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# Comparison and Evaluation of the Accuracy for Thoracic and Lumbar Pedicle Screw Fixation in Early-Onset Congenital Scoliosis Children

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**Background: Compared to adult scoliosis, correcting scoliosis in children often presents greater challenges. This is attributed to two key factors. Firstly, it involves accounting for the growth potential of children. Secondly, the thinner pedicles in children can complicate screw insertion, particularly when dealing with existing deformities. The utilization of intraoperative navigation technology offers a modest improvement in the precision of screw placement but does come with the drawback of increased radiation exposure. The aim of this study is to investigate and assess the accuracy of manually inserting pedicle screws in the thoracic and lumbar spine to rectify deformities in children with early-onset congenital scoliosis.**

**Methods: In this retrospective study, 26 hospitalized patients diagnosed with early-onset congenital scoliosis between December 2014 and December 2019 were selected. The cohort comprised 16 boys and 10 girls, aged between 2 and 10 years, with an average age of 4.68 ± 2.42 years. Pedicle screw fixation was applied in the segment spanning from T1 to L5. Pedicle screws were inserted manually, guided by the positioning of the C-arm and anatomical markers. The assessment of pedicle screw placement was based on the distance of penetration into the medial, lateral, or anterior bone cortex of the vertebral body, including the pedicle, categorized into three grades: Grade 1 (placement <2 mm), Grade 2 (placement between 2–4 mm), and Grade 3 (placement >4 mm). Grade 1 indicates accurate pedicle screw placement, while Grades 2 and 3 signify abnormal pedicle screw placement. Complications related to pedicle screw insertion were also recorded, both during and after the surgical procedure.**

**Results: A total of 173 pedicle screws were inserted in this study, with an average of 6.65 screws per patient. Accurate screw placement was achieved in 143 cases (82.7%), while 30 pedicle screws were found to be abnormal. Among the abnormal screws, 24 were categorized as Grade 2 (13.9%), and 6 as Grade 3 (3.5%). Grade 2 abnormalities were distributed across 20 thoracic vertebrae and 4 lumbar vertebrae, while Grade 3 abnormalities affected 5 thoracic vertebrae and 1 lumbar vertebra. When comparing the lumbar and thoracic vertebral regions, a significant difference in the rate of abnormal screw placement was observed ($\chi^2 = 5.801, p < 0.05$). The rate of abnormal screw placement was higher in the thoracic vertebral region with abnormal vertebral bodies than in the lumbar vertebral regions. Furthermore, a statistically significant difference in the rate of abnormal screw placement was found between the concave and convex sides ($\chi^2 = 23.047$, $p < 0.05$). The concave side of the abnormal vertebral body had a higher rate of abnormal screw placement (55.6%, 15/27) compared to the convex side (20.1%, 7/34), and this difference was statistically significant ($p < 0.05$). Throughout the intraoperative and postoperative follow-up period, spanning from 12 to 56 months, only one patient experienced issues with wound healing, and no complications related to pedicle screw placement occurred, such as hemopneumothorax, pedicle fracture, nerve root injury, aortic injury, screw loosening, pullout or breakage, or spinal cord injury.**

**Conclusions: In children under 10 years of age with early-onset congenital scoliosis, the freehand placement of thoracic and lumbar pedicle screws demonstrates a high level of accuracy. Moreover, complications associated with pedicle screw insertion are infrequent following surgery. It is advisable to exercise caution when placing pedicle screws in thoracic vertebral bodies and morphologically abnormal vertebral bodies, with particular attention to the concave side when screw placement is required in these regions.**

**Keywords:** thoracic and lumbar vertebra; early-onset congenital scoliosis; pedicle screw; accuracy

## Introduction

Congenital scoliosis arises from the asymmetric growth of the spine due to abnormal vertebral development during the fourth to sixth weeks of gestation. This condition can be attributed to vertebral segmental disorders, formation disorders, or a combination of both [1]. The severity of the associated spinal deformity varies depending on the type and location of the affected vertebral bodies [2]. Early-onset scoliosis (EOS) refers to spinal deformities occurring before the age of 10 and is categorized into five types based on their etiology: idiopathic, congenital, thoracogenic, neuromuscular, and syndromic [3,4]. Early-onset congenital scoliosis specifically pertains to congenital scoliosis in individuals under the age of 10. Due to the presence of congenital vertebral deformities and ongoing asymmetric spinal growth, it can lead to severe consequences, including cardiopulmonary injury and paraplegia [5]. In such cases, non-surgical treatments often yield limited therapeutic effects. Cast or brace treatment can serve as an option [6] for clinicians but typically only delays the age at which surgical intervention becomes necessary.

Treatment approaches have evolved from the original *in situ* fusion to early deformity correction. Pedicle screw fixation plays a crucial role in providing stability to the anterior, central, and posterior columns of the spine, forming the foundation for correcting three-dimensional spinal deformities. Achieving deformity correction and implementing osteotomy procedures require robust internal fixation, with pedicle screw placement being a particularly challenging task due to the essential requirement for accuracy [7]. Studies have indicated that inaccuracies in screw placement can result in pedicle screw loosening [8]. Accuracy is not solely limited to the final fixation but also extends to the initial screw placement. Research has shown [9] that altering the orientation to achieve an optimal fixation position can compromise biomechanical integrity, leading to a loss of fixation strength of approximately 28%.

In children, the spine is in a continuous growth stage, exhibiting distinct anatomical, physiological, and biomechanical characteristics [10]. Notably, the corresponding vertebral pedicles are relatively smaller in comparison to those of adults. In cases of vertebral deformities, the spatial sequence of the vertebral bodies becomes disordered, and anatomical landmarks are often blurred or even absent. These factors significantly augment the complexity of screw placement. Aberrant screw placement can not only result in a loss of fixation strength but also give rise to complications such as spinal cord injury, peripheral organ injury, or pedicle fractures [11,12]. While intraoperative navigation technology is increasingly prevalent, its success largely hinges on the operator's extensive clinical experience [13]. Furthermore, the high associated economic costs [14] can limit its widespread adoption to a certain extent. As a result, free-hand screw placement proves to be more versatile and holds greater practical significance, making it a suitable option for a broader range of settings. The combination of the young age and incomplete skeletal development in patients with early-onset congenital scoliosis, along with vertebral deformities, presents greater challenges in pedicle screw implantation compared to the adult population. The aim of this study is to assess the accuracy of thoracolumbar pedicle screw placement in children with early-onset congenital scoliosis through Computerized Tomography (CT) analysis, aiming to offer valuable clinical insights into free-hand pedicle screw placement.

## Material and Methods

### *General Information*

In this study, a total of 26 patients were enrolled, comprising 16 boys and 10 girls, aged between 2 and 10 years, with an average age of ($4.68 \pm 2.42$) years. The preoperative Cobb Angle ranged from 16.3 to 57.6 degrees, with an average of ($32.74 \pm 8.62$) degrees. Following the surgical intervention, the postoperative Cobb Angle ranged from 1.2 to 21.2 degrees, with an average of ($7.15 \pm 5.09$) degrees.

### *Inclusion and Exclusion Criteria*

The inclusion criteria for this study encompassed the following: (1) Age of 10 years or younger; (2) Diagnosis of congenital scoliosis affecting the thoracic and/or lumbar spine; (3) Completion of preoperative and postoperative CT examinations utilizing AQUILON PRIME TSX-302A (Toshiba, Minato-ku, Tokyo, Japan) for all patients. The exclusion criteria for this study comprised the following: (1) Previous history of spinal surgery; (2) Performance of anterior spinal surgery; (3) Diagnosis of idiopathic scoliosis, neuromuscular scoliosis, or syndromic scoliosis.

### *Procedure of Surgery*

#### Preoperative Evaluation

To establish the fusion range, the preoperative anteroposterior and lateral views of the entire spine, as well as spinal CT scans, were employed. The transverse diameter of the pedicle was assessed by measuring the inner diameter of the pedicle isthmus on the image section that displayed the widest slice of the pedicle, aligned parallel to the pedicle's longitudinal axis. A straight line was then drawn from the midpoint of this transverse diameter to the anterior edge of the vertebral body, bisecting the pedicle in the process. This line served as the reference for selecting the length of the pedicle screw. The dimensions of the pedicle screws used (Fule, Posterior Spinal system, Beijing China) were determined based on the preoperative CT evaluation results. The screw length varied from 25 to 45 cm, and the diameter ranged from 3.5 mm to 5.5 mm.

Pedicle Screw Placement

Subperiosteal dissection was carried out to expose various anatomical structures, including the spinous process, lamina, facet joint, and transverse process, using a posterior median spinal approach. For the thoracic spine, the entry point was determined at the intersection of a vertical line drawn through the midpoint of the facet joint and a horizontal line placed at the upper third of the transverse process. In the case of the lumbar spine, the entry point was selected at the intersection of a vertical line aligned with the lateral facet joint border and a horizontal line through the midpoint of the transverse process. At the chosen entry point, the cortical bone was removed using a rongeur to expose the cancellous bone. Following positioning with a 1.5 mm Kirschner wire, C-arm fluoroscopy was utilized to confirm the entry point, with a 1.5 cm marker needle used for marking. After verifying the direction of needle insertion through C-arm fluoroscopy, a rigid probe was employed to establish the screw path along the cancellous bone within the pedicle. Subsequently, a soft probe was used to recheck the entry point and the passage through the pedicle. The pedicle screw was then placed manually. The satisfactory placement of the screw was confirmed through X-ray fluoroscopy. In the case of patients with bone bridge and costal deformities, the deformity's location was determined prior to pedicle screw placement. Subsequent to determining the deformity, resection of the bone bridge and costal correction were performed. Throughout the procedure, somatosensory evoked potential (SEP) and motor evoked potential (MEP) monitoring were maintained. For patients with hemivertebra deformities, complete resection of the hemivertebra was performed after the placement of pedicle screws.

Postoperative Management

Following surgery, the children were required to wear a brace for a period of 3 months. They underwent regular follow-up appointments every 3–6 months, during which full-length anteroposterior and lateral X-rays of the spine were taken to assess the extent of scoliosis. In the event that scoliosis was found to have worsened post-surgery, with an increase of more than 10 degrees every 6 months, reoperation was deemed necessary.

### *Indicators of Evaluation*

Measurements were conducted twice on thin-section CT scans by the same orthopedic surgeon using ImageJ (Version 1.53t, National Institute of Health, Bethesda, MD, USA) software, and the results were averaged. The measurement index focused on the distance from the point where the pedicle screw penetrated the vertebral body (encompassing the pedicle) to the inner wall, outer wall, or anterior edge of the vertebral body (Fig. 1). This measurement was categorized into three grades: Grade 1 (<2 mm), Grade 2 (2–4 mm), and Grade 3 (>4 mm) [15] (Fig. 1). Grade 1 screw placement was considered accurate, while any placement falling outside of this classification was deemed abnormal.

Concurrently, any complications related to pedicle screw placement, whether observed intraoperatively or postoperatively, were meticulously recorded. The analysis of the abnormal screw placement rate took into account factors such as the location of the screws (thoracic or lumbar segment), convex or concave side, and the normal or abnormal morphology of the vertebrae. Abnormal vertebral morphology included congenital anomalies like butterfly vertebrae, block vertebrae, and bone bridge junctions, while normal vertebral bodies exhibited no such irregularities. The safety evaluation encompassed the identification of adverse outcomes resulting from pedicle screw placement during or after surgery. These outcomes included hemopneumothorax, pedicle fracture, nerve root injury, aortic injury, screw loosening, extraction, breakage, and spinal cord injury [16].

### *Statistical Analysis*

The data analysis was conducted using SPSS 25.0 software (IBM SPSS Statistics, Chicago, IL, USA). Measurement data that followed a normal distribution were expressed as mean $\pm$ SD (standard deviation), while count data were presented as cases and percentages. Group comparisons were performed using the $\chi^2$ test. Statistical significance was defined as $p < 0.05$.

## Results

This study included a total of 26 patients who were hospitalized between December 2014 and December 2019, with a minimum follow-up duration of 1 year. In total, 173 pedicle screws were inserted, averaging 6.65 screws per patient (ranging from 4 to 11). Among these, 143 screws (82.7%) were accurately placed, while 30 screws were considered abnormal, comprising 24 in Grade 2 (13.9%) and 6 in Grade 3 (3.5%). Specifically, 25 abnormal screws were placed in the thoracic spine (14.5%), and 5 in the lumbar spine (2.9%) (Table 1). The difference in abnormal screw placement rates between the two spinal regions was statistically significant ($\chi^2$ = 5.801, $p < 0.05$, Table 1).

Of the abnormal screw placements, 8 occurred in normal vertebral bodies, accounting for 4.6% of the total number of vertebral bodies and 71.4% of normal vertebral bodies. In contrast, 22 abnormal screws were identified in abnormal vertebral bodies, making up 12.7% of the total vertebral bodies and 36.7% of abnormal vertebral bodies. The difference in abnormal screw placement rates between these two categories was statistically significant ($\chi^2$ = 23.047, $p < 0.05$, Table 2.

Furthermore, there was a statistically significant difference in the abnormal screw placement rate between abnormal vertebral bodies in the thoracic and lumbar spine regions ($\chi^2$ = 4.448, $p < 0.05$), with the thoracic spine

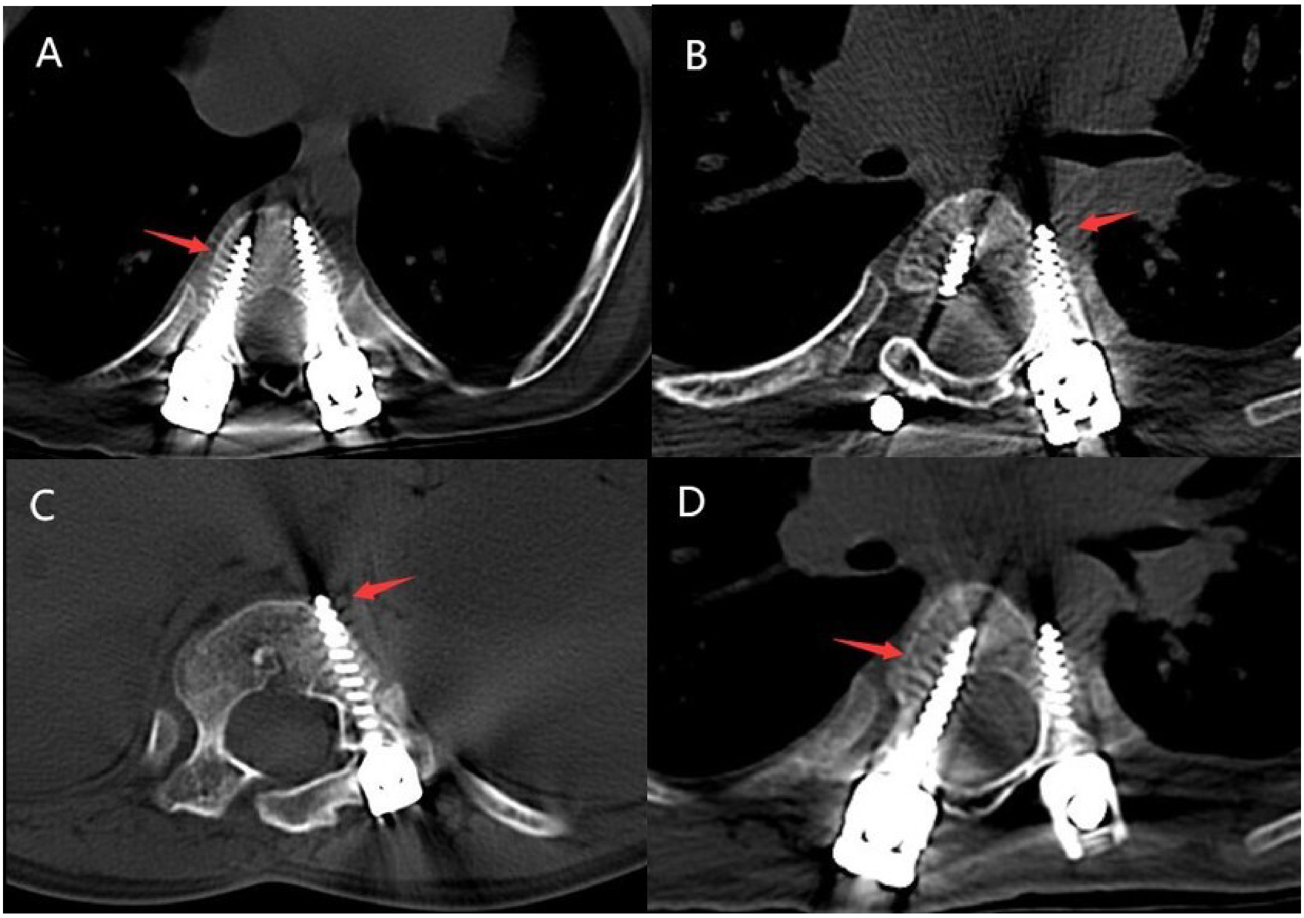


**Fig. 1. Evaluation of the accuracy of pedicle screw placement using Computerized Tomography (CT) scans is illustrated here.** (A,B) In Grade 1, the pedicle screw breaks through the vertebral cortex <2 mm. (C) In Grade 2, the pedicle screw breaks through the vertebral cortex 2 to 4 mm. (D) In Grade 3, the pedicle screw breaks through the vertebral cortex >4 mm. The arrows indicate the corresponding grades.

exhibiting a higher rate (Table 3). Out of the 79 screws placed on the concave side, 17 were abnormally positioned (9.8%). On the convex side, where 81 screws were placed, 13 were abnormally positioned (7.5%). The difference in abnormal screw placement rates between the two sides was not statistically significant ($\chi^2 = 1.771, p > 0.05$, Table 4). However, a statistically significant difference was observed in the abnormal screw placement rate between the concave and convex sides ($\chi^2 = 7.980$, $p < 0.05$), with the concave side displaying a higher abnormal placement rate (55.6%, 15/27) compared to the convex side (20.1%, 7/34, Table 5). Fortunately, no complications related to pedicle screw placement occurred during or after the operation. Lower limb movement remained unaltered, and no neurological or other complications associated with pedicle screw placement were reported during the operation and follow-up. Only one patient experienced poor wound healing, which resolved successfully following wound cleaning and dressing changes. To provide a visual illustration of our operation, refer to Fig. 2.

## Discussion

With the continuous advancement of spinal surgery technology, the utilization of pedicle screws in the treatment of spinal deformities has become increasingly refined and prevalent. This is particularly evident in the treatment of scoliosis in children, where the application is on the rise, and the age at which it is employed continues to decrease, allowing for more effective treatment interventions. This particular study [17] suggested that thoracic and/or lumbar pedicle screw fixation is a safe and effective approach for addressing a variety of spinal conditions in children under the age of 10. Moreover, research has demonstrated that when vertebral deformities are present, the likelihood of suboptimal screw placement is higher during free-hand screw insertion compared to cases involving normal vertebral bodies [18]. Our findings align with the same conclusion: the accuracy of screw placement was 104 out of 112 for normal vertebral bodies and 39 out of 61 for abnormal vertebral bodies. Additionally, our study revealed that the concave side of vertebral bodies with abnormal morphology

Table 1. **Comparison of screw placement accuracy between thoracic vertebra and lumbar vertebra.**

| Group | n | Accurate placement | Abnormal placement |
|---|---|---|---|
| Thoracic vertebra | 111 (64.2%) | 86 (49.7%) | 25 (14.5%) |
| Lumbar vertebra | 62 (35.8%) | 57 (32.9%) | 5 (2.9%) |

Note: $\chi^2 = 5.801, p < 0.05$.

**Table 2. Comparison of screw placement accuracy between normal and abnormal morphology vertebra.**

| Group | n | Accurate placement | Abnormal placement |
|---|---|---|---|
| Normal vertebra | 112 (64.7%) | 104 (60.1%) | 8 (4.6%) |
| Abnormal morphology vertebra | 61 (35.5%) | 39 (22.5%) | 22 (12.7%) |

Note: $\chi^2 = 23.047, p < 0.05$.

was more susceptible to misinsertion. Previous studies have indicated that the extent of pedicle deformity is notably pronounced on the concave side of idiopathic scoliosis [19]. In other words, the pedicle on the concave side tends to be less developed and smaller compared to the convex side [20].

Based on this reasoning, one might expect that the rate of abnormal screw placement would be higher on the concave side compared to the convex side, regardless of the vertebral body's normalcy. However, our study did not find a statistically significant difference. Upon analysis, the possible reasons for this observation are as follows:

(1) The focus of our study is congenital scoliosis, which may have distinct characteristics compared to adolescent idiopathic scoliosis.

(2) The patients with congenital scoliosis in our study were younger, and the degree of scoliosis may not have significantly impacted the vertebral bodies at this stage of development.

(3) The deformity in congenital scoliosis is typically confined to the vertebral body with congenital malformation, and the hypoplasia of vertebral pedicles is generally limited to the concave side of the vertebral body with abnormal morphology. This limited involvement could explain the lack of a statistically significant difference in screw placement accuracy between the concave and convex sides in our study.

It's worth noting that previous research has revealed that the epidural space between the spinal cord and the vertebral body is typically less than 1mm on the concave side of scoliosis, while it ranges from 3 to 5 mm on the convex side [21]. Simultaneously, the likelihood of abnormal screw placement on the concave side of the abnormal vertebral body is relatively high, leaving limited room for error. Therefore, it is imperative to adhere to the principle of "better outside than inside" when inserting screws on the concave side of the abnormal vertebral body to minimize the risk of screw penetration into the spinal canal and the potential for occult spinal cord injury.

The occurrence of abnormal screw placement depends on the severity of the deformity and the surgical technique employed by the surgeon. However, it's worth noting that the actual incidence of abnormal screw placement may be higher, as many patients with such placements often remain asymptomatic and are challenging to identify [22]. In adults, pedicle screws generally have a relatively large tolerance, and complications are infrequent. Nevertheless, when complications do arise in both adults and children, the consequences can be quite severe [23]. Additionally, due to the significant growth potential in children, even though numerous studies [24,25] have indicated that pedicle screw fixation in children rarely leads to related complications or clinical symptoms, it remains crucial to strive for the utmost accuracy in screw placement. Asymptomatic screws can be likened to a "ticking time bomb" for children, potentially posing a threat down the line. Over time, as the spine grows and the deformity progresses, there's a risk of implant "displacement". The growth of the spine relative to the implant may result in the implant protruding into the spinal canal or causing damage to peripheral nerves. Instances have been documented in the literature where patients developed clinical symptoms, and pedicle screws were observed to be displaced and repositioned during subsequent operations, occurring 2 to 6 years after the initial surgery [26]. In another study by Canavese *et al.* [27], a patient experienced neurological symptoms due to the displacement of the fixation rod into the spinal canal, which occurred 5 years after the surgery. Given the substantial growth potential of children, it is highly beneficial to assess the accuracy of pedicle screw placement in pediatric spinal patients for safety reasons. This research aims to offer valuable insights for clinical practice by investigating the precision of pedicle screw placement in the thoracic and lumbar spine of children with early-onset (<10 years old) congenital scoliosis, particularly when placed by hand.

A retrospective analysis of adult patients with scoliosis indicated that the accuracy rate of screw placement was 93.8% when assessed using CT evaluation [28]. In contrast, a case study involving pediatric scoliosis patients revealed that the accuracy rate of pedicle screw placement was 89.5% [29]. Research has also shown that [30] the accuracy of free-hand screw placement is positively correlated with the diameter of the pedicle screw. It is reasonable to anticipate that pedicle screw insertion becomes progressively less challenging with increasing age. Age indeed

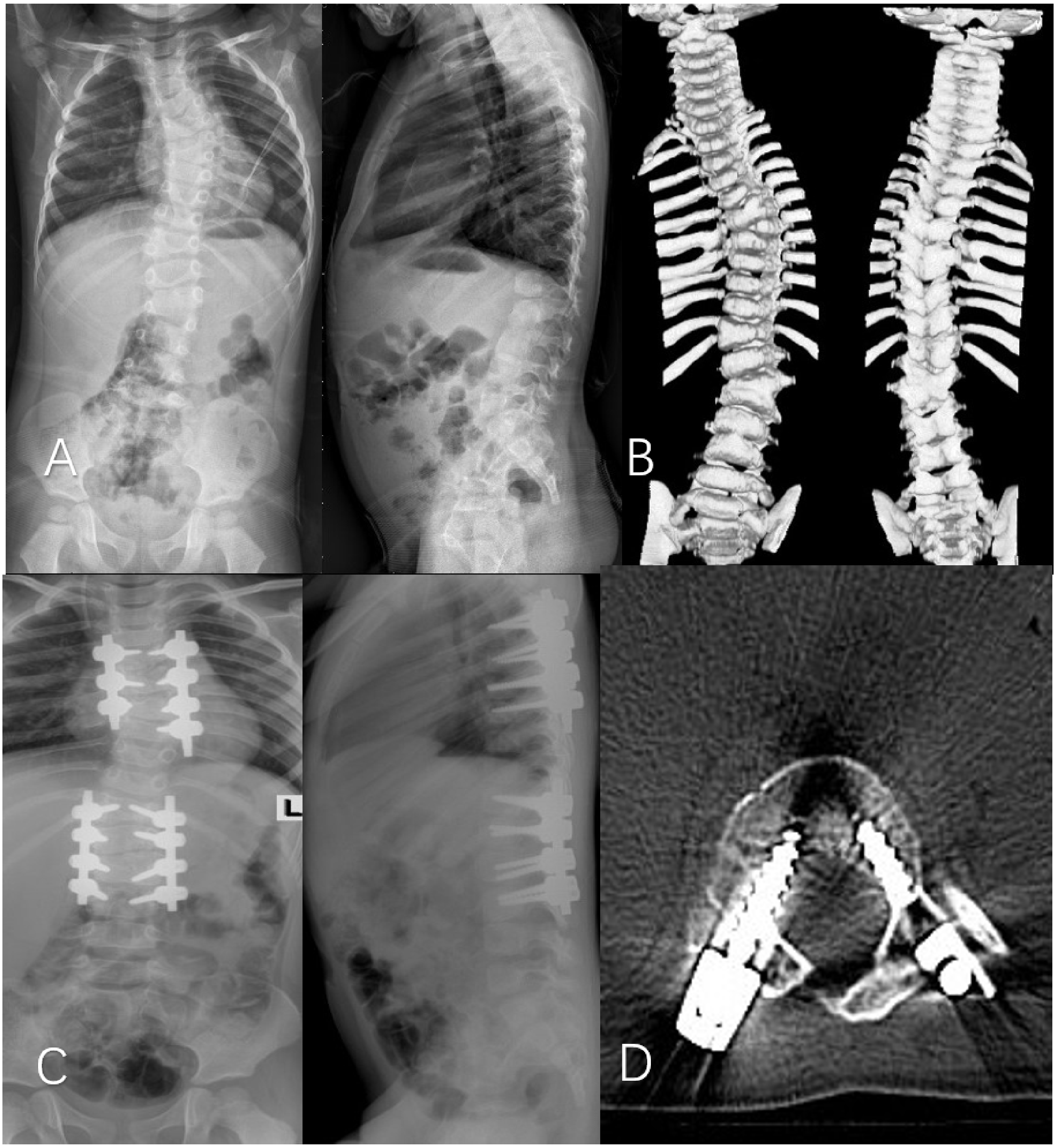


**Fig. 2. The above picture shows a 2-year-old boy with hemivertebra deformity at left T5, T7, right T12 and left L2, who underwent hemivertebra resection and pedicle screw fixation for scoliosis correction.** (A) The preoperative anteroposterior and lateral X-rays of the whole spine; the preoperative thoracic curve was 26.1 degrees and the lumbar curve was 25.6 degrees. (B) The 3D image of the spine CT. (C) The postoperative anteroposterior and lateral X-ray of the whole spine. The postoperative thoracic curve was 4.2 degrees and the lumbar curve was 3.3 degrees. (D) The right thoracic 4 pedicle screw, which broke through the medial wall of the pedicle by 4 mm and was a Grade 2 screw placement.

plays a pivotal role in pedicle screw placement. Younger patients tend to have less developed vertebral bodies and smaller pedicles, which heightens the complexity of screw placement and the risk of wall penetration. Additionally, within the same individual, the lumbar pedicle is generally wider than the thoracic pedicle, further reducing the difficulty of screw placement. Studies examining electrical stimulation signals [31] have found that the thoracic pedi-

**Table 3. Comparison of screw placement accuracy between the normal vertebra and abnormal morphology vertebra with thoracic/lumbar vertebra.**

| Group | Normal vertebra | | | Abnormal morphology vertebra | | |
|---|---|---|---|---|---|---|
| | n | Accurate placement | Abnormal placement | n | Accurate placement | Abnormal placement |
| Thoracic vertebra | 70 (40.5%) | 64 (37.0%) | 6 (3.5%) | 41 (23.7%) | 22 (12.7%) | 19 (11.0%) |
| Lumbar vertebra | 42 (24.3%) | 40 (23.1%) | 2 (1.2%) | 20 (11.6%) | 17 (9.8%) | 3 (1.7%) |

Note: normal vertebra, $\chi^2 = 0.144$, $p > 0.05$; abnormal vertebra, $\chi^2 = 4.448$, $p < 0.05$.

**Table 4. Comparison of screw placement accuracy between concave and convex.**

| Group | n | Accurate placement | Abnormal placement |
|---|---|---|---|
| Concave | 79 (45.7%) | 62 (35.8%) | 17 (9.8%) |
| Convex | 94 (54.3%) | 81 (46.8%) | 13 (7.5%) |

Note: $\chi^2 = 1.771$, $p > 0.05$.

cle is more susceptible to abnormal screw placement compared to the lumbar spine. Similarly, in a study involving patients undergoing pedicle screw fixation for adult spinal disorders, it was observed [32] that the thoracic spine was more prone to misplacement than the lumbar spine. Furthermore, Sarwahi *et al.* [22] analyzed the pedicle morphology in scoliosis and identified that most of the abnormal pedicles were situated in the thoracic spine, predominantly in the upper thoracic spine. They proposed that the smaller size of the upper thoracic vertebral body might contribute to this anomaly. The reduced size of the vertebral body itself and the presence of deformities can collectively increase the difficulty of pedicle screw placement, creating a situation where "1+1 > 2". This same principle applies to the thoracolumbar spine in our study. Given the smaller vertebral morphology in the thoracic spine and the higher prevalence of abnormal vertebral bodies in this region compared to the lumbar spine, the likelihood of abnormal screw placement in the thoracic spine is greater. Consequently, it is imperative to heighten safety awareness during thoracic pedicle screw fixation.

Precise pedicle screw placement is essential, as it not only guarantees safety but also maintains crucial biomechanical characteristics [33]. However, the precise definition of precision may vary, typically concerning whether it allows for placement within 2 mm or 4 mm. For instance, in a study that investigated severe idiopathic scoliosis in both adults and adolescents, it was observed that the rate of screw misplacement, exceeding 2 mm beyond the cortical bone, was 3.7% [34]. Moreover, previous studies have indicated [9,19] that in children, screws placed manually, approximately 9% of them penetrated the cortical bone by more than 4 mm. These findings underscored that the conclusions drawn can be influenced by the varying ranges of accuracy definitions. However, the primary concern is how to better constrain this range, particularly in the case of children. An extensive literature review [23] suggested that a deviation of up to 2 mm is generally considered acceptable for cortical bone penetration. Nevertheless, some scholars [35,36] have proposed defining a safe zone within 4 mm of the intraspinal penetration. This highlighted the ongoing debate regarding the optimal range for pedicle screw accuracy, especially concerning pediatric patients. However, these studies do not take into consideration the different locations of the broken wall. Several case studies [26,27,37–39] have reported that patients with poor screw placement that breaks through the medial or lateral wall develop corresponding neurological complications as the lateral curve progresses during growth and development. With the growth of the vertebral body, the protrusion degree of the screws breaking through the anterior wall of the vertebral body will decrease, so the adverse effects of the protruding screws on the human body will subsequently decrease [40]. The proposed ranges are contingent on the location of the screw, where deviations within 4 mm may involve breaking through the lateral wall of the pedicle or the anterior wall of the vertebral body. However, for children with scoliosis and vertebral deformities, it's imperative to consider the risk of screws penetrating the inner wall of the pedicle, as such penetrations could lead to migration into the spinal canal as the deformity progresses with growth and development.

Studies [41] have demonstrated that children with severe spinal deformities or congenital spinal deformities may exhibit anatomical variations in spinal cord blood vessels or congenital spinal cord development abnormalities. These factors reduce their tolerance for medial pedicle protrusion. For the safety of children, a more stringent "safe zone" with a range of less than 2 mm may be considered to enhance accuracy and safety. In cases where children exhibit medial wall breakthroughs, we recommend follow-up appointments every 6 to 12 months. This approach ensures that any corresponding neurological symptoms are promptly addressed. It is also worth noting that in addition to pedicle and vertebral body size, the thickness and length of the screw should be taken into consideration. Using relatively shorter and thinner pedicle screws may help reduce the incidence of abnormal screw placement. Nonetheless, it's important to acknowledge that the use of relatively shorter and thinner pedicle screws can significantly compromise biomechanical efficiency. The screws we opted for were intentionally longer for several reasons. First, this choice was made to prioritize the stability of fixation. Second, it's essential to remember that children, especially those with

**Table 5. Comparison of screw placement accuracy between normal vertebra and abnormal morphology vertebra with concave/convex side.**

| Group | Normal vertebra | | | Abnormal morphology vertebra | | |
|---|---|---|---|---|---|---|
| | n | Accurate placement | Abnormal placement | n | Accurate placement | Abnormal placement |
| Concave | 52 (30.1%) | 50 (28.9%) | 2 (1.2%) | 27 (15.6%) | 12 (6.9%) | 15 (8.7%) |
| Convex | 60 (34.7%) | 54 (31.2%) | 6 (3.5%) | 34 (19.7%) | 27 (15.6%) | 7 (4.0%) |

Note: normal vertebra, $\chi^2 = 0.798$, $p > 0.05$; abnormal vertebra, $\chi^2 = 7.980$, $p < 0.05$.

spinal deformities, are distinct from adults. Spinal deformities in children may exacerbate as their spines continue to grow. Consequently, selecting relatively longer pedicle screws can offer enhanced holding force and fixation, thereby addressing the evolving nature of the deformity.

The accuracy of pedicle screw placement is influenced by numerous factors, and the choice of evaluation methods can also introduce subjectivity that affects the assessment of screw placement accuracy. One study [42] found that when X-rays were employed for assessment, the risk of poor screw placement in children was less than 4%. However, when CT was used as the evaluation method, the incidence of abnormal screw placement rose to 6.8% [43]. Furthermore, another study reported that the rate of abnormal pedicle screw placement, as determined by postoperative CT evaluation, was as high as 15.7% [23] in patients undergoing free-hand screw placement. CT offers a more precise evaluation of the position and extent of screw protrusion compared to X-rays. Additionally, the use of titanium alloy pedicle screws in CT produces very few artifacts, making it the preferred imaging method for assessing screw positions after surgery [44]. Nevertheless, it's crucial to consider the potential effects of radiation exposure. Additionally, it is worth noting that we did not routinely perform postoperative CT scans but rather required abdominal or chest CT scans for other medical reasons. This approach was adopted because studies have indicated [45] that children and adolescents face a higher risk of cancer associated with the same radiation exposure compared to adults. Even with the advent of the latest low-dose CT technology, the incidence of cancer remains unaffected. While technological advancements bring progress, it's crucial to recognize that there are "side effects" that cannot be overlooked. In recent years, there has been a growing trend in the application of intraoperative navigation technology. However, it also comes with potential risks stemming from CT radiation. Studies have revealed that the radiation dose associated with CT navigation in spinal surgery is 2.7 times higher than that of intraoperative X-ray fluoroscopy [46]. Hence, it is imperative to weigh the pros and cons of new technologies before implementing them. Furthermore, not all pediatric spine patients or vertebral segments require navigation assistance. Clinicians can benefit from strategies for screw placement based on disease type and the vertebral level with the highest risk of screw misplacement, making navigation a favorable choice [18]. For regions and hospitals lacking intraoperative navigation equipment, it is vital to understand the high-risk segments and vertebral bodies for screw placement. Reducing the density of pedicle screws and limiting their placement in high-risk areas can significantly decrease the occurrence of screw misplacement [47]. This approach effectively mitigates the risk of inaccurate screw placement.

Additionally, it is crucial to consider the findings of other studies [48], which have indicated that the use of intraoperative navigation in cases of non-severe spinal malformations can lead to increased radiation exposure without a corresponding improvement in pedicle screw placement accuracy. Another important issue that cannot be overlooked is wound healing. The subjects of our study were children with early-onset congenital scoliosis. These patients are typically under 10 years of age and may also face challenges related to eating and growth retardation due to their deformities. Consequently, there is a higher likelihood of prominent screw heads and increased skin incision tension after implant placement. Theoretically, this increases the risk of postoperative incision complications compared to adults. Although one patient in our study experienced poor wound healing, the remaining patients achieved primary wound healing. This outcome may be attributed to the relatively short segment of our surgical procedures. However, if insufficient attention is given to wound infection, there is a risk of deep infection, which could ultimately result in the failure of internal fixation, with potentially catastrophic consequences for children.

This study serves as a valuable reference for pediatric spine surgeons involved in pedicle screw placement for early-onset scoliosis patients. It underscores the importance of giving special attention to the thoracic vertebrae, especially in cases involving abnormal vertebrae and the concave side of the spine. However, it's essential to acknowledge the limitations of this study. It is retrospective in nature and based on a relatively small sample size. Future research should consider conducting prospective studies with larger sample sizes to enhance the robustness of the findings.

## Conclusions

In children under 10 years old with early-onset congenital scoliosis, the manual placement of thoracic and lumbar pedicle screws demonstrates a high level of accuracy.

Moreover, complications associated with pedicle screw insertion are infrequent after surgery. It is advisable to exercise caution in thoracic vertebral bodies and morphologically abnormal vertebral bodies when placing pedicle screws, especially to the concave side in these regions.

## Availability of Data and Materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

## Author Contributions

Conceptualization: XKZ, XZG. Data curation: XZG, JG. Formal analysis: CW, JG. Investigation: FW. Methodology: XZG, ZM, HZ. Acquisition of data: YQ, ZM, XKZ. Supervision: XZG. Validation: ZM, HZ, ZWM. Writing — original draft: XZG, JG, CW, FW, HZ, ZWM. Writing — review & editing: XZG, XKZ, ZM, YQ. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

## Ethics Approval and Consent to Participate

The experimental protocol was established, according to the ethical guidelines of the Helsinki Declaration and was approved by the Human Ethics Committee of the Children's Hospital of Hebei Province (Medical Research No. 157). Written informed consent was obtained from individuals or guardian participants.

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## Conflict of Interest

The authors declare no conflict of interest.

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