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ORIGINAL ARTICLE

Zonal differences in risk and pattern of pedicle screw perforations in adolescent idiopathic scoliosis (AIS): a computerized tomography (CT) review of 1986 screws

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Abstract
Purpose To evaluate the zonal differences in risk and pattern of pedicle screw perforations in adolescent idiopathic scoliosis (AIS) patients.
Methods The scoliosis curves were divided into eight zones. CT scans were used to assess perforations: Grade 0, Grade 1(< 2 mm), Grade 2(2–4 mm) and Grade 3(> 4 mm). Anterior perforations were classified into Grade 0, Grade 1(< 4 mm), Grade 2(4–6 mm) and Grade 3(> 6 mm). Grade 2 and 3 (except lateral grade 2 and 3 perforation over thoracic vertebrae) were considered as 'critical perforations'.
Results 1986 screws in 137 patients were analyzed. The overall perforation rate was 8.4% after exclusion of the lateral perforation. The highest medial perforation rate was at the transitional proximal thoracic (PT)/main thoracic (MT) zone (6.9%), followed by concave lumbar (6.7%) and convex main thoracic (MT) zone (6.1%). The overall critical medial perforation rate was 0.9%. 33.3% occurred at convex MT and 22.2% occurred at transitional PT/MT zone. There were 39 anterior perforations (overall perforation rate of 2.0%). 43.6% occurred at transitional PT/MT zone, whereas 23.1% occurred at concave PT zone. The overall critical anterior perforation rate was 0.6%. 5/12 (41.7%) critical perforations occurred at concave PT zone, whereas four perforations occurred at the transitional PT/MT zone. There were only two symptomatic left medial grade 2 perforations (0.1%) resulting radiculopathy, occurring at the transitional main thoracic (MT)/Lumbar (L) zone.
Conclusion Overall pedicle perforation rate was 8.4%. Highest rate of critical medial perforation was at the convex MT zone and the transitional PT/MT zone, whereas highest rate of critical anterior perforation was at the concave PT zone and the transitional PT/MT zone. The rate of symptomatic perforations was 0.1%.

Keywords Pedicle screw · Perforation · Adolescent idiopathic scoliosis · Computed tomography

Introduction

Scoliosis causes changes in the pedicle morphometry, relations between the viscera and the vertebrae and the rotational alignment between vertebrae [1–4]. The incidence of abnormal pedicle in idiopathic scoliosis was as high as 31.9% [5]. There were more abnormal pedicles at the concavity and at the proximal thoracic zone [5–7]. The visceral structures which are at risk during pedicle screw insertion in a scoliosis patient also differ at each individual vertebral level. There is also higher risk of injury to the spinal cord at the proximal thoracic concave side screws at T2 and T3 levels and main thoracic concave side screws at T5–T9 levels [8]. Jiang et al. [9] also reported the highest risk of injury to the aorta occurred at T5–T11 levels on the concave main thoracic curve on the left side. In a recent study, Jiang et al. [10] noted that the left subclavian artery adopted a closer position to the vertebrae in proximal thoracic curve of Lenke 2 AIS patients. These differences alter the level of difficulty and risk during pedicle screw instrumentation. Therefore, the aim of this study was to analyze the rate and pattern of

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pedicle screw perforations at the various 'zones' in adolescent idiopathic scoliosis (AIS) (Fig. 1).

Materials and methods

Study design

This retrospective study was carried out in a single academic institution. Ethical committee approval was obtained prior to commencement of the study (NMRR-16-137-29365). We reviewed AIS cases operated using pedicle screw instrumentation between July 2009 and June 2014. Only cases with pre-operative whole spine erect anterior–posterior (AP) view and post-operative computerized tomography (CT) scans were included. 198 cases of AIS were operated within the study duration. 164 patients had CT scans performed between 3 and 6 months after surgery to assess for spinal fusion. 27 patients were excluded from the study due to poor quality CT scans and lost pre-operative radiographs. 137 cases were included in the final analysis.

Pedicle screw surgical technique

We used the funnel technique when the pedicle channel was present. The funnel was identified after removing 5–8 mm of overlying cortical bone. Subsequently, a pedicle probe was advance into the vertebral body. The track of the screw was checked with a pedicle sound to detect any pedicle perforations. An appropriate screw size and length was then inserted (4.5–5.5 mm × 25–30 mm in the upper thoracic, 5.0–6.5 mm × 30–35 mm in the lower thoracic and 5.5–6.5 mm × 35–40 mm in the lumbar zone). In this study, no Triggered Electromyography (Pedicle Screw Stimulation) was performed.

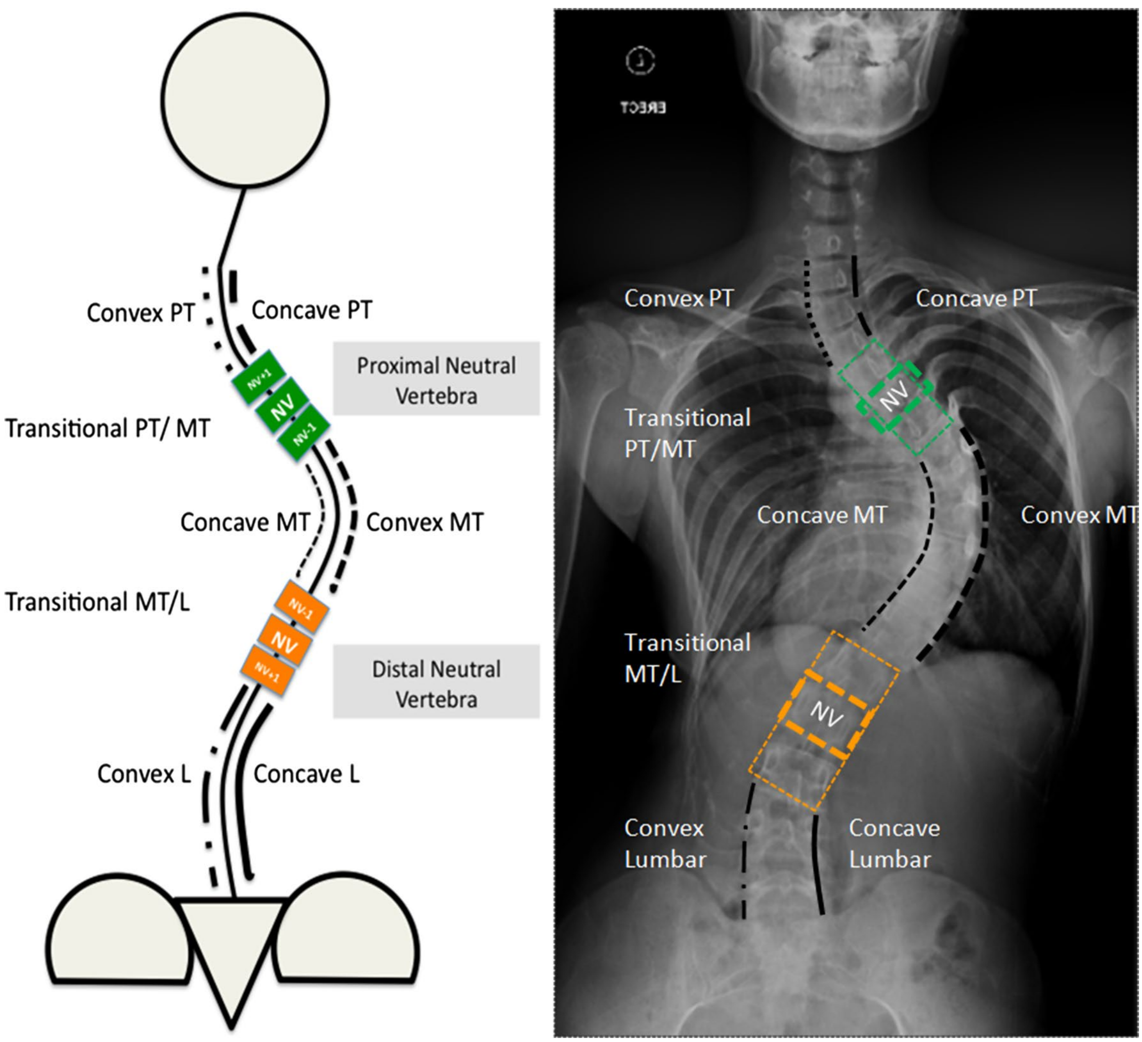

Fig. 1 The zone classification used to assess accuracy of pedicle screw placement

Extrapedicular screw insertion technique

Fluoroscopic guided technique was used for dysplastic pedicles. In this technique, the lateral pedicle wall was breached and the pedicle finder was engaged on the lateral body wall at a depth of 15–20 mm. After confirming optimal positioning of the probe, the pedicle finder was advanced into the vertebral body. A sound was used to confirm absence of perforations. A cannulated screw system was used in this technique. Screw position was then checked with image intensifier images.

Reduction technique

Following screw insertion, scoliosis reduction was performed using rod translation technique and segmental vertebral derotation.

Classification of the zones

The zones were classified based on the pre-operative radiograph. In Lenke 1,2,3,4 and 6 curves, the proximal neutral vertebra and the distal neutral vertebra of the main thoracic curve was determined. In Lenke 5 curves the proximal neutral vertebra of the Lumbar curve was determined. The 'transitional' zone included the neutral vertebra and one vertebra proximal and distal to it. Therefore, in Lenke 1,2,3,4 and 6 there would be a Transitional proximal thoracic (PT)/main thoracic (MT) zone and a transitional MT/lumbar (L) zone. In Lenke 5 curves, there would be a transitional MT/L zone only. The zonal classification is illustrated in Fig. 1. A pilot study was carried out to test the inter rater reliability of the zone classification. Two assessors selected the proximal neutral and distal neutral vertebrae in 15 AIS patients and classified 196 screws with the zone classification. The inter rater reliability was examined using Kappa statistics and the results are shown in Table 1. The inter rater reliability had a κ value of 0.964 ($p < 0.001$), 95% CI (0.937, 0.911)

Assessment of pedicle screws using computerized tomography (CT) Examination

Evaluation of screw perforation was performed on PACs system (Centricity PACs, version 5.0, GE Healthcare). This software allowed adjustment of the bone window to reduce the amount of metal artefacts. Axial cuts, sagittal and coronal reconstructed images were reviewed to detect pedicle perforations.

For medial, lateral, superior and inferior perforations, the pedicle perforations were assessed using a classification described by Gertzbein and Robbins [11] with modification by Rao et al. [12]. (Grade 0: no violation; Grade 1: < 2 mm perforation; Grade 2: 2–4 mm perforation; and Grade 3: > 4 mm perforation). For anterior perforations, the pedicle perforations were assessed using a modified grading system (Grade 0: no violation, Grade 1: < 4 mm perforation; Grade 2: 4–6 mm perforation; and Grade 3: > 6 mm perforation). Grade 2 and 3 perforations were considered 'critical perforations' with the exception of the for grade 2 and 3 lateral pedicle perforation over the thoracic zone as extrapedicular screws that breach the lateral pedicle wall at the thoracic zone were still contained within the pedicle-rib junction and were safe. In this study, the accuracy of pedicle screws was assessed by the two surgeons (KMK and CCYW). The inter rater reliability between the two assessors was adequate with a kappa value of 0.85.

Definitions

The following are definition of terms used in this study:

Table 1 Inter rater reliability testing comparing Rater 1 and Rater 2 for the zonal classification [the inter rater reliability had a Kappa value of 0.964 ($p < 0.001$), 95% CI (0.937,0.911)]

Rater 2	Rater 1								Total number of screws
	Transitional PT/MT	Transitional MT/L	Concave PT	Convex PT	Concave MT	Convex MT	Concave Lumbar	Convex Lumbar	
Transitional PT/MT	30	0	1	1	0	0	0	0	32
Transitional MT/L	0	34	0	0	0	0	0	0	34
Concave PT	0	0	12	0	0	0	0	0	12
Convex PT	0	0	0	10	0	0	0	0	10
Concave MT	0	1	0	0	32	0	0	0	33
Convex MT	0	1	0	0	0	31	0	0	32
Concave lumbar	0	1	0	0	0	0	18	0	19
Convex lumbar	0	1	0	0	0	0	0	23	24
Total	30	38	13	11	32	31	18	23	196

1. *Total perforation rate* (%) (Total number of perforations/Total number of screws inserted) × 100.
2. *Lateral perforation* Lateral breach of the pedicle margin (*including extrapedicular screws over the thoracic zone*).
3. *Anterior perforation* Breach beyond the anterior vertebral body or anterior to the costo–vertebral joint complex.
4. *Medial/superior/inferior perforation* Breach of pedicle cortices medially, superiorly or inferiorly.

Complications

Clinical complications and remedial actions which were taken in those cases were retrieved from the patient case records.

Statistical analyses

Data collected was entered into a computerized spreadsheet. Analyses were done with SPSS v.14 statistical software (SPSS, Chicago, IL, USA). The α-level was set at 0.05 to declare significance. Statistical analyses were done with the *t* test for quantitative variables and the χ^2 test for qualitative variables. Inter-rater reliability was assessed using Cohen's kappa statistics.

Results

1986 screws were assessed. The average patient age was 16.0 ± 3.7 years old. 123 (89.8%) patients were female while there were 14 (10.2%) males. Most of the curves were classified under Lenke 1 subtype (54.7%) followed by Lenke 2 (13.1%) and Lenke 3 (10.9%) and Lenke 5 (10.2%). The average major cobb angle was 70.3 ± 18.0° (Table 2).

392 screws (19.7%) were inserted in the transitional PT/MT zone, 435(21.9%) in the Transitional MT/L zone, and 311 (15.7%) screws were inserted in the convex MT zone (Table 3). The overall perforation rate was 20.3%. The zone with the highest perforation rate was in the concave PT zone (56.7%). This was followed by the transitional PT/MT zone (35.2%) and the Concave MT zone (18.2%). The zone with the lowest perforation rate was the Convex Lumbar zone (7.6%) followed by the Transitional MT/L zone (10.6%) (Table 3). The difference in perforation rate between the different zones was statistically significant ($p < 0.001$).

Most of the perforations in this study were lateral perforations which accounted for 66.3% (268/404) of all perforations giving a overall lateral perforation rate of 13.5% (268/1986). This was mainly due to the use of 'extrapedicular technique' in the thoracic spine. This was reflected by the trend of lateral perforation which was highest in the concave PT zone (45.8%, 55/120) followed by the transitional PT/MT zone (23.0%, 90/392) and the MT concave zone having a lateral perforation rate of 15.0% (43/286). With exclusion of the lateral perforation in the thoracic zone, the overall perforation rate dropped to from 20.3 to 8.4% and the overall lateral perforation rate was only 1.5% (30/1986) (Table 4). With inclusion of lateral perforations in the thoracic spine, cross tabulation of lateral perforation vs. zonal classification showed a *p* value of < 0.001. When lateral thoracic perforations were excluded the correlation between lateral perforations and the zone classification remained significant with a *p* value was < 0.001.

The highest medial perforation rate was at the transitional PT/MT zone (6.9%, 27/392). This was followed by the concave lumbar zone with a perforation rate of 6.7% (10/150) and the convex MT zone with a medial perforation rate of 6.1% (19/311). The lowest medial perforation rate occurred at the convex PT zone (1.7%) and the Concave MT (2.1%) zone (Table 4). The correlation between medial perforations

Table 2 Patient demographics, curve classification and Cobb angle

Total patients	137
Age (years)	16.0 ± 3.7
Total number of screws	1986
Gender	
Male	14 (10.2%)
Female	123 (89.8%)
Lenke classification	
1	74 (54.7%)
2	18 (13.1%)
3	15 (10.9%)
4	2 (1.5%)
5	15 (10.2%)
6	13 (9.5%)
Major Cobb angle (°)	70.3 ± 18.0

Table 3 Number of screws inserted and perforation rate stratified by zone classification

Zone	No. of screw (%)	No. of perforations (perforation rate in %)
Transitional PT/MT	392 (19.7)	138 (35.2)
Transitional MT/L	435 (21.9)	46 (10.6)
Concave PT	120 (6.0)	68 (56.7)
Convex PT	120 (6.0)	21 (17.5)
Concave MT	286 (14.4)	52 (18.2)
Convex MT	311 (15.7)	46 (14.8)
Concave lumbar	150 (7.6)	20 (13.3)
Convex lumbar	172 (8.7)	13 (7.6)
Total number of screws/overall perforation rate	1986 (100.0)	404 (20.3)

Table 4 Perforation rate stratified by zone and the direction of perforation

Zone	No. of perforations (perforation rate %)	Direction of perforation (no. of perforations (perforation rate %))					No. of perforations (perforation rate %)	Direction of perforation [excluding lateral perforation from T1–T12 vertebrae (no. of perforations (%)]				
		Medial	Lateral	Superior	Inferior	Anterior		Medial	Lateral	Superior	Inferior	Anterior
Transitional PT/MT	138 (35.2)	27 (6.9)	90 (23.0)		4 (1.0)	17 (4.3)	48 (12.2)	27 (6.9)			4 (1.0)	17 (4.3)
Transitional MT/L	46 (10.2)	14 (3.2)	28 (6.4)		2 (0.5)	2 (0.5)	36 (8.3)	14 (3.2)	18 (4.1)		2 (0.5)	2 (0.5)
Concave PT	68 (56.7)	3 (2.5)	55 (45.8)	1 (0.8)		9 (7.5)	13 (10.8)	3 (2.5)		1 (0.8)		9 (7.5)
Convex PT	21 (17.5)	2 (1.7)	15 (12.5)			4 (3.3)	6 (5.0)	2 (1.7)				4 (3.3)
Concave MT	52 (18.2)	6 (2.1)	43 (15.0)			3 (1.0)	9 (3.1)	6 (2.1)				3 (1.0)
Convex MT	46 (14.8)	19 (6.1)	23 (7.4)			4 (1.3)	23 (7.4)	19 (6.1)				4 (1.3)
Concave Lumbar	20 (13.3)	10 (6.7)	10 (6.7)				18 (12.0)	10 (6.7)	8 (5.3)			
Convex Lumbar	13 (7.6)	8 (4.7)	4 (2.3)		1 (0.6)		13 (7.6)	8 (4.7)	4 (2.3)		1 (0.6)	
Total number of perforations	404 (20.3)	89 (4.5)	268 (13.5)	1 (0.1)	7 (0.4)	39 (2.0)	166 (8.4)	89 (4.5)	30 (1.5)	1 (0.1)	7 (0.4)	39 (2.0)
p value		< 0.001*	< 0.001*	0.604	0.262	0.032*	*p* value	0.073	< 0.001*	0.098	0.541	< 0.001*

vs. the zonal classification had a p value of < 0.001 (including lateral thoracic perforations) and 0.073 (excluding lateral thoracic perforations).

There were 39 anterior perforations which accounted for 9.6% (39/404) of the total perforations [overall anterior perforation rate was 2.0% (39/1986)). 43.6% (17/39) of the anterior perforations were at the transitional PT/MT zone (perforation rate 4.3% (17/392)] whereas 23.1% (9/39) of anterior perforations occurred at the concave PT zone [perforation rate 7.5% (9/120)] (Table 4). The Chi-square test for anterior perforation vs. zonal classification had a *p* value of 0.032 (including lateral thoracic perforations) and < 0.001 (excluding lateral thoracic perforations).

There were 18 critical medial perforations giving a critical overall medial perforation rate of 0.9% (18/1986). 33.3% (6/18) of these critical medial perforations were at the convex MT zone followed by 22.2% (4/18) at the transitional PT/MT zone. The medial critical perforation rate was highest at the convex MT zone (1.9% (6/311)) followed by transitional PT/MT zone [1.0% (4/392)] and concave MT zone [1.0% (3/286)] (Fig. 2, Table 5).

Excluding grade 2 and 3 lateral perforation at the thoracic zone, there were 11 critical lateral perforations which gave an overall critical lateral perforation rate of 0.6% (11/1986). 4 (36.4%) occurred at the convex lumbar zone, while there were three perforations at the Transitional MT/L and four perforations at the Concave Lumbar zone (Table 5).

The overall critical anterior perforation rate was 0.6% (12/1986). Five out of the 12 critical perforations were at the concave PT zone, whereas four grade 3 perforations occurred at the transitional PT/MT zone (Table 5). The highest anterior critical perforation rate was at the concave PT zone with a perforation rate of 4.2% (5/120). This was followed by the transitional PT/MT zone which had a critical anterior perforation rate of 1.0% (4/392). There were also two grade three anterior perforations at the Concave MT zone. There was no critical anterior perforation at the convex PT zone.

The *p* value for critical medial perforations, critical lateral perforations and critical anterior perforations when cross-tabulated against the zonal classification was 0.088, < 0.001 and 0.037, respectively.

Clinical complications

Two perforations (0.1%) were symptomatic. One of the screws was a grade 2 medial perforation at T12, causing numbness over the left iliac crest area (Fig. 3). The area of numbness reduced at the end of 2 years. The other screw was a L2 screw which caused L2 radiculopathy (Fig. 3). Patient was treated with oral anti-inflammatory and gabapentin. The patient was treated conservatively and the symptoms subsided in 3 months. These two screws were inserted at the

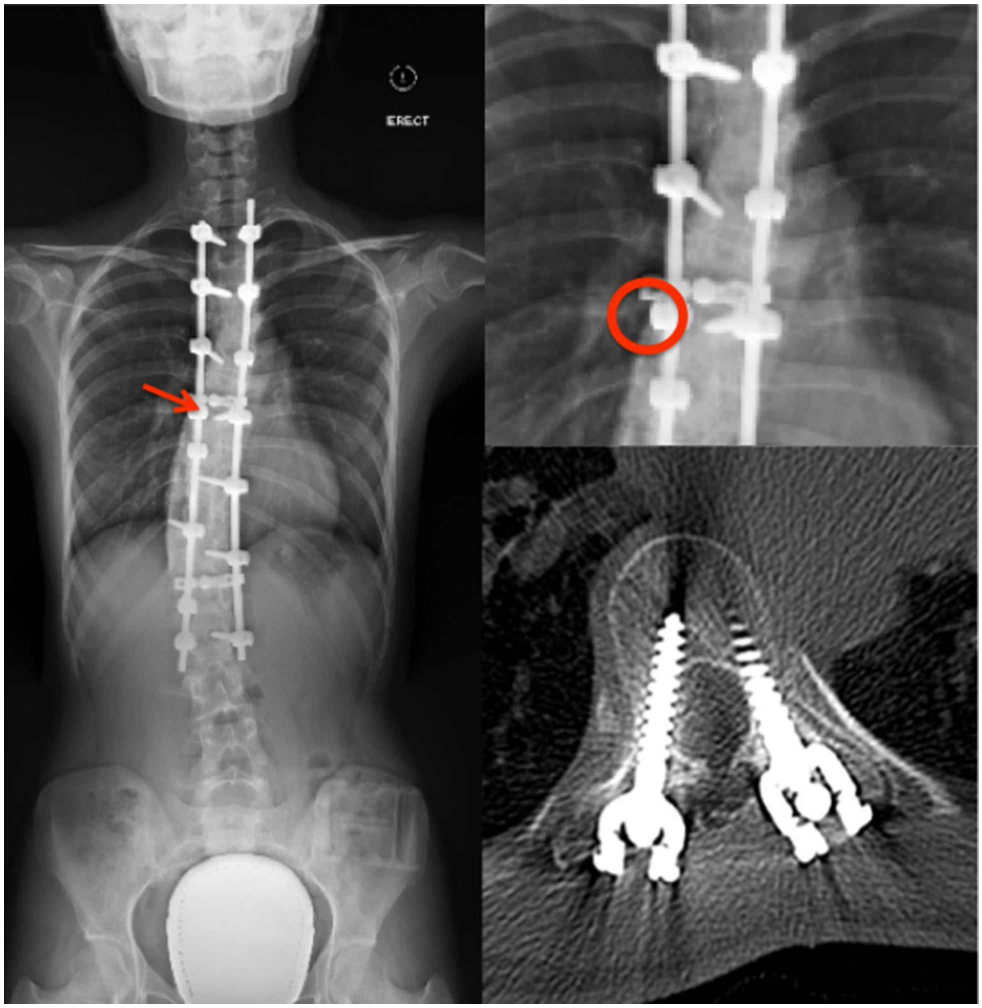

Fig. 2 Critical medial perforation at the transitional PT/MT zone in a Lenke 1 AR curve following PSF T2-L2

Transitional MT/L zone. Four anterior grade 3 perforations caused aortic abutment but no aneurysmal enlargement of the aorta was noted. Two of these screws were inserted at the transitional PT/MT zone and two screws at the Concave MT zone (Fig. 4a). Six screws abutted the lung with three screws at the transitional PT/MT zone, two screws at the concave PT zone and one screw was at the convex MT zone (Fig. 4b). Two 'grade 1' anterior perforations at T2 and T3 (convex PT zone) abutted the esophagus (Fig. 4c) but the patients did not complain of any swallowing difficulty. One screw (grade 1 anterior perforation) abutted the trachea at T4 level (transitional PT/MT zone) (Fig. 4d).

Discussion

Pedicle screw instrumentation in idiopathic scoliosis has led to better correction rate and newer correction techniques [13–18]. However, the safety of pedicle screws remains a concern. The incidence of new neurological deficit in idiopathic scoliosis was 0.73% [19]. The rate of pedicle screw malpositioning shows wide variation from 1.2 to 65.0% [20–29]. In a recent publication whereby 2020 pedicle screws were analyzed using CT Scans, the overall pedicle screw perforation rate was 8.6% with a critical perforation rate of 2.2% [30]. Clinical events associated with pedicle screw malpositioning were rare. In a meta-analysis of 14,570 screws in 1666 patients, only 1/1666 patients had temporary neurological deficit. Aortic abutment occurred in 0.07% of cases [31].

The low rate of neurological events associated with pedicle screw malpositioning could be attributed to under reporting. Dede et al. [32] reported an incidence of symptomatic pedicle screw malpositioning of 1.9%. Samdani et al. [33] reported a rate of early return to the operating theatre of 2.0% for revision of malpositioned pedicle screws. Mac-Thiong et al. [34] described a case series of 9 cases with intracanal pedicle screws. Two patients presented with acute

Table 5 Pedicle perforation stratified to direction and grade

Zone	Direction of perforation									Direction of perforation (lateral perforation from T1–T12 is excluded)								
	Medial			Lateral			Anterior			Medial			Lateral			Anterior		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
Transitional PT/MT	23 (5.9)	4 (1.0)	0	13 (3.3)	11 (2.8)	66 (16.8)	13 (3.3)	0	4 (1.0)	23 (5.9)	4 (1.0)	0	0	0	0	13 (3.3)	0	4 (1.0)
Transitional MT/L	11 (2.5)	3 (0.7)	0	14 (3.2)	3 (0.7)	11 (2.5)	2 (0.5)	0	0	11 (2.5)	3 (0.7)	0	15 (3.4)	3 (0.7)	0	2 (0.5)	0	0
Concave PT	2 (1.7)	1 (0.8)	0	7 (5.8)	9 (7.5)	39 (32.5)	4 (3.3)	1 (0.8)	4 (3.3)	2 (1.7)	1 (0.8)	0	0	0	0	4 (3.3)	1 (0.8)	4 (3.3)
Convex PT	2 (1.7)	0	0	7 (5.8)	4 (3.3)	4 (3.3)	4 (3.3)	0	0	2 (1.7)	0	0	0	0	0	4 (3.3)	0	0
Concave MT	3 (1.0)	3 (1.0)	0	5 (1.7)	3 (1.0)	35 (12.2)	1 (0.3)	0	2 (0.7)	3 (1.0)	3 (1.0)	0	0	0	0	1 (0.3)	0	2 (0.7)
Convex MT	13 (4.2)	4 (1.3)	2 (0.6)	8 (2.6)	3 (1.0)	12 (3.9)	3 (1.0)	0	1 (0.3)	13 (4.2)	4 (1.3)	2 (0.6)	0	0	0	3 (1.0)	0	1 (0.3)
Concave lumbar	10 (6.7)	0	0	5 (3.3)	3 (2.0)	2 (1.3)	0	0	0	10 (6.7)	0	0	4 (2.7)	3 (2.0)	1 (0.7)	0	0	0
Convex lumbar	7 (4.1)	1 (0.6)	0	0	3 (1.7)	1 (0.6)	0	0	0	7 (4.1)	1 (0.6)	0	0	3 (1.7)	1 (0.6)	0	0	0
Total	71 (3.5)	16 (0.8)	2 (0.1)	59 (3.0)	39 (2.0)	170 (8.5)	27 (1.4)	1 (0.1)	11 (0.6)	71 (3.6)	16 (0.8)	2 (0.1)	19 (1.0)	9 (0.5)	2 (0.1)	27 (1.4)	1 (0.1)	11 (0.6)
Total	89 (4.5)			268 (13.5)			39 (2.0)			89 (4.5)			30 (1.5)			39 (2.0)		

neurological deficit while another patient developed delayed Brown-Sequard Syndrome. Aortic injury or esophageal injury has also been reported [35, 36].

From the literature, it is known that there is a variation in pedicle morphometry and viscera vertebral relations at each zone. Liljenqvist et al. [37] reported smaller endosteal pedicle on the concavity of the middle thoracic curve. A similar finding was reported by Davis et al. [38] who noted significantly smaller, shorter pedicles at the periapical region with more acute trajectory over the convex side of the curve. Watanabe et al. [39] described a novel pedicle channel classification and noted absent pedicle channel was more prevalent at the concave PT zone. A similar finding was described by Sarwahi et al. [5] Abnormal pedicle increases the risk of malposition by three times. Interestingly, Chen et al. [40] reported post-operative aorta movement which could increase the risk of aortic abutment by pedicle screws in Lenke 5C curves.

However, Heidenreich et al. reviewed CT scans of pediatric patients with scoliosis and noted that the apical concavity did not have higher risk of malpositioning. Highest rate of screw malpositioning was between T3 and T8 and severe breaches were more often directed laterally [41]. In another series of 9 patients who had intracanal screws, 6/9 patients had screws misplaced at the left (convex) proximal thoracic levels at T3 or T4 level [34].

The pattern of perforation at the various zones in the current study has not been described in previous studies. The highest medial perforation rate was at the transitional PT/MT zone (6.9%) followed by concave lumbar zone (6.7%) and convex MT zone (6.1%). In contrast the concave MT zone had a medial perforation rate of only 2.1%. The highest rate of anterior perforations occurred at the concave PT zone (7.5%) and the transitional PT/MT (4.3%).

The highest rate of critical medial perforation occurred in the convex MT zone (1.9%) and transitional PT/MT zone (1.0%). At the convex MT zone, critical medial pedicle perforation occurred due to failure to recognize the vertebral rotational alignment which alters the pedicle trajectory. At this zone, the pedicle channel is often present. A critical medial perforation at this zone may result in neural injury. In contrast, at the transitional PT/MT zone, there is a change in pedicle trajectory and the incidence of dysplastic pedicle is higher. In this study, the two symptomatic screws occurred at the transitional MT/L zone.

The highest rate of critical anterior perforation was at the concave PT zone (4.2%). At the concave PT zone, the medial rotation of the vertebrae and absent pedicle channel predispose to anterior perforation. By understanding the danger and the likely direction of pedicle screw misplacement at each zone, care could be taken to avoid critical pedicle perforation. Lee et al. reported the used of cannulated pedicle screw systems to reduce the rate of pedicle screw perforation

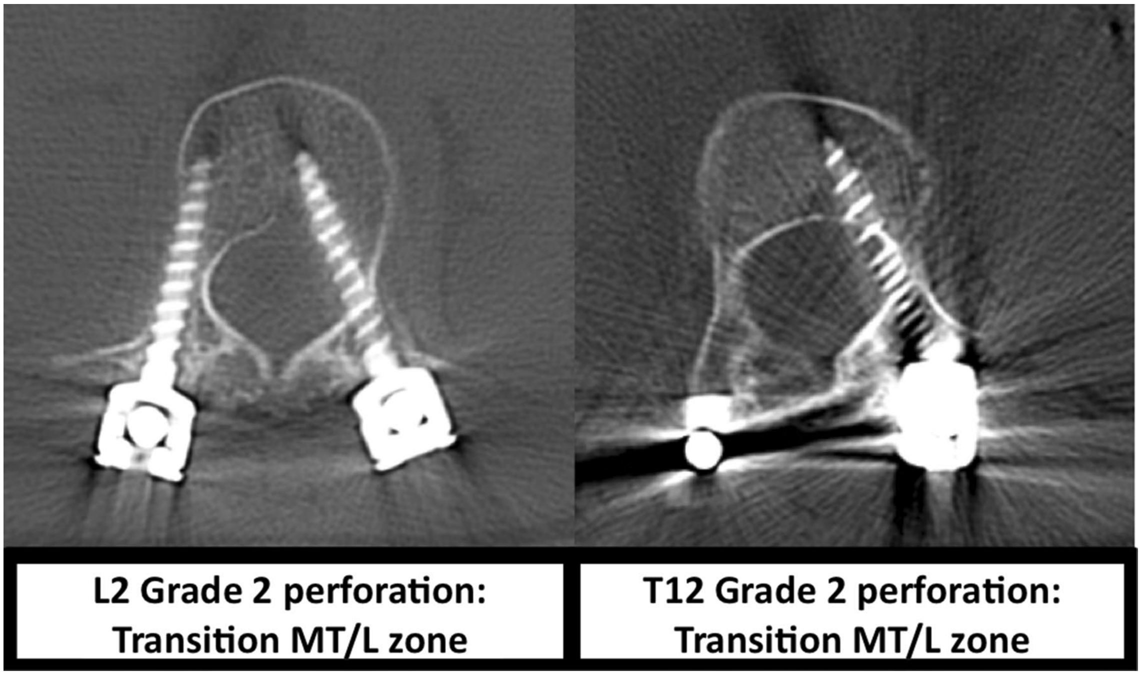

Fig. 3 Two symptomatic screws caused by grade 2 medial perforation at T12 and L2 at Transitional MT/L Zone

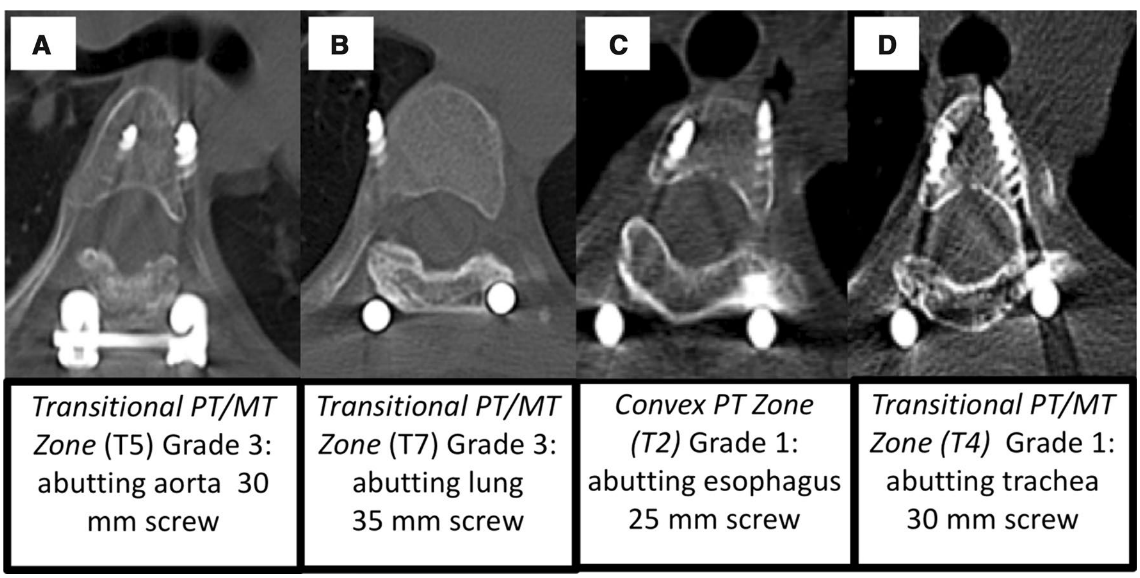

Fig. 4 **a** Grade 3 anterior perforation at transitional PT/MT zone causing abutment of the aorta, **b** Grade 3 anterior perforation at concave PT Zone causing abutment of the lung parenchyma, **c** Grade 1 anterior perforation at convex PT zone causing abutment of the esophagus and **d** Grade1 anterior perforation at the transitional PT/MT zone causing tracheal abutment

from 15.6 to 4.5%. The authors also reported that this technique reduced the rate of critical screw perforations [42]. A misdirected 25–30 mm pedicle screw places the viscera in danger especially at the PT zone. The cases illustrated in Fig. 4 showed abutments of the aorta and the lung caused by critical grade 3 anterior perforations at the transitional PT/MT and concave PT zone. This is consistent with a report by Takeshita whereby at T4, the length of the pedicle was only 30.5 mm at the concave side and 29.4 mm at the convex side [43]. Sariyilmaz et al. [36] reported a case of esophageal perforation due to placement of a 40 mm screw at left T4 level. In our study, we demonstrated that even a 25 mm screw causing anterior perforation at the convex PT zone (Fig. 4c) could potentially injure the esophagus.

There were some limitations in this study. Other risk factors for pedicle screw perforation such as bone density and bleeding were not accounted for. 198 patients fulfilled the inclusion criteria which was patients who underwent posterior spinal fusion using pedicle screw instrumentation. 34 cases did not have post-operative CT scans, whereas 27 patients had post-operative CT scans but were excluded as the CT scans were of poor quality. We did not have data for this group of patients and could not determine the accuracy of pedicle screw instrumentation in them as this was a retrospective study. The data in this group of patients could affect the overall outcome in this current study. We also did not analyze the discrepancy between screw size and pedicle morphometry which could alter the perforation risk of the pedicle. The outcome of pedicle screw insertion in dysplastic pedicles was not reported in this study as well.

Conclusions

In conclusion, significant differences exist in the rate of pedicle perforation at the various zones. Overall rate of pedicle malpositioning was 20.3% (including lateral perforation in the thoracic spine) and 8.3% (excluding lateral thoracic perforation). Highest rate of critical medial perforation was at the convex MT zone (1.9%) whereas highest rate of critical anterior perforation was at the PT concave zone (4.1%).

Compliance with ethical standards

Conflict of interest All authors declared that they have no potential conflict of interest.

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