SCIENTIFIC ARTICLE

Anatomy and Imaging Studies on Cortical Bone Screw Freehand Placement Applying Anatomical Targeting Technology

Paerhati Rexiti, MD[1], Ailixier Aierken, MD[2], Aierken Sadeer, MD[1], Shuiquan Wang[3], Nueraihemaiti Abuduwali, MD[4], Qiang Deng, MD[1], Wei-bin Sheng, MD[1], Hai-long Guo, MD[1]

Department of [1]Spine Surgery and [4]Imaging Center, The First Affiliated Hospital of Xinjiang Medical University, [2]Department of Spine Surgery, The Sixth Affiliated Hospital of Xinjiang Medical University and [3]Department of Anatomy, College of Basic Medicine, Xinjiang Medical University, Ürümqi, China

Objectives: A series of constant anatomical structures were used as guide targets for screw placement to improve the accuracy of cortical screw placement and reduce surgical injury and fluoroscopy radiation. The most commonly used angles and distances between the cortical bone screw insertion point and the lateral margins of the isthmus were selected as the contents of the questionnaire.

Methods: A total of 40 physicians were selected to determine the specific values for each angle and distance. Screw placements were performed on four dry and six wet lumbar spine specimens according to the proposed anatomical target guidance technique. A total of 100 cortical bone trajectories were evaluated using X-ray and CT scanning of the specimens to verify the practicability, accuracy, and safety of the anatomical target guidance technique in screw placement.

Results: The average deviation rates for angle and distance determination were 105.5% and 14.33%, respectively, indicating a significant difference between the estimated and actual values from other angles ($P < 0.05$). Based on visual inspection, probe penetration, X-ray, and CT examination of 100 cortical bone trajectories, the excellent rate of 40 trajectories on four dry specimens was 95%, while that of 60 trajectories on six wet specimens was 88.7%.

Conclusion: Use of lumbar constant anatomical structures as targeting guidance could assist cortical bone screw placement and reduce surgical damage.

Key words: Accessory process crest; Cortical bone trajectory; Lateral margin of Isthmus; Transverse process

Introduction

Cortical bone trajectory (CBT) is a method for screw placement that was proposed in 2009[1]. CBT utilizes the screw path at 25° and 10° on the sagittal and horizontal planes, respectively, instead of the long axis of the pedicle used in the traditional method. With the utilization of the standard CBT method and accurate placement direction, the screw track will gradually move away from the nerve roots to avoid nerve damage. CBT increases the contact surface between the screw and the cortical bone, ensuring that the screw is tightly surrounded by dense cortical bone[2–6]. Therefore, CBT ensures that the screw is fixed on the cortical bone lateral wall of the pedicle. This enhances the pullout resistance of the screw and increases the screw holding force 1.7-fold compared with that of the traditional trajectory[7–11]. However, the insertion point of the cortical bone screw for this technique is closer to the spinal canal and nerves than that of the traditional trajectory. Therefore, the neighboring

Address for correspondence Hai-long Guo, MD, Department of Spine Surgery, The First Affiliated Hospital of Xinjiang Medical University, No. 137 South Liyushan Road, Urumqi, Xinjiang Uygur Autonomous Region, China 830054 Tel: +86-18699184664; Fax: +86-0991-4365444; Email: guohailong@tom.com.
Grant Sources: This study was supported by the Natural Science Foundation of Xinjiang Uygur Autonomous Region (Grant No. 2016D01C290).
Disclosure: The authors declare no conflict of interest.
Received 8 June 2020; accepted 11 July 2020

nerve tissue is easily damaged following the insertion of the screw at an incorrect angle.

Traditional insertion of the screw often relies on the subjective experience of the surgeon, intraoperative X-ray examination, and classical reference angles to determine the orientation of the screw placement. However, the position, posture, and screw insertion point of the patient during surgery affect the angle of placement. Notably, clinical orthopaedic surgeons often misjudge the angle of placement.

In this study, the principle of traditional pedicle screw placement[12] and angle control of the digital navigation device system were used to assist the insertion of the CBT screw. The aim of this approach was to better define the screw insertion point, and to improve the freehand screw placement technology and success rates of surgeries. During the insertion, spinal intrinsic anatomical landmarks visually observed by operators were also set as orientation targets to guide the insertion process. The relationship between the insertion point and landmarks was determined to minimize the number of intraoperative fluoroscopy examinations, shorten operative time, and reduce the occurrence of complications.

Methods

Specimen Selection

Forty doctors, including attending physicians and senior physicians from the orthopaedic center of our hospital, were included in this questionnaire survey. Four complete lumbar dry specimens (randomly selected from 25 dry specimens) and six lumbar wet specimens were selected for screw insertion and CBT evaluation. All samples were collected from the Department of Anatomy, Xinjiang Medical University (Urumqi, China). This study was approved by the ethics committee of our institution.

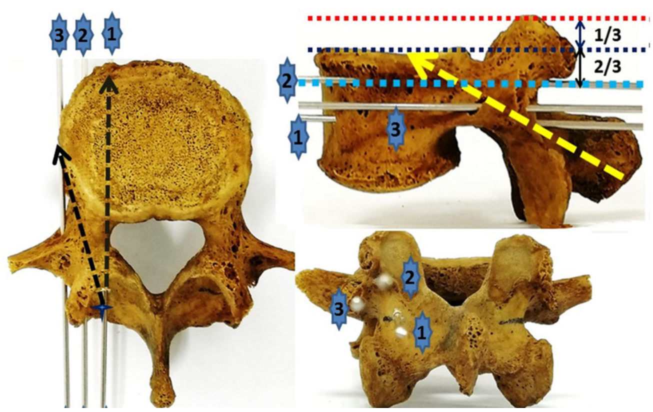

Fig. 1 Diagram of screw placement. 1. Screw insertion point of the cortical bone in the isthmus. 2. The sagittal angle of the screw was determined using the vertex of the "∧" shape crest and horizontal line of the upper one-third of the facet joint (the sagittal angle was determined using the vertex of the "∧" shape crest and the horizontal line of the upper half of the facet joint at the L_5 segment). 3. The abduction angle of the screw was determined using the vertex of the "∧" shape crest and the tail of the accessory process.

Imaging Instruments

A Hitachi 500 mA DR X-ray machine (Tokyo, Japan), Siemens CT system (Berlin, Germany), and PACS image software system provided by the Image Center of our hospital were used in this study.

Questionnaire Survey

The three most commonly used angles of the lumbar pedicle screws and cortical bone screw placements (i.e. 5°, 10°, and 20°) and the distances between the cortical bone screw insertion point and the side margins of the isthmus (i.e. 2, 4, and 6 mm) were selected as the contents of the questionnaire (Supplementary Fig. S1), as previously reported[12]. A total of 40 physicians in the orthopaedic center were selected to determine the specific values for each angle and distance drawn, requiring a maximum accuracy deviation of 1° or 1 mm, respectively. The degree of deviation based on recorded data (i.e. distance and angle collected from the questionnaire) was calculated to determine the accuracy of judgments, followed by statistical analysis:

$$\text{Deviation degree} = \frac{\text{Actual value} - \text{Measured value}}{\text{Actual value}} \times 100\%$$

Screw Placement in Anatomical Specimens

Isthmus parameters, including D1[12], D2, and D3, were introduced into the process of screw placement. The D2 value was measured as the vertical distance between the line connecting the vertexes of the isthmus and the inferior border of the transverse process. The anatomical specimen lumbar isthmus parameter (D3) was obtained as D2–1 mm. CBT placements were conducted on six wet specimens according to the average value of each parameter measured on the collected 25 dry specimens. Of note, screw placement on the four dry specimens, which were randomly selected from the 25 dry specimens, could be directly observed by the naked eye. The lumbar isthmus tangent point was taken as a benchmark. Subsequently, the D3 value was longitudinally shifted toward the head side to obtain the vertical axis of the cortical screw insertion point when determining the screw insertion. The horizontal axis of the screw insertion point was confirmed by referring to the D1 value[12] of the lateral border of the isthmus. The position at which the vertical axis and horizontal axis intersect at the inside border of the isthmus was regarded as the cortical screw insertion point[13,14].

Without the aid of an X-ray machine, four dry specimens and six lumbar wet specimens were selected for cortical bone screw placement through the anatomical structure targeting technique: the sagittal angle of the screw was in accordance with the inferior border of the spinous process, the "∧" shape crest, and the horizontal line of the upper one-third of the superior articular process. The abduction angle of the screw refers to the lateral border of the isthmus, the "∧" shape crest, and the tail of the accessory process (Fig. 1). The obtained 100 trajectories were evaluated through visual observation, probe penetration, X-ray examinations, and CT scans. The evaluation criteria were scored as follows: level I, all the screws in the pedicle; level II, <50% of the screw diameter penetrated the pedicle; and level III, >50% of the screw diameter penetrated the pedicle. Levels II and III were regarded as negative screw positions.

Statistical Analysis

A paired *t*-test was used for the comparison between the estimated and actual values of the angle. A $P < 0.05$ denoted statistically significant difference. The results of screw insertion in dry and wet anatomical specimens were statistically analyzed based on excellent rates.

Results

Distance and Angle Assessment

As shown in our previous study (Table 1)[12], the mean deviation degree of the angle (105.5%) determined by the orthopaedic clinician was significantly higher than the average deviation degree of distance (14.33%). These findings indicated that the accurate determination of distance was easier. There was no statistical difference between the clinician's value for the "distance 2" value (minimum distance: 2 mm) and the actual value ($P = 0.058$). However, for the other angles or distance, there were extremely significant differences between the estimated and actual values ($P < 0.001$), except for "distance 1" ($P = 0.003$).

X-Ray and CT Results of Screw Placement in Anatomical Specimens

The results of X-ray and CT scans conducted after screw insertion on the selected four dry and six wet lumbar spine specimens are presented in Figs 2, 3, and 4, derived from our previously published articles[13,14].

In the process of insertion, the screw successively passed through the cortical of the isthmus, the cortical of the pedicle inner wall, and the cortical of the pedicle lateral wall, finally reaching the vertebral lateral cortical bone of the vertebral body or the vertebral endplate[2]. According to the criteria proposed by Xu *et al.*[15], a total of 100 cortical bone tracts of the four dry and six wet specimens were visually observed, probed, and evaluated through X-ray and CT examinations. The results are summarized in Table 2. The excellent rates in dry and wet specimens were 95% (38/40) and 88.7% (53/60), respectively, showing good performance of screw placement.

Discussion

This study set a series of different constant anatomical structures or landmarks as targeting references for intraoperative screw placement to accurately control the direction of the screw, reduce the damage of nerves and other adjacent structures, reduce the duration and dose of X-ray examination, and reduce the operation time and bleeding. The distance and angle between these anatomical targeting references and entry points are constant and will not be affected by changes in the posture of the patient. At the beginning, middle, and end of the cortical bone screw placement process, the researchers set targets to ensure that the screw passed through each targeting reference to achieve appropriate placement. Following the insertion of the screw in dry and wet specimens through the proposed method, the excellent rates of the targeting reference based on constant anatomical landmarks showed that this approach could improve the accuracy of screw insertion.

Questionnaire Analysis of Distance-Angle Judgment

According to the statistical analysis, we observed that smaller values for the distance and larger values for the angle were associated with more accurate decisions by the physicians. Because distance is more commonly used in clinical practice than the angle, the judgment of distance is more accurate than that of the angle. Therefore, when judging the screw insertion angle during a surgical operation, the distance parameter is more reliable and it is easier for the operator to control the process of screw placement. The lumbar osseous structure and the distance between the screw and the adjacent nerves or blood vessels yielded small values, suggesting that the use of the distance parameter may improve the precision and safety of clinical screw placement compated to the application of angle references. Parameter D1 assisted in controlling the horizontal angle of the traditional pedicle screw placement and determining the insertion point of cortical bone

TABLE 1 "Distance–angle" questionnaire study (Mean ± SD)

Parameter	Estimated value	Actual value	Deviation degree (%)	*F*	*P*-value	Significance (Y/N)
Angle 1	21.58 ± 7.85	10.00 ± 0.00	115.80	128.346	0.000	Y
Angle 2	11.22 ± 5.35	5.00 ± 0.00	124.40	101.074	0.000	Y
Angle 3	35.26 ± 8.97	20.00 ± 0.00	76.30	121.126	0.000	Y
Distance 1	4.56 ± 1.24	4.00 ± 0.00	14.00	82.056	0.003	Y
Distance 2	2.20 ± 0.72	2.00 ± 0.00	10.00	93.391	0.058	N
Distance 3	7.14 ± 2.11	6.00 ± 0.00	19.00	130.534	0.000	Y

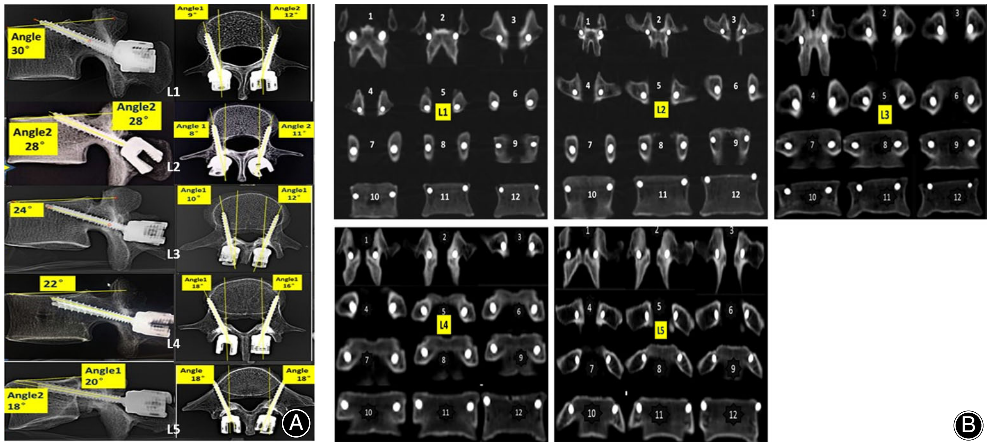

Fig. 2 (A) X-ray examination of screw insertion from L_1 to L_5 segments on an anatomical lumbar spine specimen; (B) CT examination of screw insertion from L_1 to L_5 segments on a dry anatomical specimen. 1–12: CT layer-by-layer scanning from the back to the front of the vertebral body. The figure is taken from an article previously published by the author[13]: Rexiti P, Aierken G, Wang S, et al. Anatomical research on strength of screw track fixation in novel cortical bone trajectory for osteoporosis lumbar spine. Am J Transl Res, 2019; 11: 6850–6859.

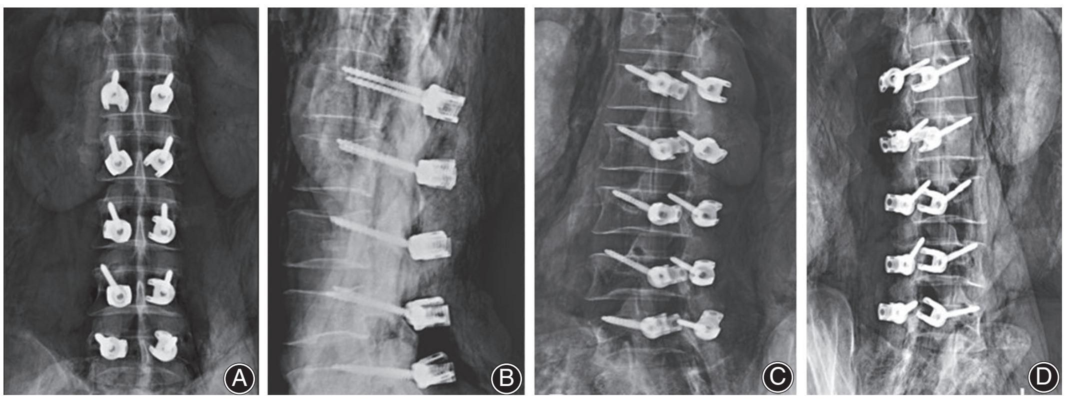

Fig. 3 X-ray examination of the placement of cortical bone trajectory (CBT) screws into wet specimens at different vertebral levels: (A) axial; (B) lateral; (C) right sagittal; and (D) left sagittal. The figure is taken from an article previously published by the author[14]: Rexiti P, Abudurexiti T, Abuduwali N, Wang S, Sheng W. Measurement of lumbar isthmus parameters for novel starting points for cortical bone trajectory screws using computed radiography. Am J Transl Res 2018; 10: 2413–2423.

screws, thereby playing a guiding role in these different internal fixation systems[12].

Cortical Screw Placement on the Sagittal Plane by Anatomy Targeting Guidance

On the sagittal plane, the direction of the cortex screw should be approximately 25° to allow the screw to move from the inferior wall to the lateral wall of the pedicle, and finally terminate at the lateral border of the vertebral endplate[8, 10, 11, 16, 17]. Zdeblick *et al.* stated that the torsion of screws into bone could be used to predict failure of the bone–screw interface[18]. The most important factor affecting the judgment of torque is the length of the cortical bone screw in the lamina; that is, the bone distance from the insertion point to the point where the isthmus and pedicle arch the undercut junction[19]. Therefore, the ideal trajectory in the sagittal plane is angulated cranially by 25°–30° along the inferior border of the pedicle and terminates in the curvature of the vertebral body wall, which corresponds to the region from the posterior third to the posterior half of the superior endplate[19].

According to a previous study, the insertion point of the cortical bone screw should be adjusted downwards to increase the cephalad angle[19]. This approach increases the length of the cortical bone screw to stick to the bone-dense part of the arch undercut junction. However, adjusting the insertion point downward from the classic position will shorten the distance between the screw and the nerve root of the intervertebral foramen. The lateral border of the isthmus

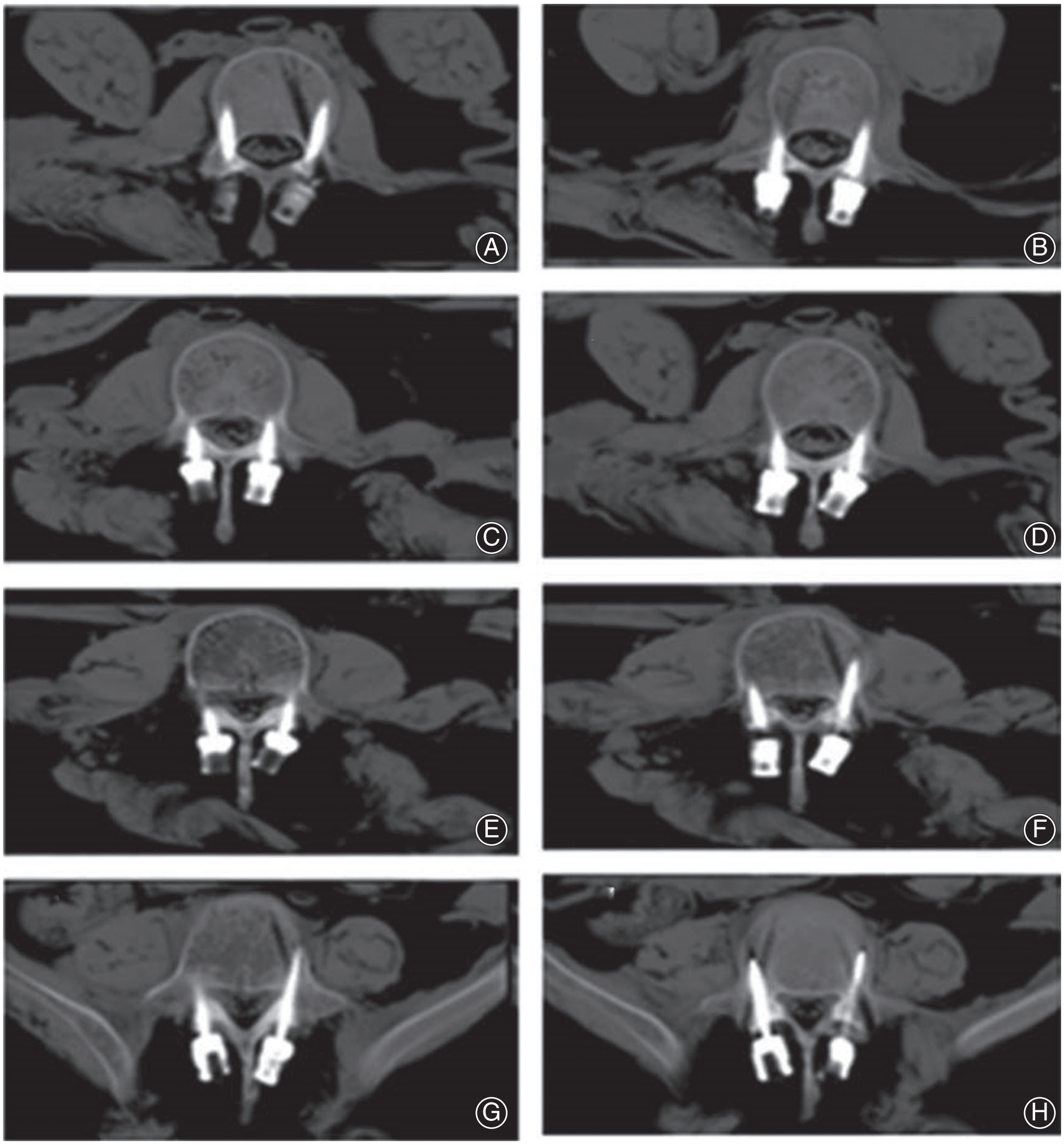

Fig. 4 CT images of the placement of cortical bone trajectory (CBT) screws into wet spines at different vertebral levels: (A) left L_1; (B) right L_2; (C) left L_3; (D) right L_3; (E) left L_4; (F) right L_4; (G) left L_5; and (H) right L_5. The figure is taken from an article previously published by the author[14]: Rexiti P, Abudurexiti T, Abuduwali N, Wang S, Sheng W. Measurement of lumbar isthmus parameters for novel starting points for cortical bone trajectory screws using computed radiography. Am J Transl Res 2018; 10: 2413–2423.

TABLE 2 Evaluation of anatomical specimens screw placement

Specimen type	I	II	III	Excellent rate (%)
Dry (*n* = 40)	38	2	0	95
Wet (*n* = 60)	53	4	3	88.7

is a curved surface; hence, considering the downward movement of the screw insertion from the classical or traditional point, the distance between the border of the screw and the lateral border of the isthmus is reduced, increasing the difficulty of screw placement (Fig. 5, taken from our previously published article[14]). If the screw position is excessively low and the screw insertion angle is excessively large, the risk of cleavage of the lateral border of the isthmus increases, further reducing the torque or holding force of the screw and stressing the nerve root. Therefore, the surgeon must carefully consider the relationships among the screw placement angle, the insertion point, the screw holding force, and the nerve injury to prevent damaging the nerve root. This is the most important factor for the operator to focus on.

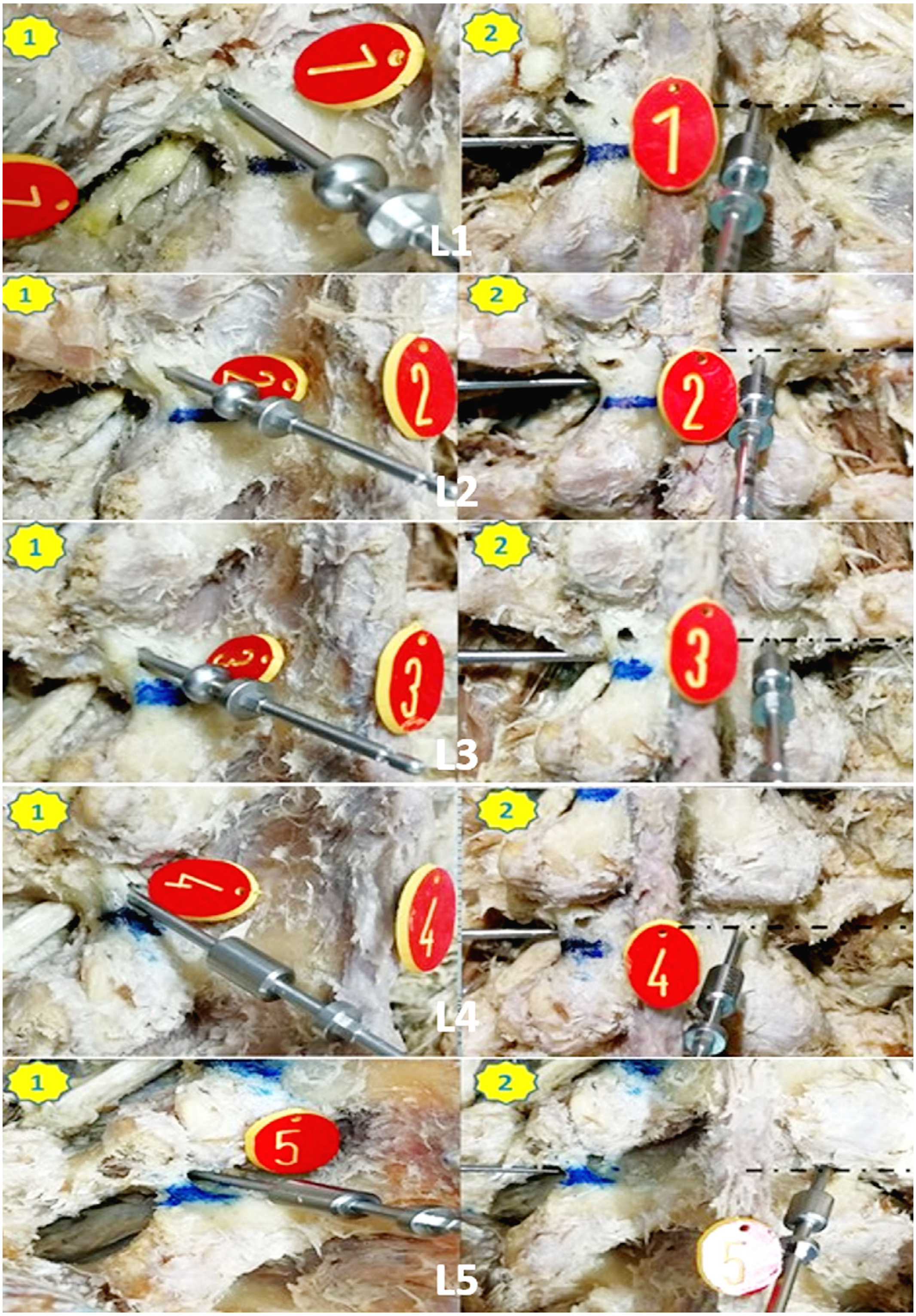

Fig. 5 Relationship between the insertion point of the cortical screw and the highest point of the inferior borders of the transverse process, nerve root, and intervertebral foramen from L_1 to L_5 segments. The figure is taken from an article previously published by the author[14]: Rexiti P, Abudurexiti T, Abuduwali N, Wang S, Sheng W. Measurement of lumbar isthmus parameters for novel starting points for cortical bone trajectory screws using computed radiography. Am J Transl Res 2018; 10: 2413–2423.

Based on the experience of screw placements in anatomical specimens and previous clinical cases, the researchers suggested that the sagittal plane starting angle of the cortical bone screws should follow the anatomical or mechanical direction of the trabecular bone direction of the isthmus (i.e. from the spinous processes of the vertebral bodies to the pedicles and, finally, to the upper endplate of the vertebral body) (Fig. 6A). The shape of the vertebrae trabecular is arranged in three directions according to the direction of the force line[20]. The lower border of the pedicle is the point at which the three bundles of trabecular bone intersect, explaining the greater bone density compared to other parts.

The direction of one of the force lines of the trabecular bone is precisely from the lower border of the spinous process of the lumbar spine to the superior endplate of the vertebral body through the isthmus and pedicle of the lumbar spine. Therefore, when confirming the sagittal plane angle of the cortical bone screw, only the direction of the lower border of the spinous process is required as a reference of screw placement to improve the rigidity of the trajectory.

Different anatomical references were proposed in this study to more accurately grasp the direction of screw placement. Because the length of the cortical screw is 35–40 mm, we advise using 11–13 mm as a distance unit in the screw placement, which is further considered the standard for depth judgment (Fig. 6A).

At the initiation stage of screw placement (initial 11–13 mm, point 1 in Fig. 6A), the angle of screw insertion was determined according to the tangential line of the lower spinous process and the direction of the isthmus bone surface. The vertex point of the "∧" shape crest as a medial targeting reference, the horizontal line of the upper one-third of the superior articular process of the final targeting, and the structure from the start targeting to the end ought to be put in a straight line to prevent injury to the nerve roots.

At the middle stage of the screw placement, the screw passes through the center of the pedicle (point 2 in Fig. 6A). Ebraheim *et al.*[21] found that the anatomical centers of the longitudinal axis of the lumbar pedicle were actually higher than those of the central axis of the transverse process. The pedicle central points of the L_1, L_2, and L_3 segments were located at 3.9, 2.8, and 1.4 mm above the central axis of the transverse processes, respectively. The pedicle center point of the L_4 and L_5 segments was only 0.5 and 1.5 mm below the central axis of the transverse process. In the present study, researchers noted that the center of the pedicle longitudinal axis (calculated from the midline of the transverse process) was

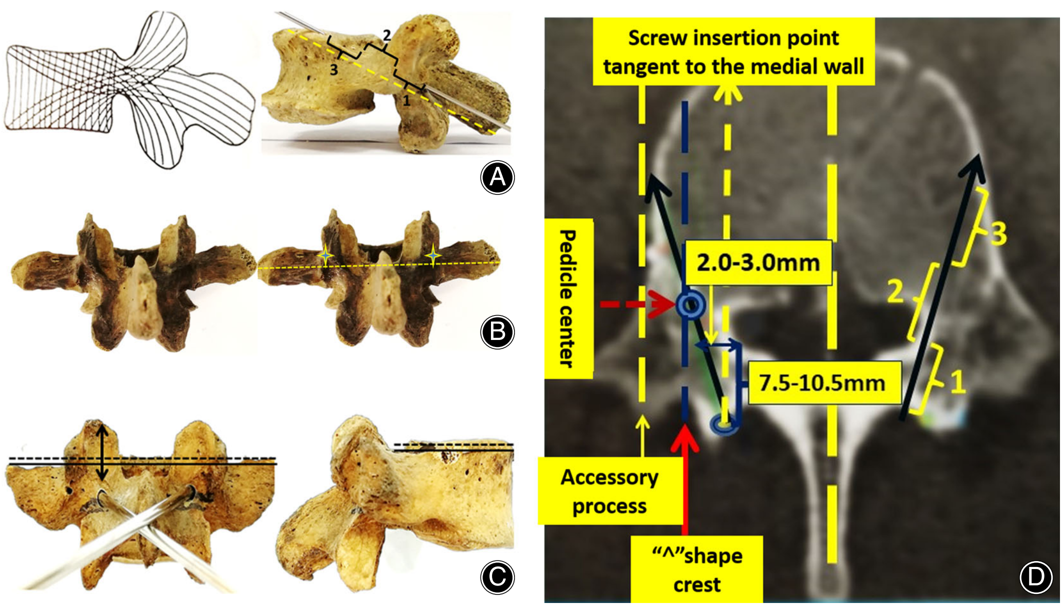

Fig. 6 (A) Diagram of the anatomical or mechanical direction of the isthmus trabecular bone direction. 1. The initiation stage of the screw placement. 2. The middle stage of the screw placement. 3. The final stage of the screw placement. (B) The anatomical relationship between the levels of the midline of the transverse process. The vertex point of the "∧" shape crest and the center of the pedicle longitudinal axis; the asterisk represents the vertex of the "∧" shape crest and the center of the pedicle longitudinal axis. (C) The relationship between the upper border of the pedicle, upper endplate surface, and midline of the long axis of the articular facet joint in the L_5 segment. The dashed line represents the upper endplate surface and midline of the long axis of the articular facet joint, while the solid line represents the upper border of the pedicle. (D) The relationship between screw placement and constant anatomical structure. During the screw placement, the head of the screw was displaced by 2–3 mm when it reached the spinal canal (7.5–10.5 mm: L_1 to L_5 cortical bone screws into the nail at the isthmus), failing to enter into the spinal canal and merely being tangential to the internal wall of the pedicle.

approximately equal to the vertex point of the "∧" shape crest at the same horizontal line (Fig. 6B).

As shown in Fig. 6A, with the screw placement method based on anatomical landmarks, screws passed through the center of the pedicle (except for the L_5 pedicle, Fig. 2B) and moved outward. Owing to the special shape of the L_5 vertebral pedicle, within the L_5 pedicle, the cortical bone screw moved close to the cortical bone of the inner and outer walls, which had more holding force. However, it did not pass through the center of the L_5 pedicle (Fig. 2B).

In the final stage of the placement (point 3 in Fig. 6A), the final direction of the cortical bone screw is toward the upper endplate of the lumbar vertebral body (i.e. horizontally toward the lower border of the superior intervertebral space). The position of the general intervertebral space is in the middle and upper one-third of the facet joint in the upper lumbar spine. However, the level of the upper border of the L_5 pedicle is basically the same as that of the upper endplate. The position of the intervertebral space in L_5 is the position of the middle and upper half of the facet joint (Fig. 6C). Correspondingly, the cephalad angle of the coronal screw at the L_5 segment should be moderately reduced (Fig. 2A).

Cortical Screw Placement on the Horizontal Plane Through Anatomy Targeting Guidance

The horizontal plane is more directly related to nerve damage compared with the sagittal plane. If the screw insertion points of the isthmus are excessively inward, the horizontal angle of the screw should be increased. Otherwise, the screw may enter the spinal canal, damaging the cauda equina and nerve roots.

Based on the screw placement experience of specimens and previous clinical cases, we propose that the carrying angle of the cortical bone screws during operations should be adjusted according to each lumbar vertebral body but not standardized to the 10° mentioned in the literature[12–18]. We recommend that the angles of L_1 and L_2 in the upper lumbar spine be controlled at approximately 10°; the angle of L_3 should be 10°–15°, and those of L_4 and L_5 should be 15°–20° (Fig. 2A).

The different anatomical targeting guidance techniques proposed in this study are applicable to determine the angle of the horizontal plane. In the initial stage of screw insertion, the lateral border of the isthmus cortical bone is the anatomical structure for the angle judgment (① in Fig. 6D). After opening the hole in the cortical bone, the opener is used to press the lower border of the spinous process and control the direction to the lateral vertebral body along the curved surface of the isthmus. The spinous process can be pressed laterally in the lower lumbar spine to ensure that the screw enters the isthmus cortical bone along the mentioned direction for obtaining a greater abduction angle. If the screw orientation is blocked by a thick spinous process in the lower lumbar spine, the thicker bony cortex of the spinous process can be skived by 2–3 mm or even excised.

During the middle stage of screw placement, the head of the screw has passed through the isthmus bone and entered the pedicle bone following the cortical bone of the pedicle inner wall. The screw passes through the midpoint of the transverse axis of the pedicle (except for the L_5 segment) and continues to terminate to the lateral wall of the pedicle (② in Fig. 6D). At this stage, the surgeon should use the sagittal plane passing through the vertex point of the "∧" shape crest as the anatomical projection of the lateral pedicle cortex to guide the screws safely through the pedicles and as close as possible to their median or lateral cortical bone without piercing (Fig. 2B).

At the final stage of screw insertion, the head of the screw has entered the vertebral body bone (③ in Fig. 6D) and continues to enter the lateral border of the upper endplate of the vertebral body. The authors used the sagittal plane of the tail of the accessory process as the boundary of the cortical bone of the lumbar spine lateral border to control the final position of the screw (Fig. 1).

In summary, a series of lumbar constant anatomical structures or landmarks were used as targeting reference for assisting cortical bone screw placement to achieve accurate and safe placement on the basis of classical theoretical angles for placement. In the initial, middle, and final stages of screw placement, the sagittal angle of the screw was in accordance with the tangent line of the lower border of the spinal process, the vertex point of the "∧" shape crest, and the horizontal line of the upper one-third of the superior articular process. Of note, the horizontal plane angle refers to the lateral border of the isthmus, the vertex point of the "∧" shape crest (the same important as horizontal plane mentioned above) and tail of the accessory process crest. During insertion, the screw was placed close to the bone cortex from the subpedicle, through the center of the pedicle, to the cortical bone on the vertebral upper endplate. Similar to the intraoperative digital navigation device, the proposed method refers to the anatomical targets, constantly corrects the track of the screw path by operators, and eventually attains the ultimate position. This approach prevents damage to the nerve and vascular tissue adjacent to the screw path, and effectively reduces the occurrence of surgical complications as well as the duration and dose of intraoperative fluoroscopy.

Supporting Information

Additional Supporting Information may be found in the online version of this article on the publisher's web-site:

Fig. S1 Questionnaire given to orthopaedic surgeons to estimate distances (2, 4, and 6 mm) and angles (5°, 10°, and 20°). Estimated values were then compared against real values to determine the accuracy of the estimates. Supplementary Fig. 1 is taken from an article previously published by the author[12]: Rexiti P, Abulizi Y, Muheremu A, Wang S, Maimaiti M, Guo H, Sheng W. Anatomical and radiologic characteristics of isthmus parameters in guiding pedicle screw placement. J Int Med Res. 2018; 46: 2386–2397.

References

1. Santoni BG, Hynes RA, Mcgilvray KC, *et al*. Cortical bone trajectory for lumbar pedicle screws. Spine J, 2009, 9: 366–373.
2. Baluch DA, Patel AA, Lullo B, *et al*. Effect of physiological loads on cortical and traditional pedicle screw fixation. Spine (Phila Pa 1976), 2014, 39: 1297–1302.
3. Matsukawa K, Yato Y, Nemoto O, Imabayashi H, Asazuma T, Nemoto K. Morphometric measurement of cortical bone trajectory for lumbar pedicle screw insertion using computed tomography. J Spinal Disord Tech, 2013, 26: E248–E253.
4. Chao CK, Hsu CC, Wang JL, Lin J. Increasing bending strength and pullout strength in conical pedicle screws: biomechanical tests and finite element analyses. J Spinal Disord Tech, 2008, 21: 130–138.
5. Seebeck J, Goldhahn J, Städele H, Messmer P, Morlock MM, Schneider E. Effect of cortical thickness and cancellous bone density on the holding strength of internal fixator screws. J Orthop Res, 2004, 22: 1237–1242.
6. Zindrick MR, Wiltse LL, Widell EH, *et al*. A biomechanical study of intrapeduncular screw fixation in the lumbosacral spine. Clin Orthop Relat Res, 1986, 203: 99.
7. Matsukawa K, Yato Y, Kato T, Imabayashi H, Asazuma T, Nemoto K. In vivo analysis of insertional torque during pedicle screwing using cortical bone trajectory technique. Spine (Phila Pa 1976), 2014, 39: E240–E245.
8. Ueno M, Imura T, Inoue G, Takaso M. Posterior corrective fusion using a double-trajectory technique (cortical bone trajectory combined with traditional trajectory) for degenerative lumbar scoliosis with osteoporosis: technical note. J Neurosurg Spine, 2013, 19: 600–607.
9. Glennie RA, Dea N, Kwon BK, Street JT. Early clinical results with cortically based pedicle screw trajectory for fusion of the degenerative lumbar spine. J Clin Neurosci, 2015, 22: 972–975.
10. Rodriguez A, Neal MT, Liu A, Somasundaram A, Hsu W, Branch CL Jr. Novel placement of cortical bone trajectory screws in previously instrumented pedicles for adjacent-segment lumbar disease using CT image-guided navigation. Neurosurg Focus, 2014, 36: E9.
11. Takata Y, Matsuura T, Higashino K, *et al*. Hybrid technique of cortical bone trajectory and pedicle screwing for minimally invasive spine reconstruction surgery: a technical note. J Med Investig, 2014, 61: 388–392.
12. Rexiti P, Abulizi Y, Muheremu A, *et al*. Anatomical and radiologic characteristics of isthmus parameters in guiding pedicle screw placement. J Int Med Res, 2018, 46: 2386–2397.
13. Rexiti P, Aierken G, Wang S, *et al*. Anatomical research on strength of screw track fixation in novel cortical bone trajectory for osteoporosis lumbar spine. Am J Transl Res, 2019, 11: 6850–6859.
14. Rexiti P, Abudurexiti T, Abuduwali N, Wang S, Sheng W. Measurement of lumbar isthmus parameters for novel starting points for cortical bone trajectory screws using computed radiography. Am J Transl Res, 2018, 10: 2413–2423.
15. Xu R, Ebraheim NA, Ou Y, Yeasting RA. Anatomic considerations of pedicle screw placement in the thoracic spine. Roy-Camille technique versus open-lamina technique. Spine (Phila Pa 1976), 1998, 23: 1065–1068.
16. Gonchar I, Kotani Y, Matsumoto Y. Cortical bone trajectory versus percutaneous pedicle screw in minimally invasive posterior lumbar fusion. Spine J, 2014, 14: S114–S115.
17. Mizuno M, Kuraishi K, Umeda Y, Sano T, Tsuji M, Suzuki H. Midline lumbar fusion with cortical bone trajectory screw. Neurol Med Chir, 2014, 54: 716–721.
18. Zdeblick TA, Kunz DN, Cooke ME, Mccabe R. Pedicle screw pullout strength. Correlation with insertional torque. Spine (Phila Pa 1976), 1993, 18: 1673–1676.
19. Matsukawa K, Taguchi E, Yato Y, *et al*. Evaluation of the fixation strength of pedicle screws using cortical bone trajectory: what is the ideal trajectory for optimal fixation?. Spine (Phila Pa 1976), 2015, 40: E873–E878.
20. Ding Z, Du X. Clinical anatomy of spinal surgery. 1st edn Jinan, Shandong: Shandong Science and Technology Press, 2008.
21. Ebraheim NA, Xu R, Ahmad M, Yeasting RA. Projection of the thoracic pedicle and its morphometric analysis. Spine (Phila Pa 1976), 1997, 22: 233–238.