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Original Article

Measurement of lumbar isthmus parameters for novel starting points for cortical bone trajectory screws using computed radiography

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Abstract: The current study aims to measure distance parameters in lumbar isthmus to develop new references for lumbar pedicle screw insertion. Using computed radiography, the distance between the median pedicle tangent and the isthmus lateral tangent (D1) and the isometric distance between the isthmus lateral tangent and the inferior border of transverse process (D2) were measured on 120 spine X-ray images. A derived distance D3 (equal to D2 minus 1 mm) was calculated. These parameters were used to define the starting points for pedicle screws. Cortical bone trajectory (CBT) fixations were carried out on six wet (including 3 male and 3 female) and 4 dry lumbar specimens using the new system, and were evaluated for accuracy and safety of screw insertion. Measurements showed that D1 (mm) was 2.1±0.13 (L1), 2.3±0.13 (L2), 3.6±0.33 (L3), 4.4±0.36 (L4), 5.7±0.36 (L1); D2 was 5±0.83 (L1), 6.19±0.84 (L2), 5.38±0.86 (L3), 3.66±0.42 (L4) and 2.30±0.37 (L5). A total of 100 CBTs were evaluated. Among them, 7 out of the 60 screws in the 6 wet specimens penetrated into the lateral pedicle bone, the successful rate was 88.7%; 2 out of the 40 screws in the 4 dry specimens penetrated through the lateral or median pedicle bone, the successful rate was of 95%. With our new system, CBT screws can be placed based on these parameters, which can be obtained less invasively, and irrespective of articular degeneration in lumbar facet and morphological variation in the transverse process. Our data show that the technique is safer, less invasive, and easier to operate. It would help reduce bleeding, intraoperative X-ray exposure and surgical time.

Keywords: Isthmus, lumbar X-ray, cortical bone trajectory

Introduction

Cortical bone trajectory (CBT) is a new lumbar pedicle screw trajectory proposed by Ueno [1] and Santoni [2] in 2009. CBT increases the contact surface between the screw and cortical bone where the screw is surrounded by dense cortical bone [3-8], which does not deform remarkably due to degeneration [9]. Compared with the traditional pedicle screw insertion, CBT increases 30% uniaxial yield pullout load and equivalency in mixed loading [10], with a holding force 1.7 times that of the traditional screw trajectory [11], allowing the use of shorter screws.

In previously studies, the starting point was proposed to be the junction of the center of the superior articular process and 1 mm inferior to the inferior border of the transverse process [1, 2, 12], although some believed that the superior margin of the intervertebral foramen on lateral X-ray image should be used as a reference for the starting point on the lateral edge of isthmus at the same height [13]. This would prevent the screw from being inserted into the intervertebral foramen to damage the nerve root.

We believe that use of these anatomical references for defining the x and y axis of the starting points has certain limitations. For example, it has been shown that the zygapophyseal joints are often prone to degeneration, which occurs in 89.2% of 60-69 age group [14-20]. Since CBT screws are mostly used in the elderly suffering osteoporosis [1-3, 21], if the starting

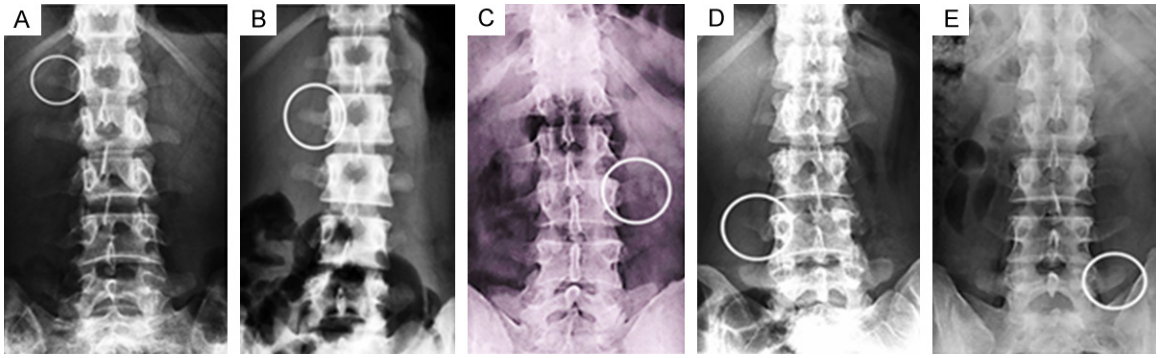


Figure 1. Spine X-rays showing the variability of transverse process in lumbar specimens. A-E. Vertebral levels 1-5. Circles indicate upturned transverse process.

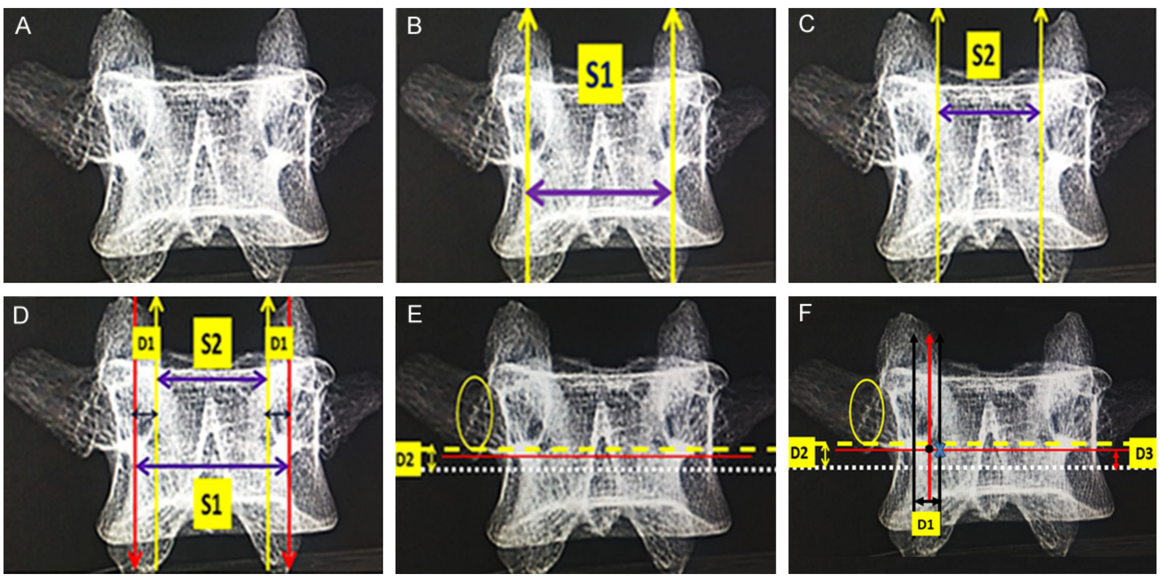


Figure 2. Measurement of isthmus parameters and determination of staring points of cortical bone trajectory screws in lumbar specimens. A. Representative reconstructed X-ray of a spine isthmus; B. Measurement of distance S1 between the left and right tangent points; C. Measurement of distance S2 between the left and right roots of vertebral arches; D. Measurement of distance D1 between the tangent lines of the lateral edges of isthmus to the medial wall of vertebral arches; E. Measurement of vertical distances D2 from the line connecting the tangent points to the inferior border of the transverse process; F. Vertical distance D3 from the line connecting the tangent points to 1 mm below the inferior border of the transverse process. Orval circles indicate accessory processes; yellow dot lines indicate the inferior border of transverse process; white dot lines are connecting lines of isthmus tangent points; X indicates the staring points of cortical bone trajectory screw described in the paper and black dot indicated reported starting point [4].

point is selected based on the midline of easily degenerated zygapophyseal joint as reported in the previous studies, the screws may hurt the nearby nerve [13]. In addition, since the x axis is 1 mm inferior to the inferior border of the transverse process, entire inferior border of the transverse process near the intervertebral foramen needs to be exposed, leading to the increased surgical invasiveness. Furthermore, the inferior border of the transverse process is often not horizontal as assumed and is often upward turned (**Figure 1**). Therefore, it would be challenging to use the reference distance of 1 mm inferior to the inferior border of the transverse process to locate the starting point due to the variability in the baseline of the transverse process. Besides, for patients who had inter-transverse process fusion surgery, it is difficult to locate the inferior border of the transverse process for revision surgery.

Table 1. Isthmus parameters measured on the X-ray images of 120 adults (means ± SD, mm)

Levels	S1	S2	D1
L1	26.0±0.59	21.8±0.52	2.13±0.13
L2	26.7±0.61	22.1±0.48	2.30±0.13
L3	29.7±0.82	22.6±0.43	3.58±0.33
L4	32.1±1.13	23.3±0.58	4.42±0.36
L5	41.7±1.45	30.3±0.81	5.73±0.36

Table 2. Isthmus parameter D2 measured on the X-ray images of 120 adults (means ± SD, mm)

Levels	Side	D2
L1	Left	4.99±0.83
	Right	5.01±0.83
	Average	5.00±0.83
L2	Left	6.21±0.85
	Right	6.18±0.85
	Average	6.19±0.84
L3	Left	5.39±0.86
	Right	5.37±0.86
	Average	5.38±0.86
L4	Left	3.64±0.44
	Right	3.69±0.43
	Average	3.66±0.42
L5	Left	2.30±0.37
	Right	2.30±0.38
	Average	2.30±0.37

Coronal plane of lumbar isthmus is curved with a tangent point and is bilateral symmetry. This is the most easily observable anatomical feature in both lumbar surgery and on X-ray image. Furthermore, as the lateral isthmus is approximate to the midline during operation, it is fully exposed and the tangent points are readily recognized. To improve the accuracy of the starting point and minimize the X-ray fluoroscopy to position the starting point, we propose a new reference system for the starting point that is based on several isthmus parameters. The aim of this study was to conduct a morphometric measurement of lumbar isthmus to develop the new reference system.

Material and methods

Subjects

X-ray images of 120 adults (including 60 males and 60 females; age range, 20-50 y; means ± SD: 36.21±7.8 y) who underwent lumbar vertebrae examinations at The First Affiliated Hospital of Xinjiang Medical between September 2015 and September 2016 were studied. Six intact wet (including 3 males and 3 females) and 4 dry lumbar specimens (provided by Department of Anatomy, Xinjiang Medical University) were used for screw insertion. Lumbar vertebrae were excluded if spondylosis, malformation and tumor were observed. This study was approved by the ethical committee of Xinjiang Medical University. All the participants provided written informed consent before participation.

Equipment and materials

Surgical drill with 2.50 mm and 2.70 mm bits, and Kirschner wires (1 mm, 1.5 mm, 2 mm, 2.5 mm and 3.5 mm) were used. Vernier caliper (0.02 mm accuracy) was used for measurement. 4.5 mm titanium alloy pedicle screws (30 and 35 mm long) (Zhengtian Medical Device, Tianjin, China) were used for placement.

Image analysis

Images were analyzed using PACS software (Siemens, Germany) for lumbar isthmus parameters defined below on lateral images (**Figure 2**). S1 was defined as the distance between the tangent points on the lateral edges of isthmus and was measured as shown in **Figure 2B**. The distance between the roots of vertebral arches was defined as S2 and was measured as shown in **Figure 2C**. The distance from the tangent lines of the lateral edges of isthmus to the medial wall of vertebral arches was measured as D1 (**Figure 2D**), which could also be calculated by deducing S1 from S2. D2 was the vertical distance from the line connecting the tangent points to the inferior border of the transverse process (**Figure 2E**). If the inferior border was not horizontal, the inferior border in the end of the accessory processes was used and the vertical distances were measured on both sides and then averaged. Vertical distance from the line connecting the tangent points to 1 mm below the inferior border of the transverse process was defined as D3 (**Figure 2F**), which could be calculated by deducing 1 mm from D2.

Screw placement in anatomical spines

Screws were inserted into the CBTs in six wet and four dry lumbar specimens. The starting

Table 3. Comparison of the isthmus parameters between male and female

Levels	Parameters	Male	Female	F	P (< 0.05)
L1	S1	26.43±0.44	25.60±0.40	0.117	0.000
	S2	22.02±0.50	21.51±0.39	2.815	0.000
	D1	2.21±0.09	2.04±0.11	1.590	0.000
	D2	5.43±0.81	4.57±0.59	9.545	0.000
	D3	4.43±0.81	3.57±0.59	9.545	0.000
L2	S1	27.09±0.46	26.34±0.49	1.086	0.000
	S2	22.36±0.47	21.91±0.36	3.025	0.000
	D1	2.38±0.10	2.22±0.11	1.463	0.000
	D2	6.56±0.92	5.83±0.56	16.897	0.000
	D3	5.56±0.92	4.83±0.56	16.897	0.000
L3	S1	30.18±0.66	29.22±0.66	0.030	0.000
	S2	22.73±0.48	22.38±0.28	16.687	0.000
	D1	3.74±0.28	3.42±0.30	0.233	0.000
	D2	5.45±0.99	5.31±0.70	9.997	0.393
	D3	4.45±0.99	4.31±0.70	9.997	0.393
L4	S1	32.98±0.87	31.39±0.73	4.055	0.000
	S2	23.65±0.63	23.03±0.30	33.188	0.000
	D1	4.66±0.24	4.18±0.30	1.121	0.000
	D2	3.73±0.49	3.60±0.32	16.503	0.071
	D3	2.73±0.49	2.60±0.32	16.503	0.071
L5	S1	42.99±0.78	40.47±0.65	3.704	0.000
	S2	30.86±0.59	29.67±0.51	3.032	0.000
	D1	6.06±0.14	5.40±0.14	0.105	0.000
	D2	2.41±0.39	2.18±0.31	3.479	0.000
	D3	1.41±0.39	1.18±0.31	3.479	0.000

points were determined based on our proposed method, where the x-axis was located D1 from the tangent point to the vertebral midline, and y-axis was located D3 up from the x-axis position (**Figure 2F**). The screws were placed as previous reported (1, 2, 26-31).

CBT assessment

The CBTs were assessed visually, by X-ray examination and CT scanning, and were classified into three grades: grade I, in which the screws were inserted within the pedicle, grade II, in which less than 50% of the screw diameter penetrated into the pedicle and grade III, in which more than 50% of the screw diameter penetrated the pedicle [22]. Grades II and III were considered poorly positioned screws.

Statistical analysis

Data were presented as means ± SD. One-way analysis of variance and the Tukey analysis were performed for statistical comparison and a *P* value of < 0.05 was considered statistically significant. All the data was analyzed using SPSS18.0 statistical software.

Results

Isthmus parameter measurements

To develop a new reference system, we measured the isthmus parameters on the X-ray images of 120 adults and the data are present in in **Tables 1-3**. Analysis showed that D1 increased caudally from L1 to L5; D2 increased from 5 mm in L1 to 6 mm in L2 and then decreased from 6 mm L2 to 2 mm in L5. Analysis showed that females had significant smaller distances in the majority of these distance parameters at all vertebral levels (**Table 3**).

X-ray and CT examinations

Representative CBT screw placements using the new starting points are shown in **Figure 3**. X-ray and CT scans of CBTs were obtained and are shown in **Figures 4-6** for wet and dry spine specimens. 100 CBTs were assessed and classified into three categories (**Table 4**). The successful rates were 88.7% and 95% for the wet and dry samples, respectively. Except for L5 in the wet spines, the successful rates were all over 87%.

Discussion

Isthmus parameter D1

In previous studies, the starting points of lumbar pedicle screws were proposed to be the junction of the center of the superior articular process and 1 mm inferior to the inferior border of the transverse process [1, 2, 12]. As these points may be challenging to be located and inappropriate for patients with severe ossifies, we propose to use a new reference system based on several isthmus parameters, including D1, D2 and D3. Compared with the distance between the traditional starting point to the inferior border of the transverse process, D1 is slightly greater and closer to the midline of the

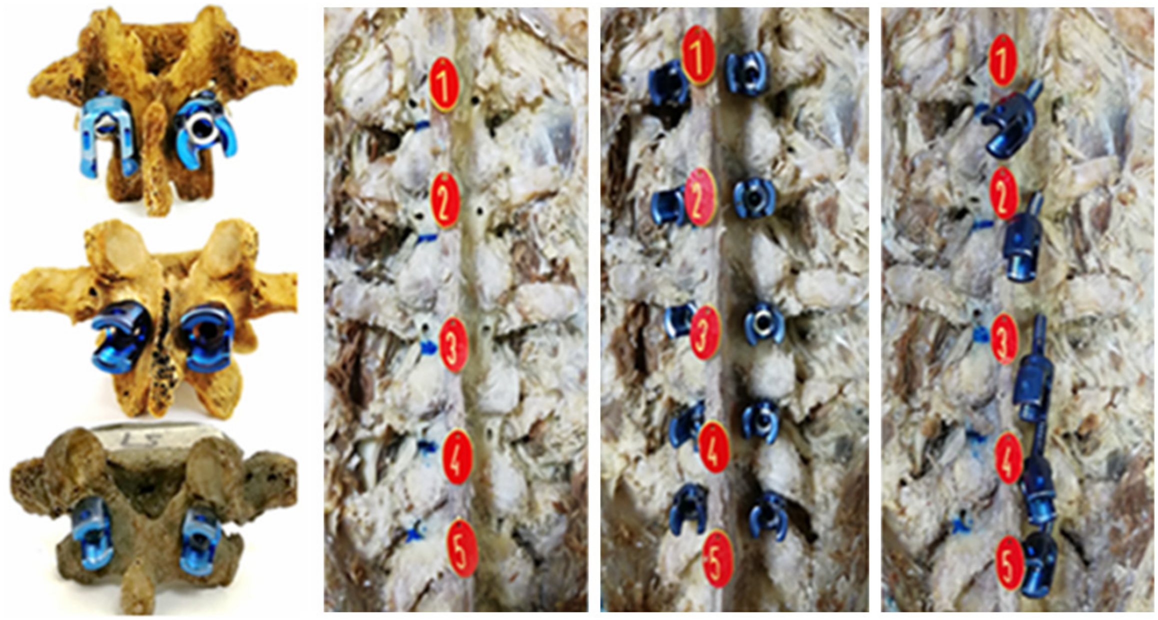


Figure 3. Photos of placement of CTB screws into dry (left) and wet (right) spines at different vertebral levels in lumbar specimens.

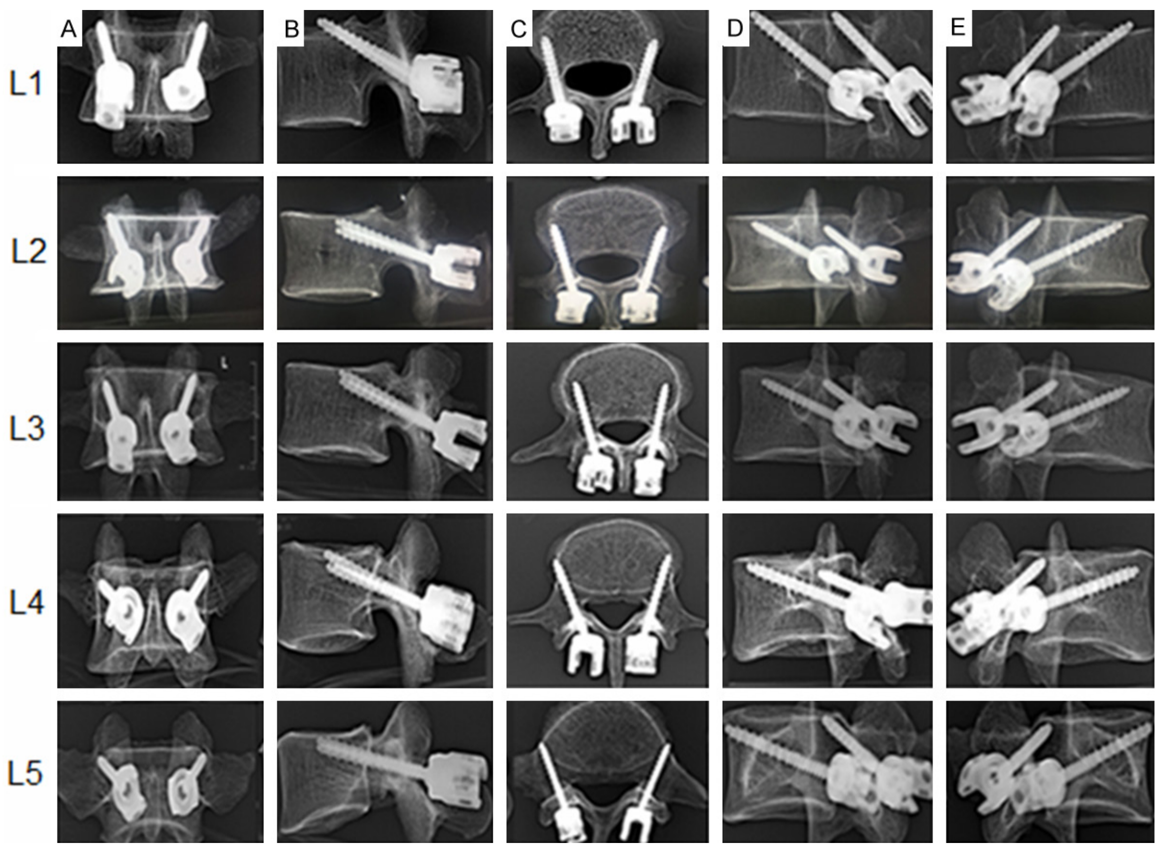


Figure 4. X-rays of placement of CTB screws into dry spines at different vertebral levels. A. Axial, B. Lateral, C. Overlook, D. Right sagittal, E. Left sagittal.

spinous process. It increases from 2 mm in L1 to about 6 mm in L5. These measurements are consistent with previous data [21]. Since the minimal diameter of the screws used clinically

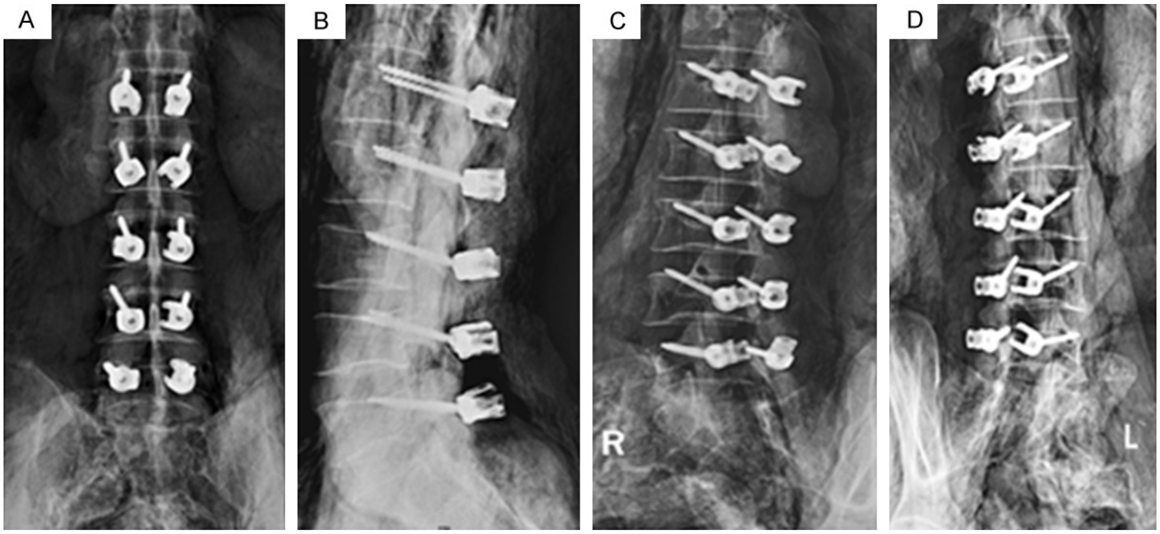


Figure 5. X-rays of placement of CTB screws into wet spines at different vertebral levels. (A) Axial, (B) Lateral, (C) Right sagittal, (D) Left sagittal.

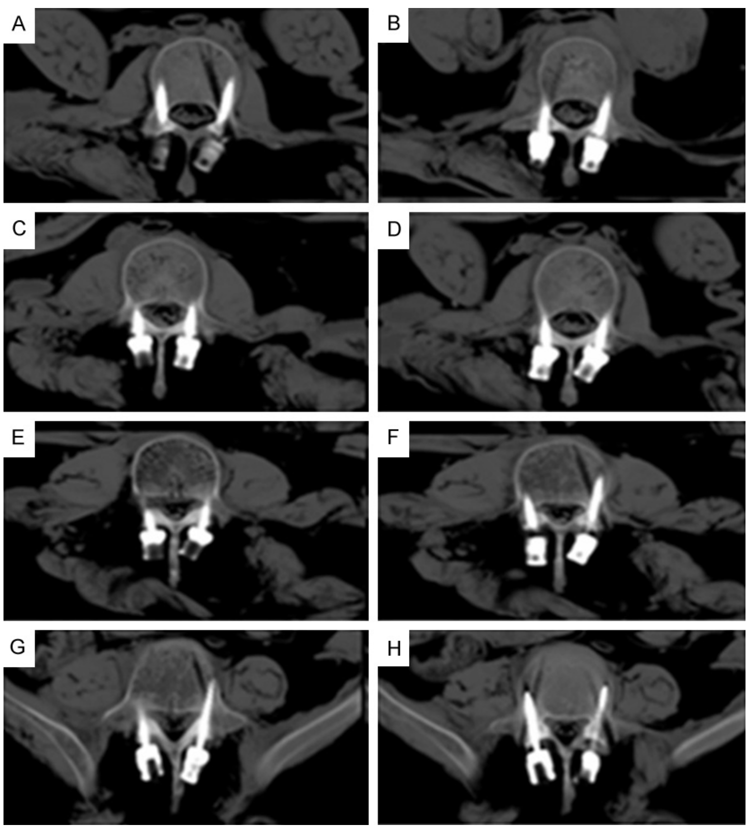


Figure 6. CT images of placement of CTB screws into wet spines at different vertebral levels. A. Left L1; B. Right L2; C. Left L3; D. right L3; E. Left L4; F. Right L4; G. Left L4; H. Right L5.

is 4.5 mm, the actual value of D1 used should not be less than 2.5 mm. Otherwise, it may cause splitting or fracture of the isthmus and desterilize the screw to press the nerve roots. Therefore, if isthmus is narrow and thin, D1 may be set to 2.5 or 3 mm in L1 and L2 vertebra, while the measured D1 may be used for drilling in L3 to L5 vertebra. Based on our assessments, it is safe when D1 is taken between 2.5 to 5.5 mm, but never greater than 6 mm in L5 vertebrae to avoid the screw being inserted into the canalis vertebralis.

Isthmus parameter D2

To use the traditional starting, it is necessary to precisely determine the distance between the starting points and the tangent points in the lateral isthmus. For this, the baseline of the inferior border of the transverse process needs to be accurately located. However, we found that except L1 and L2 vertebra, the inferior borders in other vertebra are often upturned obliquely (**Figure 1**). Particularly, the inferior borders in the L4 and L5 vertebra are often irregularly shaped that makes the horizontal part of the inferior border hard to identify to be used as reference. In our cohort of 120 patients, the

Table 4. Evaluation of CBTs in anatomic spines

Spine Level	I	II	III	Successful rate (%)
Wet				
L1	10	1	1	88.3 (10/12)
L2	11	0	1	91.7 (11/12)
L3	12	0	0	100 (12/12)
L4	11	1	0	91.7 (11/12)
L5	9	2	1	75 (9/12)
Total	53	4	3	88.7 (53/60)
Dry				
L1	7	1	0	87.5 (7/8)
L2	7	1	0	87.5 (7/8)
L3	8	0	0	100 (8/8)
L4	8	0	0	100 (8/8)
L5	8	0	0	100 (8/8)
Total	38	2	0	95 (38/40)

inferior borders were considerably variable and upwarded >5° in 3.3% (L1), 5% (L2), 21.6% (L3), 72.5% (L4) and 51.7% (L5), respectively. As a result, transverse processes in L1 and L2 are shorter and straight, in L3 is longer and relatively straight, but in L4 and L5 are often irregularly shaped.

Since the inferior border is morphologically variable, inaccurate identification of the inferior border would result in the insertion of the screws above or below the desirable starting points, or complications such as nerve injury due to the entering of screw into the intervertebral foramen. To avoid this, it was proposed to determine the superior margin of the intervertebral foramen using lateral fluoroscopy as reference points to accurately position the screw insertion points [13]. However, since the accessory process near the base of transverse process is connected to the lumbar vertebra, it can be used as measurement reference when the inferior border is difficult to locate (**Figure 2E**, **2F**). As an important anatomical feature, the end of accessory process is often within 1 to 2 mm to the inferior border of the transverse process. The junction of the inferior borders of the transverse process and pedicle is where the intervertebral foramen is located, and the end of accessory process is at the superior margin of the intervertebral foramen in lateral fluoroscopy. Therefore, we believe that the accessory process is a reliable anatomical marker and measurement baseline, which can be applied irrespective of the variability of transverse process.

On X-ray images, except at L3 level, D2 was significantly different between males and females, particularly in the upper vertebra, while in the lower vertebra, the difference was less than 1 mm between genders. On average, D2 increased from L1 to L2 and then decreased from L2 to L5.

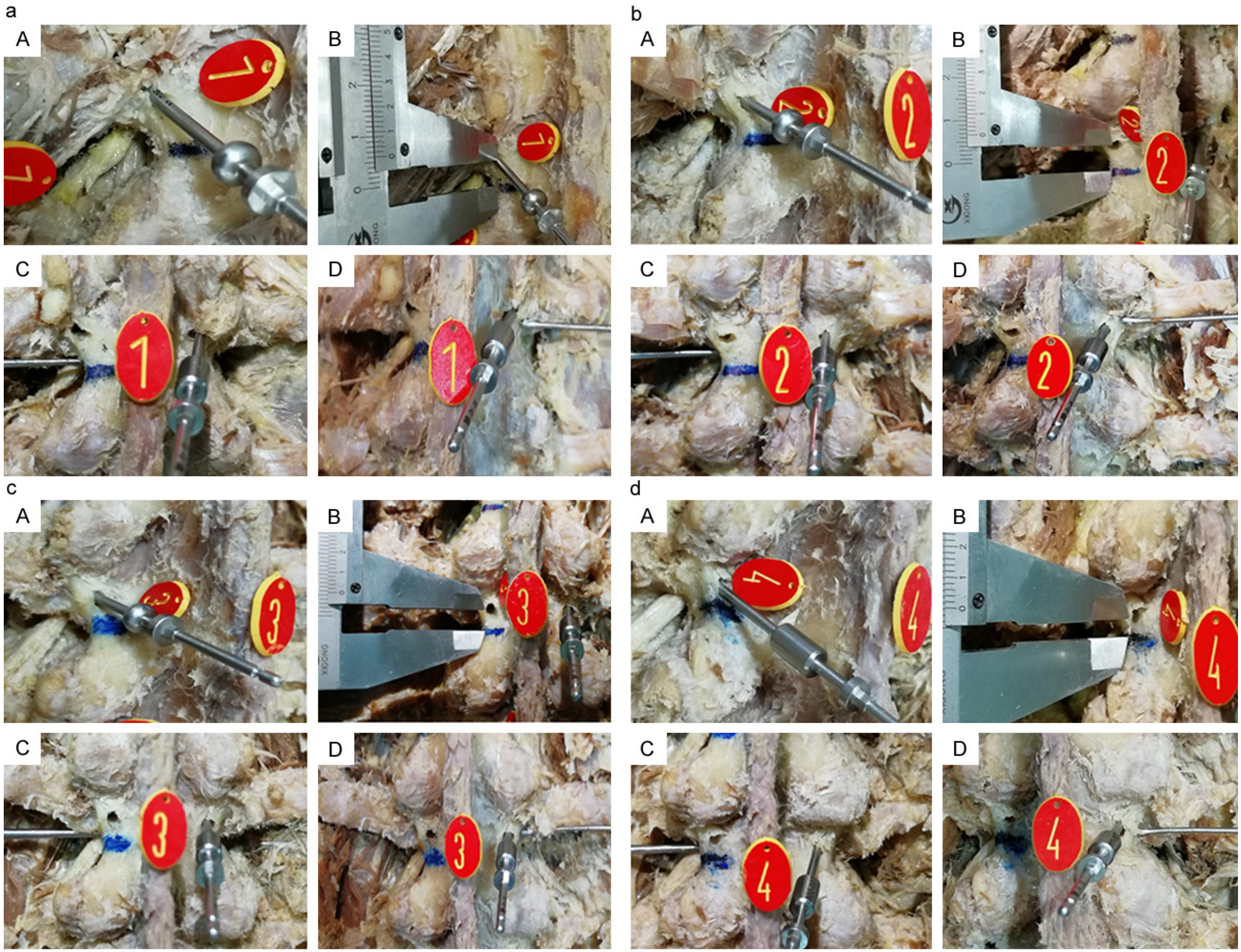
Isthmus parameter D3

D3 can be calculated based on D2, and is therefore a reflection of D2. We propose to use this as a reference for the starting point of screw. Compared with the traditional point, the new starting point has the same position on the vertical axis with different anatomical marker, is D3 mm over the tangent point of isthmus lateral border, instead of 1 mm below the baseline of the inferior border of the transverse process (traditional method). Since the lateral border is used as reference instead of inferior border, it is more symmetrical on the left and right sides and the tangent points on both sides are basically located on a straight line, making the operation more practical, less invasive and more convenient.

Relationship between the proposed starting points and anatomical structures

We tested the new reference system in the screw placement. The vertical axis of starting points was located cephalad D3 mm from the isthmus tangent point, while the horizontal axis position was determined based on D1 value. The cross point of the vertical axis and horizontal axis inside the lateral border of isthmus was selected as the starting point for the screws (**Figure 2F**). As such, the starting point is located obliquely above the adjacent nerve root, while the isthmus tangent points are below the nerve root (**Figure 7A**). The bone cortex between the screw and lateral border of the isthmus is relatively thin in L1 and L2 using traditional CBT and might lead to bone fracture. However, since D1 is slightly greater, we did not find such complications during placement using the novel starting point.

The distances between the tangent points and the starting points equal to D3 (**Figure 7B**), which also increased from L1 to L2 and then decreased from L2 to L5, as in case of D2. The distance between the starting point and the superior margin of the intervertebral foramen was relatively greater (**Figure 7C**) and the start-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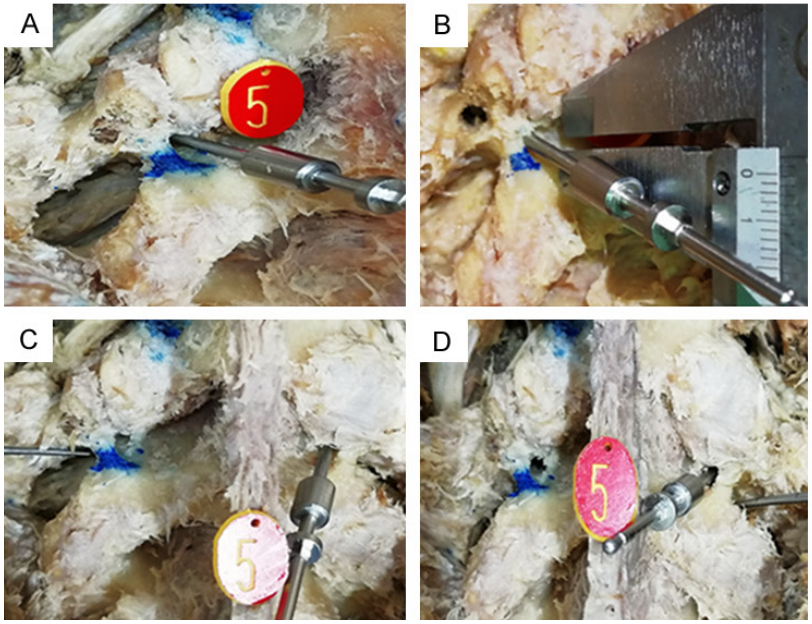

Figure 7. a. Relationship between cortical screw starting point and the adjacent anatomical structures at L1. b. Relationship between cortical screw starting point and the adjacent anatomical structures at L2. c. Relationship between cortical screw starting point and the adjacent anatomical structures at L3. d. Relationship between cortical screw starting point and the adjacent anatomical structures at L4. e. Relationship between cortical screw starting point and the adjacent anatomical structures at L5. A. Relative to tangent points and nerve root; B. Relative to tangent points; C. Relative to intervertebral foramen; D. Relative to the inferior borders of the transverse process.

ing point was 1 mm below or parallel to the baseline connecting the inferior borders of the transverse process (**Figure 7D**). These relationships are consistent at different vertebral levels. If the sagittal and the horizontal planes of the screw are properly controlled, the starting points are relatively safe and unlikely to damage the nerve roots.

CBT screws are inserted with a 25° cephalad angle from the sagittal plane and 10° outward angle from the horizontal plane [1-3, 10, 21]. Although D1 we used is closer to the midline, due to the outward angle, CBT is gradually away from the medial wall of the pedicle and the nerve root during fixation. For example, when the screw reached the medial wall after diagonally advancing 7 and 10 mm in the isthmus bone or lamina in L1 and L5, it just touched the bone in the medial wall of vertebral arch but did not break the medial wall when reaching the pedicle medial wall. This would further increase the holding force between the screw and the cortical bone. On the sagittal plane, it is necessary and safe to shift a caudocephalad distance of D3 from the baseline of the isthmus tangent point to avoid nerve injury. Longitudinally, this position is the same as the traditional starting point. Imaging assessment of 100 CBTs showed that successful rates were 88.7 (53/60) and 95% (38/40) for the six wet and 4 intact dry lumbar spine specimens, respectively, indicating that the new starting points for CBT screw placement are effective, less invasive, safe, accurate and practical. Using this CBT technique, transverse process does not need to be fully exposed and incision is smaller just to expose the lateral edge of pars interarticularis. Also, it is not affected by articular degeneration in the lumbar facet and morphological variation in the transverse process.

Conclusion

D1 tends to increase from 2 mm in L1 to 5.5 mm in L5 and is variable among individuals. Based on the diameter of CBT screw, D1 in L1 and L2 may be set at 2.5 mm or 3 mm to avoid isthmus splitting during placement. From L3, measured D1 should be used, but should not be more than 6 mm for L5.

D2 increases from L1 to L2, and then decreases from L2 to L5. D3 is calculated from D2 (D2-1 mm), and is therefore a function of D2. These parameters are significantly different between genders except in L3.

With our new system, CBT screws can be placed using these parameters just by exposing the lateral edge of isthmus, without need to expose the whole transverse process and the start points are not affected by articular degeneration in lumbar facet and morphological variation in the transverse process. Our data show that the technique is safer, less invasive, and easier to operate. It would help reduce bleeding, intraoperative x-ray exposure and surgical time.

Disclosure of conflict of interest

None.

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