positioning was performed through slice intersection; that is, after a certain position point was selected on a certain plane, the other two planes simultaneously displayed the position of the point on the plane, which was used for the 3D positioning of the multi-plane identical mark points. The planes were located at the sagittal midline, the horizontal plane was located at the lowest point of L5, and the model was repaired layer by layer upward. If the transverse section of L5 was shown on the horizontal plane and defects were found in the staining, the blank space was stained with a 3–5 mm circular staining pen using an independent staining device, and the color applied by the staining device was the same as the staining threshold value; if redundant staining was found (e.g., if the staining range around the vertebral bodies was too large, or significant adhesion was caused between the intervertebral spaces due to excessively low threshold selection), and the vertebral bodies could not be identified, or the boundary was blurred due to the irregular shape of the spinal canal, the erase function would be used to remove the redundant

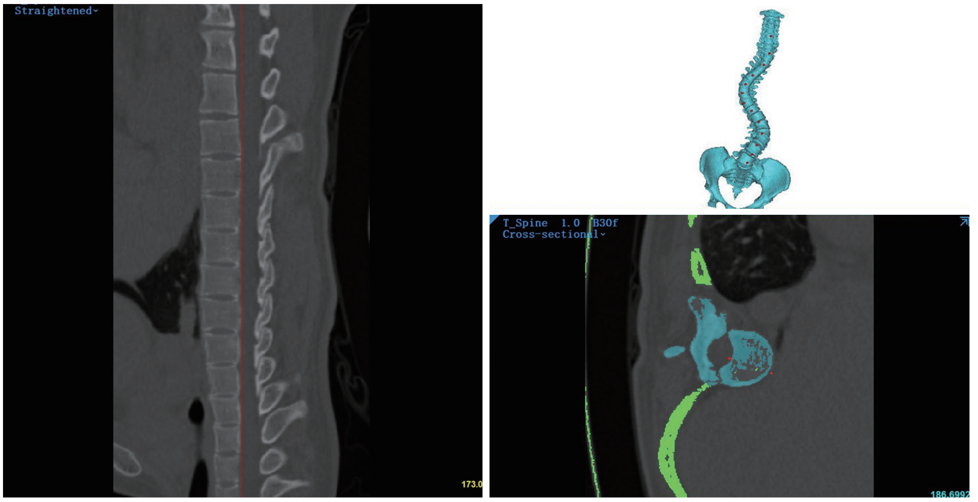

Figure 3 Precision cut of the three-dimensional model. The red dots indicate the line that the re-sliced computed tomography followed.

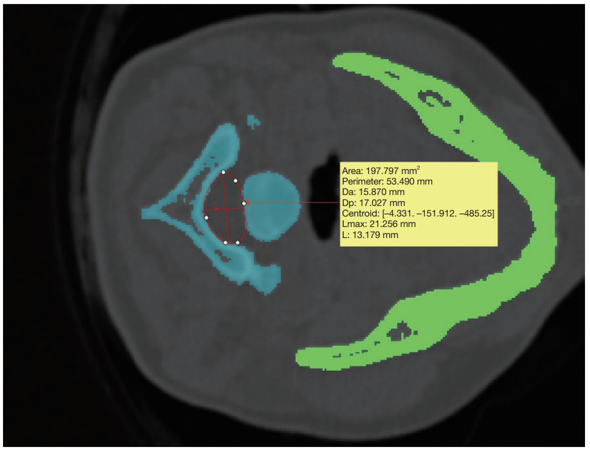

Figure 4 Spinal canal contour with markers. The red circle indicates the area of the spinal cord of the plane.

staining around the vertebral bodies and inside the spinal canal, and the inside of the spinal canal and the contour would be depicted with an independent staining device to ensure the accuracy of the subsequent measurements. The operation was repeated at all segments. In one case, to ensure that all the vertebral bodies were completely stained and that all the spinal canal contours were clear and identifiable, without redundancy or staining leakage, a completed 3D model reconstruction of scoliosis was generated after the completion of the internal repair of the vertebral bodies and the trimming of the spinal canal contours (*Figure 2B*).

Model cutting

The CT plane was re-sliced along the curve according to the spinal morphology. Using the cutting function, each vertebral body was cut on the pedicle plane, which was the plane passing through the midpoint of the sagittal pedicle and parallel to the upper endplate, which simulated the plane of the insertion angle of the pedicle screws to facilitate the determination of the spinal canal position (*Figure 3*).

Marking to outline spinal canal and measurement

After the cutting was completed, a closed complete curve was drawn on the axial plane along the inner wall of the spinal canal as the shape of this segment of the spinal canal, and this step was repeated for all the vertebral bodies (*Figure 4*). Some segments of the spinal canal can have extremely irregular shapes; thus, at this time, according to the shape of the spinal canal in the upper and lower adjacent segments, a certain degree of trimming was performed to ensure the continuity and consistency of the spinal canal morphology. After the completion of the spinal canal delineation, the software calculated the gravity center of the outlined spinal canal shape as the center point of the spinal canal on the axial plane. The central point was then taken as a cross that intersected with the front, back, left, and right of the spinal canal. The longitudinal cross was parallel to the longitudinal axis of the vertebral body, and the transverse cross was parallel to the transverse axis of the vertebral body. The intersection of the cross and the outline of the spinal canal were marked as the anterior, posterior, left and right points

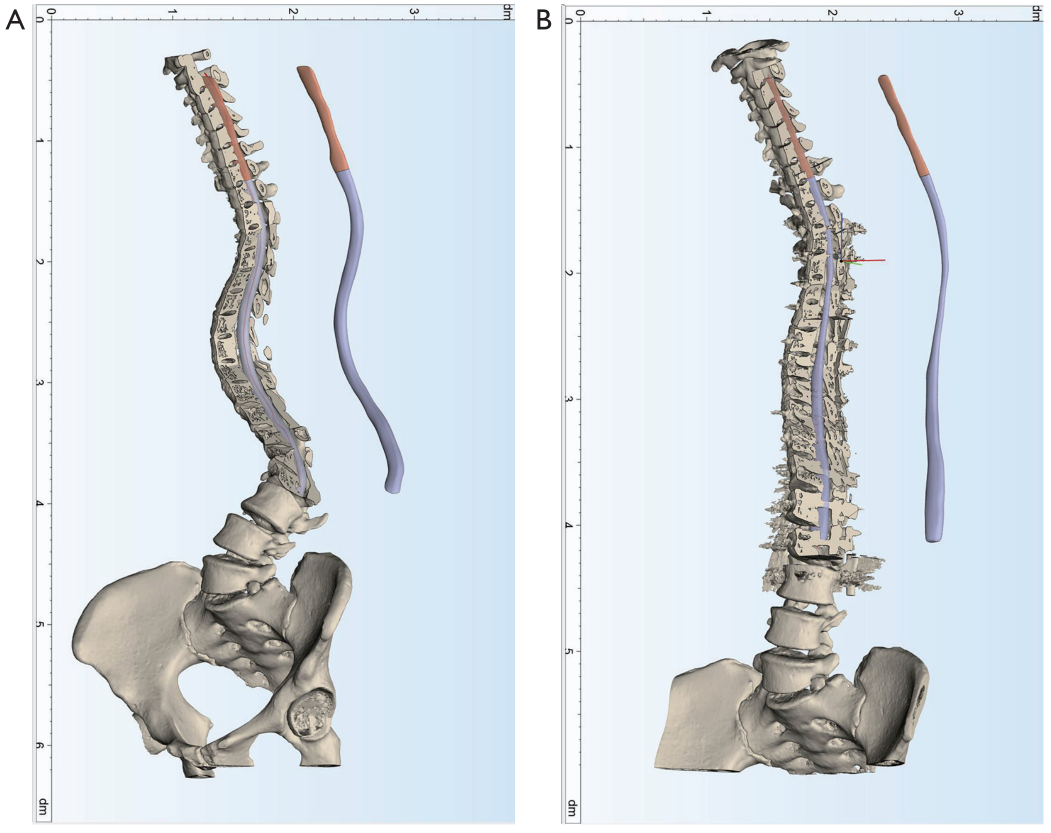

Figure 5 Segment measurement of pre- (A) and post-operative (B) spinal canal diameters.

of the spinal canal (*Figure 5*), and the spinal canal was marked using this approach in all planes. Finally, the marked points at the center of the spinal canal in each plane were connected by the curve of the chord length or the square root of the chord length. For the patients with AIS and PAIS associated with single syringomyelia, the spinal cord generally stayed at the L1 or L2 level. We measured the spinal canal length between C1–C7, T1–L2 and, C1–L2, respectively.

Statistical analysis

SPSS 19.0 software was used for the statistical analysis. The measurement data are expressed as the mean (minimum to maximum). The *t*-test was used for mean comparisons between groups, and the Chi-square (χ^2) test or Fisher's exact test was used for the enumeration data. A P value <0.05 was considered statistically significant.

Results

A total of 365 patients were included in the study, of whom 318 had AIS and 47 had PAIS associated with syringomyelia (*Figure 6*). The average age of the patients was 15.6 years (11–18 years), and 26.8% of the patients were male. All the patients were followed up for more than 2 years. The pre-operative baseline data of the patients with AIS and PAIS associated with syringomyelia are summarized in *Table 1*. There were no statistically significant differences between the two groups in terms of age, gender, Risser grade, the ODI, the SRS-22 score, CB, and the SVA. However, the Cobb angles of the MC and TK differed significantly between the two groups.

In terms of the main radiographic parameters for the patients in the AIS and PAIS groups, the coronal MC, sagittal TK, and CB and sagittal balance of the two groups were significantly better immediately post-operatively than preoperatively, and there was no significant orthopedic loss at the last follow-up. There was no significant difference in the radiographic parameters at the last follow-up between the groups. In terms of the clinical function scores, the ODI and SRS-22 clinical function scores were significantly better immediately post-operatively than preoperatively, and the

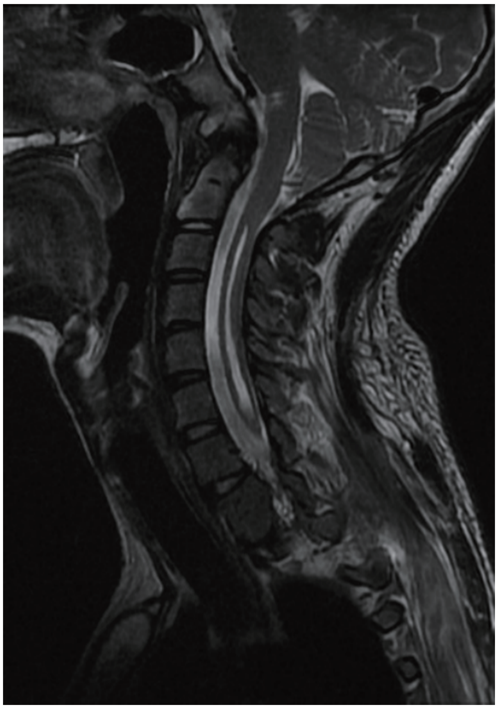

Figure 6 A 16-year-old female patient with presumed adolescent idiopathic scoliosis with syringomyelia.

effects continued until the last follow-up. There was no significant difference in the clinical function scores at the last follow-up between groups. A comparative summary of the post-operative clinical radiographic data of the patients with AIS and PAIS associated with single syringomyelia is shown in *Table 2*.

In relation to the change in the overall length of the spinal canal (C1–L2), in the AIS group, the overall length of the spinal canal increased by 5.6 mm (4.3–7.1 mm) from 443.8 mm (387.6–462.1 mm) pre-operatively to 449.4 mm (393.4–465.1 mm) post-operatively, and the improvement rate was 1.3% (0.9–1.5%). While in the PAIS group, the overall length of the spinal canal increased by 5.5 mm (4.4–6.7 mm) from 410.5 mm (384.5–452.1 mm) pre-operatively to 416.0 mm (387.5–458.2 mm) post-operatively, and the improvement rate was 1.3% (0.8–1.5%). There was a significant difference in the pre-operative and post-operative total lengths of the spinal canal in both groups (P<0.05), but there were no statistically significant differences in the changes and improvement rates of the total lengths of the spinal canal between the two groups.

In relation to the change in the length of the entire

Table 1 Comparison of the pre-operative clinical and imaging data of the patients with AIS and PAIS associated with syringomyelia

Parameter	AIS (n=318)	PAIS (n=47)	P value
Age (years)	16.2 [11–18]	15.4 [12–18]	0.31
Males (%)	26.4	29.8	0.17
Risser	2.7 [2–5]	2.6 [1–5]	0.42
Location of syringomyelia			
Above the correction	–	21	
Within the correction	–	26	
Below the correction	–	0	
ODI	33.4 [12–42]	34.1 [12–43]	0.47
SRS-22	83.1 [67–98]	84.2 [66–96]	0.37
MC (°)	83.6 [61.4–98.3]	76.6 [45.4–120.3]	0.03*
CB (mm)	20.3 [4.3–46.2]	19.6 [4.2–42.1]	0.24
TK (°)	35.1 [8.3–62.4]	43.5 [22.9–66.9]	<0.001*
SVA (mm)	−21.3 [−103.1 to 95.4]	−21.6 [−104.4 to 80.1]	0.33

Data are presented as mean [range], percentage, or number. *, P<0.05 was considered statistically significant. AIS, adolescent idiopathic scoliosis; PAIS, presumed adolescent idiopathic scoliosis; ODI, Oswestry disability index; SRS-22, Scoliosis Research Society-22; MC, main curve (Cobb angle); CB, coronal balance; TK, thoracic kyphosis; SVA, sagittal vertical axis.

Table 2 Comparison of the post-operative clinical and imaging data of the patients with AIS and PAIS associated with syringomyelia

Parameter	AIS	PAIS	P value
MC			
Immediate post-op			
Magnitude (degree)	21.2 [2.6–43.1]	18.3 [6.3–36.1]	0.81
Correction rate (%)	74.6 [64.1–94.2]	76.1 [64.3–96.1]	0.11
Last follow-up			
Magnitude (degree)	22.2 [4.3–66.2]	20.4 [6.1–58.7]	0.21
Correction rate (%)	73.4 [62.1–96.3]	74.4 [63.1–94.2]	0.23
Correction loss (%)	3.1 [−7.3–7.4]	2.1 [−7.1–8.5]	0.45
CB (mm)			
Immediate post-op	10.2 [0.2–38.4]	11.4 [0.1–40.1]	0.18
Last follow-up	9.6 [0.2–41.3]	11.1 [2.1–38.4]	0.20
TK (°)			
Immediate post-op	43.6 [10.1–62.3]	42.5 [8.2–58.7]	0.23
Last follow-up	41.3 [8.6–56.4]	42.1 [10.2–58.9]	0.31
SVA (mm)			
Immediate post-op	−7.3 [−112.1–92.4]	−6.7 [−98.3–78.2]	0.22
Last follow-up	−15.3 [−96.2–79.1]	−13.4[−92.1–74.3]	0.27
ODI			
Immediate post-op	15.3 [6–23]	15.7 [5–24]	0.53
Last follow-up	12.2 [4–20]	11.8 [5–21]	0.52
SRS-22			
Immediate post-op	96.5 [82–101]	95.7 [78–99]	0.31
Last follow-up	96.2 [84–101]	95.9 [77–98]	0.44

Data are presented as mean [range]. AIS, adolescent idiopathic scoliosis; PAIS, presumed adolescent idiopathic scoliosis; MC, main curve (Cobb angle); CB, coronal balance; TK, thoracic kyphosis; SVA, sagittal vertical axis; ODI, Oswestry disability index; SRS-22, Scoliosis Research Society-22.

cervical spinal canal (C1–C7), in the AIS group, the length of the cervical spinal canal increased by 0.6 mm (0.2–1.0 mm) from 93.1 mm (86.2–97.1 mm) pre-operatively to 93.7 mm (87.1–97.6 mm) post-operatively, and the improvement rate was 0.64% (0.4–1.4%). While in the PAIS group, the length of the cervical spinal canal increased by 0.5 mm (0.3–1.2 mm) from 87.2 mm (82.5–96.2 mm) pre-operatively to 87.7 mm (83.2–97.4 mm) post-operatively, and the improvement rate was 0.57% (0.5–1.7%). There was no statistically significant difference in the length of the cervical spinal canal before and after the operation, or in the changes in the spinal canal and the change rate between the two groups.

In relation to the change in the length of the thoracolumbar spinal canal (T1–L2), in the AIS group, the length of the thoracolumbar spinal canal increased by 5.0 mm (3.7–6.1 mm) from 350.7 mm (294.8–365.0 mm) pre-operatively to 355.7 mm (306.3–367.5 mm) post-operatively, and the improvement rate was 1.4% (0.7–1.8%). While in the PAIS group, the length of the thoracolumbar spinal canal increased by 4.9 mm (3.6–5.1 mm) from 323.3 mm (302.4–355.9 mm) pre-operatively to 328.2 mm (304.3–360.8 mm) post-operatively, and the improvement rate was 1.5% (0.6–1.7%). The pre- and post-surgery thoracolumbar spinal canal lengths differed significantly

Table 3 Changes in the spinal canal length in the patients with AIS and PAIS associated with syringomyelia

Parameter	AIS	PAIS	P
Full length (C1–L2)			
Pre-op (mm)	443.8 (387.6–462.1)	410.5 (384.5–452.1)	<0.001*
Post-op (mm)	449.4 (393.4–465.1)	416.0 (387.5–458.2)	<0.001*
Change (mm)	5.6 (4.3–7.1)	5.5 (4.4–6.7)	0.87
Change rate (%)	1.3 (0.9–1.5)	1.3 (0.8–1.5)	0.72
Cervical segment (C1–C7)			
Pre-op (mm)	93.1 (86.2–97.1)	87.2 (82.5–96.2)	<0.001*
Post-op (mm)	93.7 (87.1–97.6)	87.7 (83.2–97.4)	<0.001*
Change (mm)	0.6 (0.2–1.0)	0.5 (0.3–1.2)	0.61
Change rate (%)	0.64 (0.4–1.4)	0.57 (0.6–1.7)	0.37
Thoracic and lumbar segments (T1–L2)			
Pre-operative (mm)	350.7 (294.8–365.0)	323.3 (302.4–355.9)	<0.001*
Post-operative (mm)	355.7 (306.3–367.5)	328.2 (304.3–360.8)	<0.001*
Change (mm)	5.0 (3.7–6.1)	4.9 (3.6–5.1)	0.43
Change rate (%)	1.4 (0.7–1.8)	1.5 (0.6–1.7)	0.52

Data are presented as mean (range). *, P<0.05 was considered statistically significant. AIS, adolescent idiopathic scoliosis; PAIS, presumed adolescent idiopathic scoliosis.

in both groups (P<0.05), but there were no statistically significant differences in the changes and improvement rates of the spinal canal lengths between the two groups. *Table 3* provides a summary of the spinal canal length changes in patients with AIS and PAIS associated with single syringomyelia.

There was no significant correlation between the changes in the cervical spinal canal length and the improvement rates of the MC, TK, SRS-22 score, and ODI. The changes in the thoracolumbar segment length and spinal canal length were found to be significantly positively correlated with the improvement rate of the MC, but no significant correlation was found with the improvement rate of TK, the improvement of the SRS-22 score, and the improvement of ODI. *Table 4* provides a summary of the correlations between the changes in the spinal canal length and the changes in the main parameters.

Discussion

The surgical strategy for patients with PAIS associated with syringomyelia remains controversial. Some spine surgeons perform the neurosurgery before scoliosis correction. PAIS patients receive at least two surgeries, and thus suffer a great deal of pain. In a previous study (15), we found that there were no significant differences in the main radiologic parameters and clinical function scores between the PAIS and AIS patients that underwent one-stage scoliosis correction surgery, which indicated that one-stage correction surgery was safe and effective for patients with PAIS associated with syringomyelia clinically. However, some clinical studies have reached different conclusions (14-21). Thus, we sought to further investigate the change in spinal canal length after scoliosis correction surgery from the perspective of 3D biomechanics, which is crucial for surgical safety.

At present, there are two main methods for the reconstruction of a 3D spinal model: (I) biplane X-ray registration imaging (27) and (II) 3D CT reconstruction (28). Both methods have their advantages and disadvantages. Notably, the biplane X-ray registration method is simple and effective, and the radiation amount is much lower than that of CT. However, manual registration is required, which can lead to reconstruction errors if a surgeon is not experienced and does not understand the anatomy thoroughly. Additionally, for patients with severe scoliosis,

Table 4 Correlations between the changes in the spinal canal length and changes in the main parameters

Parameter	Cervical segment	Thoracic and lumbar segment	Whole length
MC correction rate	0.125/0.552	0.511/0.006*	0.613/0.001*
TK correction rate	0.139/0.498	–0.124/0.548	–0.244/0.229
SRS-22 improvement	0.038/0.849	0.089/0.660	0.229/0.251
ODI improvement	0.135/0.504	0.036/0.859	0.246/0.217

Data are presented as correlation/P value. *, P<0.05 was considered statistically significant. MC, main curve (Cobb angle); TK, thoracic kyphosis; ODI, Oswestry disability index; SRS-22, Scoliosis Research Society-22.

the anatomical marks of the thoracic segment are difficult to identify, and the accuracy is also further compromised due to severe vertebral rotation. The greatest advantage of reconstructing the model from 3D CT is its high accuracy. The greatest real reduction of spinal anatomy can be achieved through high-resolution CT and software reconstruction. However, the radiation volume of the CT imaging is too large. Further, CT imaging is conducted in the decubitus position, which places the spine under gravity and should be noted. Additionally, for some patients with scoliosis, the curvature improvement may not be obvious or may even disappear in the decubitus position. In such cases, the reconstructed model cannot fully reflect the pathological spinal structure. Glaser *et al.* (28) compared the two-plane X-ray registration technology with the CT reconstruction technology for a 3D model and concluded that the accuracy of the 3D CT reconstruction model was much higher than that of the two-plane X-ray registration, making it the only choice for the 3D analysis of the spine at this stage. In this study, the reconstruction of a 3D model of scoliosis enabled the analysis of the same vertebral body and plane on the pre-operative and post-operative 3D models, ensuring the consistency and accuracy of the pre-operative and post-operative spinal canal morphology.

For patients with PAIS associated with intraspinal abnormalities, the monitoring of abnormal changes in the spinal canal after orthopedic surgery is essential for surgical safety, but there is currently no effective method for measuring the changes in the 3D length of the spinal cord during orthopedic surgery. Only a few studies have measured changes in the spinal canal length in patients with scoliosis before and after surgery using X-ray or CT images, and the obtained results differed significantly due to factors such as the technical means or sample differences (24-26). Bridwell *et al.* (24) measured the change in the length of the spinal canal post-operatively in scoliosis patients through X-ray and found that the post-operative extension of the central spinal canal was 8.4 mm (3.7–12.7 mm). Yahara *et al.* (25) reported an extension of 10.1 mm (3.6% of the length between T2 and L2, from 2.3 to 28.8 mm) in the central spinal canal between T2 and L2 following scoliosis surgery using 3D CT images. Based on our review of the literature, we know that the results of animal experiments (the maximum tensile length and proportion that the spinal cord can withstand) do not apply to humans due to species differences. Additionally, in the previous study (29), due to different measurement methods, the results in the current study were larger than those reported in the literature.

The changes in the full length of the spinal canal (C1–L2) in this study differed significantly from those reported in the literature and were shorter than those reported in other reports. In the AIS group, the total length of the spinal canal increased by 5.6 mm (4.3–7.1 mm) after surgery, with an improvement rate of 1.3% (0.9–1.5%). While in the PAIS group, the total length of the spinal canal increased by 5.5 mm (4.4–6.7 mm) after surgery, and the improvement rate was 1.3% (0.8–1.5%). Conversely, the mean extension reported by Bridwell *et al.* (24) was 8.4 mm, and the length measured by Yahara *et al.* (25) between T2–L2 was 10.1 mm (2.3 to 28.8 mm, equivalent to 3.6% of the length of the T2–L2 spinal canal). The difference in the measurement results was large. One of the main reasons for this was the difference in the measurement methods. The measurement method reported in the literature was performed using two X-ray and CT images. When measuring the length of the spinal canal by X-ray, it is difficult to identify the mark, which leads to measurement deviations; additionally, pre-surgery and post-surgery X-rays can lead to calibration errors due to position and proportion problems, which can also lead to inaccurate measurement results. When using 3D CT image measurements, as it cannot be guaranteed that each section of the CT is parallel to the upper endplate, many of the scanning planes obliquely incise the vertebral body, and thus the desired center point of the spinal canal may not be marked, which can also lead to error. In addition, when the position and orientation of the vertebral bodies change after surgery, the CT tomograms will not be in precisely the same plane as those before surgery, which leads to the spinal canal being measured under different marks before and after surgery and also decreases the accuracy of the measurements.

In this study, we performed accurate and complete 3D CT modeling of the whole spine before and after surgery in patients with AIS and PAIS associated with syringomyelia. After the accurate and complete reconstruction, we performed accurate 3D cutting and marked the spinal canal from the inner wall of the spinal canal, and finally established a complete spinal canal model. The lengths of the cervical spinal canal, thoracic, and lumbar spinal canal, and the total spinal canal length in the two groups were measured, respectively. The results of the study showed that there were significant differences in the pre-operative and post-operative thoracolumbar spinal canal lengths between the two groups, but no statistically significant differences were found in the changes and improvement rates of the spinal canal lengths. Moreover, the changes in the thoracolumbar length and the changes in the spinal canal length were significantly positively correlated with the improvement rate of the MC but were not significantly correlated with the improvement rate of TK, the improvement of the SRS-22 score, and the improvement of the ODI. From a 3D biomechanics perspective, this revealed that one-stage posterior orthopedic surgery was similar in AIS and PAIS in terms of the change in the spinal canal length, and thus it is completely feasible to apply the treatment principle of AIS to patients with PAIS. This study further confirmed the safety and effectiveness of one-stage posterior correction surgery for patients with PAIS from the perspective of 3D biomechanics.

Limitations of this study

This study had some limitations. As an MRI examination of all patients with PAIS was a requirement of this study, there may have been a selection bias in the results of this study. In addition, in this study, only the length of the central spinal canal was measured, and the concave side and convex side were not separated for measurement. Finally, the spinal cords of the patients with scoliosis tended to be biased to one side in the apical region, which might have caused certain biases in the study results.

Conclusions

The changes in the MC, TK, MB, SVA, ODI, and SRS-22 score, the cervical and thoracolumbar spinal canal length, and the whole spinal canal length before and after surgery were similar in the patients with AIS and PAIS associated with syringomyelia who underwent one-stage posterior correction surgery. The changes in the thoracolumbar spinal canal length and the whole spinal canal length were significantly positively correlated with the improvement rate of the MC but were not significantly correlated with the improvement rate of the TK, SRS-22 score, and ODI. This study indicated the safety and efficacy of one-stage posterior correction surgery for patients with PAIS in terms of both the main radiologic parameters, clinical function scores, and 3D biomechanics.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Ethics Board of Beijing Chao-Yang Hospital (No. 2019-02-

1821), and the requirement of informed consent for this retrospective analysis was waived.

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