How to improve the safety of bicortical pedicle screw insertion in the thoracolumbar vertebrae with osteoporotic: Analysis base on three-dimensional CT reconstruction of patients in prone position

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Abstract

Background: Three-dimensional CT reconstruction of prone position could measure the relative position between the Great vessels and the thoracolumbar vertebrae. The Great vessels positions of the thoracic and lumbar segments were studied to improve the accuracy of pedicle screw insertion, reduce the risk of vascular injury.

Methods: Twenty-four adults participated in the present study. Three-dimensional reconstruction of thoracolumbar (T9-L3) CT was performed in the prone and supine positions. The relative distance between the arteriovenous vessels and vertebrae distance (AVD/VVD) was obtained, respectively. The relative position angle of the arteriovenous vessel and the vertebral body was calculated as \( \angle AOY/\angle VOY \). Self-controlled experiments were carried out in the prone and supine positions. The data obtained were analyzed using SPSS 22.0 statistical software.

Results: With regard to AVD, the AVD of the T12 was the smallest, > 3.2 mm. The difference among the T9, T10, L2 level was statistically significant (P < 0.05). And AVD was greater in the prone position than in the supine position; while the value of \( \angle AOY \) is the descending from T9-L3 gradually, there were statistically significant differences in \( \angle AOY \) between T9-T12, L2 and L3 in prone and supine position (P < 0.05). The aorta in the prone position was closer to the midline than that of the supine position, varying from 0° to 30° near the Y axis. With regard to VVD, there was no significant difference in contrast between the prone and supine positions (P ≥ 0.05), and the VVD was the smallest in the L3 level > 5.4 mm.

Conclusion: The pre-vertebral position of the aorta may change from T9 to L3 due to changes in body position. When the T9-L3 thoracolumbar spine disease was treated with pedicle screw double cortical fixation, the screw was safe and reliable within a range of ≤ 3 mm when
broken the pre-cortex. The three-dimensional reconstruction of prone position CT could be used to more accurately assess the relative position of the vertebral body and the blood vessel.

1. Background

Pedicle screw internal fixation is currently the first choice method for treating thoracolumbar spine disease.[1] During this procedure, most clinicians consider it appropriate to insert the screw to a depth of 80% into the bone-screw channel. [2] However, in treating elderly patients with osteoporosis, the pedicle screw bi-cortical fixation is commonly used. When the screw is placed deeper, the screw-to-bone contact area is larger and the stress is dispersed throughout the anterior cortical bone, thus strengthening the fixation of the screw within the vertebral body. Specifically, the holding power of the vertebrae enhances the internal fixation strength, reduces looseness and disengagement of the screw, and improves the success rate of the operation.[3, 4]

However, this technique risks damaging the blood vessels in the anterior cortex of the vertebral body.[5-7] To evaluate this risk and accurately implement bi-cortical fixation, the present study used imaging to examine the anatomical positional relationship and relative distance between the vertebral body and the blood vessel; it also explored ways to improve the accuracy of bi-cortex fixation and reduce the risk of vascular injury.

2. Methods

2.1 Participants

Twenty-four adults were selected to participate in the study: fourteen men and ten
women aged 21–64 years old (mean age: 52.3 years old). All subjects were free of thoracolumbar deformities, major vascular malformations, and vascular lesions in front of the thoracic and lumbar spine, and none had any history of retroperitoneal surgery or thoracolumbar surgery.

2.2 Materials

Computed tomography was carried out using PHILIPS brilliance iCT 256-row spiral CT, with PHILIPS image post-processing system. All subjects were injected with iodine contrast agent, and statistics were analyzed using SPSS 22.0 statistical software.

2.3 Methods

The thoracolumbar region was reconstructed in three dimensions, with the patients in the prone position and supine position. Angiography was performed by injection of iodine contrast agent during the scanning process. The acquired images were reconstructed using the post-processing workstation of PHILIPS iCT image. Figure 1 shows an axial image of the optimal pedicle screw placement plane, with a description of the positioning method. The following measurements were acquired: pre-vertebral arteriovenous-vertebral body distance (AVD/VVD), blood vessel angle relative to the vertebral body median line (Y axis; $\angle AOY/\angle VOY$; Fig. 1); the measurement method described below. Self-control experiments were performed on changes of body position in the prone and supine positions. The data obtained were analyzed using SPSS 22.0 statistical software.

2.3.1 Scanning protocol

CT scanning of the spine ranged from T9 to L3, with the following scanning conditions: 120 kV and 300 mAs, a scanning layer thickness of 0.625 mm, a bulb
rotation time of 0.27 s, a matrix of 512*512, and a pitch of 0.915. Full-field axial scanning was used, with experience value scan timing, in which the arterial phase is 25–35 s after injection and the venous phase is 60–70 s.

2.3.2 Contrast mode

The right elbow was automatically injected with intravenous contrast agent using a Medrad Stellant double-tube CT high-pressure syringe, according to the setting procedure (contrast agent dose: 1.5 mL/kg; injection rate: 3–5 mL/s).

2.3.3 Image localization method

The sagittal and coronal images of the vertebral body were reconstructed in the image post-processing workstation, in which the reference line was the space coordinate axis X, Y, Z, with origin O (Fig. 2). The coordinate origin O was located at the midpoint of the posterior margin of the vertebral plane vertebral body, and the XY axis was adjusted on the axial image so that the X axis passed through the posterior edge of the vertebral body and the Y axis passed through the midline of the vertebral body (Fig. 2A). The sagittal image YZ was adjusted. The axis as such that the Y-axis passed through the midline of the vertebrae, paralleling the upper and lower edges of the vertebral body, while the Z-axis passed through the posterior edge of the vertebral body (Fig. 2B). The X-axis of the coronal image was adjusted so that the Z-axis passed through the midline of the vertebral body, while the upper and lower edges of the X-axis paralleled the vertebral body (Fig. 2C). Each axis was finely adjusted again, the optimal pedicle axis position was located on the image, and the data were measured.

2.3.4 Data measurement method

On the axial image, the ray was emitted from origin O to a tangential point on both
sides of the blood vessel. The average of the angle between the two lines and the Y-axis was measured (Fig. 3A, B) was taken as the location of the blood vessel relative to the vertebral, and the distance from the blood vessel to the vertebral body AVD/VVD was measured. The angle from the line to the Y-axis was recorded as the arteriovenous angle relative to the vertebral body (∠AOY/∠VOY; Fig. 3C, D). The results were recorded separately.

2.4 Statistical methods

The paired t-test was performed on the data obtained using SPSS 22.0 statistical software. Differences were defined as statistically significant at P-values < 0.05. Experimental data are expressed as mean ± standard deviation.

3. Results

3.1 Anterior arteriovenous and vertebral body distance AVD/VVD

At the T9–L3 vertebral level, the distance between the vertebral body and the anterior vertebral artery was first decreased and increased in the prone and supine positions, as shown in Fig. 4. In the prone position, the minimum AVD was at T12: 3.38 ± 1.00 mm, followed by L1: 3.61 ± 1.45 mm; the maximum AVD was at L3: 6.08 ± 2.24 mm. In the supine position, the minimum AVD was at T12: 3.21 ± 0.71 mm, followed by L1: 3.66 ± 0.84 mm; the maximum AVD was at L3: 5.91 ± 2.77 mm. The AVD increased more in the prone position than in the supine position, and the AVD values measured at the T9, T10, L2 vertebral bodies differed significantly between the prone and supine positions (P < 0.05; Table 1). The distance of the prone position was greater than the supine position.
At the level of the L1–L3 vertebral bodies, the distance between the vertebral body and the IVC showed a decreasing trend in the prone and supine positions (Fig. 5). In the prone position, the VVD of the L1–L3 levels was reduced: 10.94 ± 6.39 mm, 10.71 ± 5.03 mm, and 5.56 ± 2.34 mm, respectively; the VVDs of the L1–L3 levels in the supine position were 12.25 ± 3.50 mm, 10.31 ± 4.35 mm, and 5.41 ± 2.67 mm, respectively. The VVD between the L1–L3 vertebral bodies did not differ significantly between the prone and supine positions (P ≥ 0.05; Table 2).

### Table 1

| level | AVD | Supine | P value | ∠AOY | Prone | Supine | P value |
|-------|-----|--------|---------|------|--------|--------|---------|
| T9    | 5.3 ± 1.73 | 4.4 ± 1.16 | 0.049* | 18.62 ± 10.74 | 32.92 ± 11.50 | 0.000* |
| T10   | 5.1 ± 2.08 | 4.0 ± 1.20 | 0.027* | 12.79 ± 10.07 | 23.60 ± 8.54 | 0.000* |
| T11   | 4.4 ± 2.71 | 3.9 ± 1.14 | 0.121 | 10.20 ± 8.90 | 16.88 ± 8.90 | 0.000* |
| T12   | 3.3 ± 1.00 | 3.2 ± 0.71 | 0.476 | 12.75 ± 6.89 | 15.68 ± 6.79 | 0.010* |
| L1    | 3.6 ± 1.45 | 3.6 ± 0.84 | 0.907 | 13.07 ± 8.91 | 14.80 ± 7.52 | 0.136 |
| L2    | 4.17 ± 1.68 | 4.74 ± 2.05 | 0.047* | 9.88 ± 8.18 | 12.00 ± 7.92 | 0.009* |
| L3    | 6.0 ± 2.24 | 5.9 ± 2.77 | 0.681 | 4.15 ± 6.04 | 7.72 ± 3.90 | 0.003* |

* Means the difference in data is statistically significant

### Table 2

| level | VVD | Supine | P value | ∠VOY | Prone | Supine | P value |
|-------|-----|--------|---------|------|--------|--------|---------|
| L1    | 10.9 ± 6.39 | 12.2 ± 3.50 | 0.400 | 25.80 ± 4.95 | 27.50 ± 3.72 | 0.180 |
| L2    | 10.7 ± 5.03 | 10.3 ± 4.35 | 0.670 | 27.94 ± 7.10 | 26.55 ± 5.17 | 0.451 |
| L3    | 5.56 ± 2.34 | 5.41 ± 2.67 | 0.360 | 26.29 ± 8.61 | 24.15 ± 4.47 | 0.279 |

#### 3.2 Anterior arteriovenous and vertebral relative position angle ∠AOY/∠VOY

In the prone position, with aorta movement from the level of the T9–L3 vertebral bodies, while the thoracic and abdominal aorta gradually shifted from the left front of the vertebral body to the anterior center line of the vertebral body (Y axis) (Fig. 6). At first, the ∠AOY gradually reduced from the level of the T9 vertebral body (18.62° ± 10.74°) to the level of the T11 vertebral body (10.20° ± 8.90°). It then...
increased, showing a brief, small peak at the level of the L1 vertical body (13.07° ± 8.91°), before decreasing to the level of L3, when it was close to zero (4.15° ± 6.04°). In this regard, the supine position showed similar results, with a gradual approach to the central tendency (Fig. 6). The $\angle$AOY of the other groups differed significantly between the prone and supine positions in all vertebrae except L1 (P < 0.05) (Table 1). Moreover, the pro-vertebral anterior aorta was closer to the anterior vertebral center line.

In the prone and supine positions, the IVC remained in the right front of the vertebral body in the L1-L3 vertebral segments (Fig. 6). However, it was limited to the 20°–30° position near the Y axis. The relative position angle $\angle$VOY did not differ significantly between the prone and supine positions $P \geq 0.05$ (Table 2).

4. Discussion

4.1 Pedicle screw bi-cortical insertion significance

As the population ages, the number of elderly patients who have osteoporosis with thoracolumbar spine disease is increasing,[4, 8–10] and pedicle screw fixation is widely used to treat such patients[1]. However, because osteoporosis involves decreases in bone density, it severely affects the holding power of the vertebral body. Loosening and dislodging of the screw directly affect internal fixation strength, which in turn determines the success of the operation.[3, 4, 10, 11] To increase the internal fixation strength of the pedicle screw in patients with osteoporosis, clinicians wisely use bone cement augmentation, cortical bone channels, and expandable pedicle screw fixation. However, these techniques significantly increase the risk of nerve injury and the operation time, as well as the amount of bleeding.[2, 9, 12, 13] Surgical techniques also enhance the internal
fixation strength, particularly increasing the diameter of the pedicle screw, the depth necessary for insertion, and the insertion angle show an advantage.[14] Studies have shown that, when the screw is placed in the anterior cortex of the vertebral body but not penetrated, the fixation strength can be increased by 16%, and the anterior cortex be broken through, which can increase the pedicle screw pull-out force by 60%, increasing 20%-25% fixed strength. [2, 15] Based on this biomechanical theory, the pedicle screw bi-cortical fixation technique is applied to patients with osteoporosis.

Double cortical fixation has two mechanical advantages over single cortical fixation: it increases the length of screw insertion and it uses cortical bone rather than cancellous bone for screw fixation. The stress is dispersed between the two cortical bones so that the fixation strength in the cancellous bone is significantly increased. [3, 4] The bi-cortical fixation technique involves significantly shorter operation time and lower risk of nerve damage than other placement techniques. However, the technique also requires precise screw placement, as protruding screw tips can damage blood vessels.[16, 17] As such, more stringent requirements are placed on the surgeon, because the screw placed in the anterior cortex of the vertebral body must not be too long. Despite this, no previous studies have investigated safe lengths for screw extrusion. Thus, the present study addressed this question and provided theoretical guidance for the accurate implementation of bi-cortical fixation.

4.2 The effect of body position on the distance between vertebral body and blood vessel

The data showed that the AVD differed significantly among the T9, T10, and L2 vertebral bodies (P < 0.05), that the AVD in the prone position was larger than that
in the supine position, and the $\angle AOV$ of T9-T12, L2, and L3 vertebral bodies differed. There was a statistically significant difference (P < 0.05), and the prone position was closer to the anterior vertebral center line than the supine position. This indicates that the positions of the artery and the vertebral body are relative activity, except in some segments. The overall position of the aorta was changed relative to the vertebral body. The lower aorte of the prone position is farther from the vertebral body and closer to the anterior vertebral center line. Vaccaro et al. [18] obtained similar conclusions. They found that prone positioning resulted in greater distances between the disc and iliac vessels at L4-L5 and L5-S1 by an average of 3 mm, probably because, in the supine position, magnetic resonance imaging (MRI) underestimates the distance between the blood vessels and the intervertebral disc. They also found changes to the active bifurcation point and IVC junction. It was found that the position in the prone position moved up from the supine position to the head side, confirming the vascular activity. Similar results were reported by Sucato et al. [19], as well as by Huitema [20].

The present study showed that the relative positions of the IVC and vertebral body in the L1-L3 segment were relatively fixed. In different postures, no obvious changes occurred: there was no significant difference in VVD between the L1-L3 vertebral body and the IVC (P ≥ 0.05). Furthermore, in the supine and prone position, there was no significant difference in $\angle VOY$ between the vertebral body and IVC (P ≥ 0.05). In the position of the IVC and vertebral body in the L1-L3 segment.

4.3 Influence of anatomical factors on the distance between vertebral bodies and blood vessel

The relative vascular distance of vertebral bodies T9-L3 decreased first and then
increased (Fig. 4). The AVD was the smallest at T12; similar results were observed by Sarlak et al[21]. in 12 patients with scoliosis. There was no significant difference in the T12 AVD and $\angle \text{AOY}$ data ($P \geq 0.05$), indicating that the relative positional distance between the T12 vertebral body and the aorta does not change with changes in body position, and that the same is true for the adjacent segments T11 and L1. Considering anatomical factors, the thoracic aorta continues into the abdominal aorta from the aortic sac of the diaphragm, which is mostly located at the T12-L1 positions and is close to the vertebral body. Thus, the aorta and vertebral bodies are fixed at this point and do not change due to changes in body position.

This study did not obtain anterior venous data at the level of the T9–T12 vertebrae. However, anatomical studies have shown that the IVC flows into the left and right common iliac veins before L5, and that it ascends to the right side of the vertebral body, entering the thoracic cavity through the vena cava, and the vena cava was at the center of the T8 vertebral body, close to the central aponeurosis, away from the vertebral body, so the blood vessels gradually move away from the vertebral body during the running process; the data shows that the distance VVD of the IVC and vertebral body of L3-L1 gradually increases, and L1, L2VVD > 10 mm, T8-T12 The distance between the anterior vertebral veins is farther, and there is no research significance. Furthermore, the IVC passes through the hepatic vena cava through the liver, and the boundary of some liver tissues is not obvious. As shown in Fig. 2A, no relevant data were obtained.

In addition, imaging studies have shown that, in elderly patients, lip-like bone hyperplasia can occur in the upper and lower margins of the vertebral body, pushing the anterior vertebral vessels to the front of the vertebral body (Fig. 2A). Right
anterior border bone hyperplasia pushes the blood vessel forward, increasing the safe distance between the blood vessel and vertebral body.[22]

4.4 Discussion on the safety distance between vertebral body and blood vessel

To ensure that the pedicle screw bi-cortex insertion is safe, distance must be placed between the vertebral body and the blood vessel. The present study found that postural changes alter the distance between the blood vessels and the vertebral body. The prone position may confer a greater safe distance. In general, three-dimensional CT reconstruction in the supine position underestimates the safe distance between the vertebral body and the blood vessel.[20, 22, 23] It provided a basis for greater safety margins during the surgical procedures.

The data showed that the vertebral body was closest to the aorta at T12 (> 3.2 mm), while the IVC was the closest to the vertebral body at L3 (> 5.4 mm). In theory, when the thoracolumbar segment (T9–L3) undergoes bi-cortical insertion, it is safe to use the left vertebral screw to break the anterior cortex length of (> 3.2 mm). The right pedicle screw has a greater safe range before rupture (≤ 5.4 mm). The distance of some segments may be below average distance due to individual differences, and we need to be carefully observed before surgery to determine whether or not the intraoperative breakthrough and the breakthrough length. At T12, due to anatomical factors, the distance from the vertebral body is the closest, and the position is relatively fixed. Special attention must be paid to the safe distance range before surgery.

When discussing safety distance, Sarwahi et al.[22] claimed that the anterior/anterior lateral cortex of the screw can be safely broken at ≤ 4 mm; the
study found that 33 screws that broke the anterior cortex did not damage the vascular organs under anatomical direct view. The undeveloped CT scan of the anterior soft tissue of the vertebral body underestimates the safe distance between the blood vessel and the vertebral body. The soft tissue within 4 mm of the anterior vertebral body can completely embed the tip of the protruding screw, rendering it safe. In patients with bi-cortical fixation, CT scans have shown prominent screws in contact with blood vessels, but most studies have found that patients with screw-to-vascular contact had no clinical symptoms.\textsuperscript{24, 25} Foxx et al.\textsuperscript{26} reviewed 107 patients with spinal internal fixation and found that 33 of the 680 screws were in contact with large vessels, with an average follow-up of 44 months. Postoperative imaging follow-up showed no vascular abnormalities at the site of contact. Therefore, screws that are in contact with blood vessels are not considered to cause vascular damage.

4.5 Effect of the angle between the vertebral body and the blood vessel on bi-cortical fixation of the pedicle screw
Relative distance is an important basis for assessing the safety of pedicle screw placement. However, the present study also revealed changes to the angle of the vessel relative to the vertebrae. Considering that the distance between the aorta and the vertebral body can also change with body position, the position of the aorta may fluctuate within a range. Using three-dimensional CT reconstruction measurement data, we simulated screw placement in the ideal pedicle plane (positioning map 3A) and found that the screws were placed within the appropriate and safe screw inclination transverse screw angle (TSA), and the protruding length of the screw from the anterior cortex of the vertebral body may partially overlap or avoid the anterior vertebral vessels. the
anterior vertebral vessels of the few segments can completely avoid the screws. As shown in Fig. 7, postoperative resection of the patients with bi-cortical fixation revealed that the anterior vessel of the L2 vertebral body avoided the direction of the screw axis. In such cases, even if the blood vessel is close to the vertebral body, screws that breaks through the anterior wall of the vertebral body are less likely to damage the blood vessels. Therefore, the risk of vessel injury due to bi-cortical fixation cannot be evaluated based on relative distance alone. Three-dimensional CT scanning in the supine position measures the position and angle of the blood vessel, predicts whether the blood vessel can avoid the screw placement range, and reveals the TSA range of the blood vessel to guide the surgeon during the operation. This is important for more precise and safe bi-cortical placement. However, it also puts higher demands on the surgeon with regards to hand-stitching.

4.6 Limitations of this experiment

It may be that the 3D CT reconstruction caused unclear visualization of vertebral soft tissue, leading to this data measurement error and underestimation of the distance between the blood vessel and the vertebral body in the present study. Thoracolumbar MRI clearly visualized the soft tissue of the anterior vertebrae. Data acquisition from these images reduced the error. However, this technique was not used because it involves the prone position MRI operation technique. To a certain extent, angiography compensated for the error, but the effect was far smaller in vein imaging than in arterial imaging, and there was still error in measuring the position of the vein.

5. Conclusions
The present data showed that T9-L3 pedicle screw bi-cortical insertion can be used to treat thoracolumbar spine disease, and that screw breakthrough before the cortex in the range of \( \leq 3 \) mm is safe and reliable. Because some vertebral body anterior safety distance can be shorter than the average due to individual differences, the CT image must be read carefully before preoperative. The anterior vertebral artery is further from the vertebral body in the prone position and closer to the anterior vertebral body center line. Therefore, CT image information in the prone position accurately reflects the safe length of the pre-cortex before the screw breaks, providing a guiding basis for the accurate and safe implementation of the bi-cortical fixation.

6. Abbreviations

AVD: Distance between aorta and vertebral body at the T9-L3 level

VV: Distance between IVC and vertebral body at the L1-L3 level

\( \angle A O Y \): Angle of position between aorta and vertebral body at the T9-L3 level

\( \angle V O Y \): Angle of position between IVC and vertebral body at the L1-L3 level

IVA: Inferior vena cava

7. Declarations

**Ethics approval and consent to participate**

Before CT scanning, the patients and their family members were informed the risks, and the patients signed an informed consent form; the experimental design met the requirements of the Ethics Committee of the Affiliated Hospital of Qingdao University, No. QYFYWZLL25636.

**Consent for publication**
Not applicable

Availability of data and materials
The data used in the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

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Authors’ contributions
CX and ZW conceptualized and designed the study. JM Scanned and located images, CX and WY helped collected clinical materials. XH and CY assists in data analysis. CX drafted the manuscript. QH and ZW revised the manuscript. All the authors have read and approved the final manuscript.

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Figures
Figure 1

Schematic showing the measured parameters: AVD = Distance between aorta and

Vertebrae.
Figure 2

Schematic showing Image localization method for T12 level in supine position. A, I
Figure 3

Schematic diagram of data measurement method 3A,B the ray was emitted from o
P-AVD is the value of AVD in prone position; S-AVD is the value of AVD in supine position.
Figure 5

P-VVD — the value of VVD in prone position; S-VVD — the value of VVD in supine position.
Figure 6

The relative position Angle of the great vessels and vertebral bodys $\angle \text{AOY}/ \text{VOY}$
Postoperative resection of the patients with bicortical fixation revealed that the a