Eur Spine J (2012) 21:23–30
DOI 10.1007/s00586-011-1962-8

ORIGINAL ARTICLE

Use of computed tomographic reconstruction to establish the ideal entry point for pedicle screws in idiopathic scoliosis

Peiqiang Su · Wentong Zhang · Yan Peng · Anjing Liang · Kaili Du · Dongsheng Huang

Received: 11 October 2010 / Revised: 6 July 2011 / Accepted: 24 July 2011 / Published online: 13 August 2011

Abstract
Objective To determine the ideal entry point for individual pedicle screw in the surgical treatment of idiopathic scoliosis using computed tomographic (CT) three-dimensional (3D) reconstruction.
Methods Twenty patients with moderate or severe idiopathic scoliosis from two groups received surgical treatment using "Free Hand technique" and "Assisted Free Hand technique". Computed tomographic scanning with 3D reconstruction of the thoracic and lumbar spine was conducted to determine the entry point and to evaluate the placement accuracy.
Results The accuracy of placement was 88.2% in convexity and 84.5% in concavity for the "Free Hand" group, and 94.1% in convexity and 94% in concavity for the "Assisted Free Hand" group. Evidence showed that "Assisted Free Hand" group had higher accuracy when screws were placed in the thoracic spine ($P = 0.02$), while no obvious difference was seen in the lumbar spine placement ($P = 0.47$).
Conclusions We conclude that in the surgical treatment of severe scoliosis, individual screw placement guided by entry points determined by CT reconstruction can result in improved accuracy and ease of the procedure.

Keywords Pedicle screw · Computed tomography · Entry point · Scoliosis

CT	Computed tomography
3D	Three dimensional
VR	Volume rendering
MPR	Multi-planar reformation

Introduction

In the treatment of spinal deformity, the use of the pedicle screw has been gaining increasing acceptance among the surgeons [1]. The implantation of pedicle screws with spinal instrumentation has shown to have improved coronal, sagittal and rotational deformity correction [2]. Because of the unique neurologic and vascular anatomy of the spinal canal and thoracic cavity, optimal screw placement is especially important for thoracic pedicle screws. Consequences of screw malposition can be devastating when it occurs in the proximity of neurovascular and visceral structures [3, 4].

Methods to aid the surgeon in appropriate screw placement include the funnel technique, [5] the anatomical landmark technique, [6] intraoperative fluoroscopy and/or radiography, [7] and computer-assisted image-guided techniques [8]. Most of these studies, however, describe different entry points at different levels as well as different insertion techniques. In our department, we used the method reported by Kim et al. [9] to determine thoracic entry point, and the method reported by Magerl [10] to determine the lumbar entry point. This resulted in a high accuracy rate and

P. Su and W. Zhang contributed equally to this work.

P. Su
Department of Orthopedics, The First Affiliated Hospital of Sun Yat-Sen University, Guangzhou, China

W. Zhang
Department of Orthopedics, Xiamen Traditional Chinese Medical Hospital, Xiamen, China

Y. Peng · A. Liang · K. Du · D. Huang (✉)
Department of Orthopedics, The Second Affiliated Hospital of Sun Yat-Sen University, 107 West Yan Jiang Road, Guangzhou, PO Box 510120, China
e-mail: huangdongshen18@hotmail.com

a low complication rate in placement of screw in patients with moderate scoliosis. In patients with severe spinal deformity, however, the situation was different. Because of possible significant abnormality in size and shape of the transverse process and/or pars due to rotation and wedging, a precise method of evaluating every individual pedicle is needed to ensure safe pedicle screw placement.

Computed tomography (CT) scan has also been used for preoperative measurement and postoperative assessment in spine surgery [11, 12]. With advances in equipment and scanning parameter settings, single-dose radiation has reached an acceptable range [13]. Multi-planar reformation (MPR) is used to determine the entry point and to obtain the length and diameter along with the sagittal transverse angles of the pedicle, thus increasing the surgeon's confidence level [14]. We conducted a study of spiral CT scanning with three dimensional (3D) reconstruction to determine the ideal entry point of each individual pedicle. The proposed advantages of this technique are easy identification of the entry point, feasible transverse screw angles and a very low incidence of medial and/or lateral pedicle wall breach.

Materials and methods

This study consisted of two different phases: determination of the ideal entry point by preoperative CT reconstruction and comparison of the different methods for screw placement.

Patients

From 2006 to 2008, patients admitted to our department with the diagnosis of moderate to mid-severe idiopathic scoliosis were enrolled in this study and divided into "Free Hand" group and "Assisted Free Hand" group for surgery, according to a random table designed by a statistician. For the "Free Hand Group," the pedicle entry point was determined from known data describing how it changed as the vertebral segment for the insertion moved upward along the spine. In the "Assisted Free Hand Group", the entry point was determined from a 3D CT reconstruction scan that determined the path where the screw was accurately inserted into the pedicle would intersect the pedicle surface. In each group, the first five patients with moderate scoliosis and the first five with mid-severe scoliosis were collected for placement accuracy analysis. The ten patients in the "Free Hand" group consisted of three males and seven females, with a mean age of 16.4 years (range, 13–21 years) and a mean Cobb angle of 58.2° (range 48°–78°). The ten patients in the "Assisted Free Hand" group consisted of four males and six females, with a mean age of 17.2 years (range, 14–20 years) and a mean Cobb angle of 58.1° (range 42°–77°). The types of scoliosis were randomized in both groups, with six patients of Lenke I, one of Lenke II, two of Lenke III, and one of Lenke V in the "Free Hand" group and five patients of Lenke I, one of Lenke II, three of Lenke III, and one of Lenke V in the "Assisted Free Hand" group. No case with transitional vertebra, hemivertebra, or abnormality of the ribs or spinal canal was observed. All patients provided written informed consent before enrollment in the study, which was approved by the appropriate institutional review board.

CT scanning with 3D reconstruction of the thoracic and lumbar spine was conducted with the assistance of a radiologist, using Siemens SOMATOM Sensation 64-slice CT (Siemens, Munich, Germany). Scanning power settings were 120 kV and 60 mA, thickness 1 mm, interval 1 mm, and scanning pitch 1. According to the radiation dose setting, the CTDIvol (CT dose index volume) was 4.59 mGy, which was one half of that used in routine lung scanning. CT reconstruction was performed with Syngo Somaris/5 software (Siemens, Munich, Germany).

Determination of entry point

"Free Hand" method

In the "Free Hand" group, the entry point was established by the method proposed by Kim and lenke [15] and Magerl [10], using the following guidelines. The entry points of the 1st and the 12th thoracic vertebrae are at the junction of the bisected transverse process and lamina at the lateral border of the pars. At the mid-thoracic region, the point tends to move slightly medial and cephalad. The entry point of lumbar spine lies at the junction of the lateral border of the superior articular process and the bisector of the transverse process. Using these guidelines and working upwards from lumbar to thoracic vertebrae, the base of the pedicle in question was then probed with a gearshift pedicle probe to locate the exact entry point.

"Assisted Free Hand" method-determination of entry point guided by 3D reconstruction

The "Assisted Free Hand" method (details of which are given below) determined the entry point through computer-assisted manipulation of the 3D CT reconstruction of the vertebral segment in question. A transverse plane represented by line T was first determined on a sagittal section image and another vertical plane represented by line V was also determined on a cross sectional image. The "intersection" of these two planes projecting on the posterior vertebra, as shown in the coronal image, was then recorded as the entry point of the pedicle screw. This entry point was mapped on a grid drawn on the pedicle surface and its location on the grid used to provide accurate guidance for the surgeon.

The reconstruction result was shown as four MPR images displayed on the workstation screen: a sagittal plane image (Fig. 1a), a cross-sectional plane image (Fig. 1b), and two 3D-rotatable dorsal volume rendering (VR) images, one of the vertebra in question (Fig. 1c) and one of the total spine (Fig. 1d). The first three images had three lines (blue-colored transverse line T: represents a plane vertically dividing the sagittal image, red-colored vertical line V: represents a plane vertically dividing the cross-sectional image, and green-colored line C: represents coronal sectioning) that could be moved and/or rotated by the operator (Fig. 1a–c).

1. Image adjustment: The dorsal plane VR image (Fig. 1d) was zoomed into focus on an entire individual vertebra and the articular processes of the adjacent vertebrae, and this image was then derotated to reduce observation error (Fig. 1c). The cross-sectional and sagittal plane images of the vertebra obtained were adjusted to moderate size for measurement
2. Tangent line adjustment: The transverse line T on the sagittal image and the vertical line V on the cross sectional image were adjusted so that they were parallel to the direction of the pedicle and divided the isthmus equally (Fig. 1a, b). At the same time, the transverse line (T) on the dorsal VR image was rotated to become perpendicular to the vertical line (V) to ensure that the pedicle was perpendicularly bisected on two planes (Fig. 1c)

After the position of the transverse line on the sagittal image was set, the coronal line C was moved so that it intersected the transverse line at posterior border of the lamina or superior facet (Fig. 1a). In the same manner, the

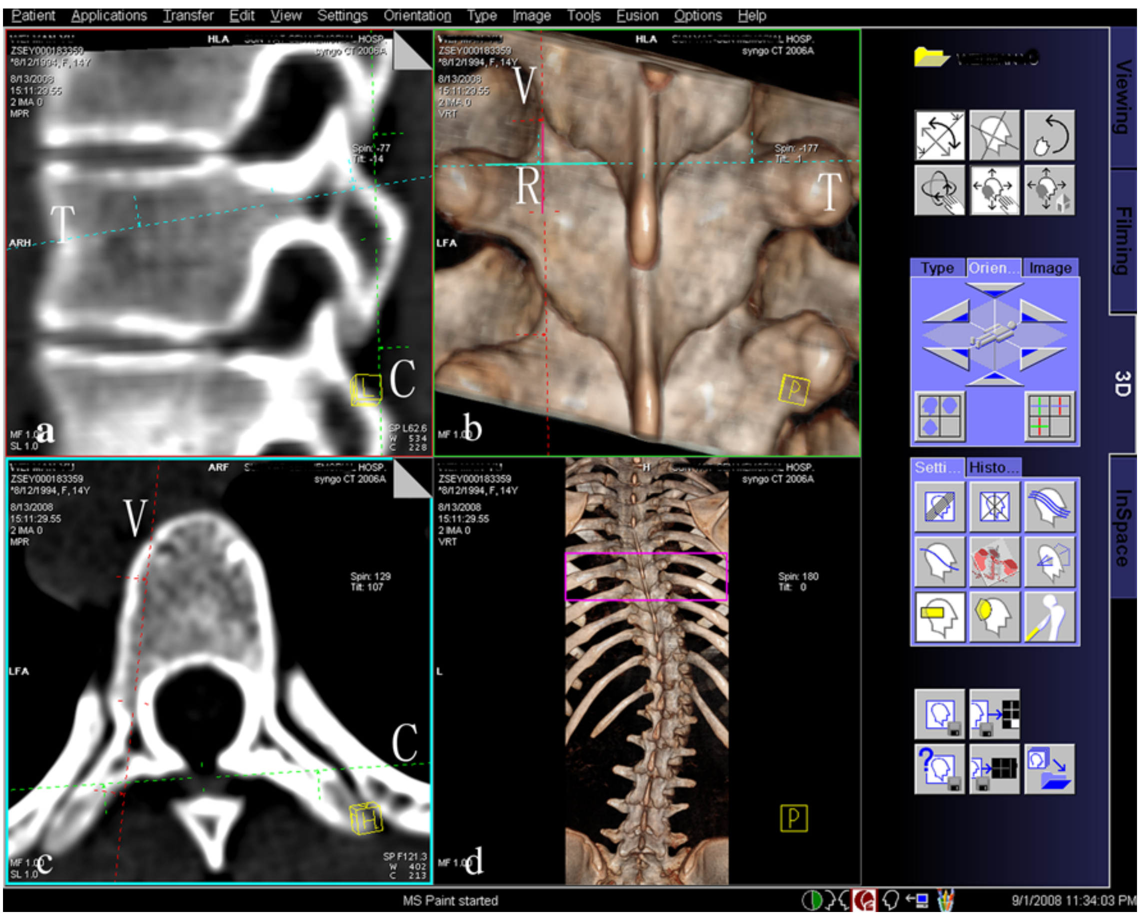

Fig. 1 a–d The figure shows the sagittal, cross-sectional, and two dorsal views of the vertebra. The lines shown are transverse (*T*) in *blue*, vertical (*V*) in *red*, and coronal (*C*) operator-controlled lines. **a** The transverse plane represented by line *T* on this sagittal image has been positioned parallel to and bisecting the pedicle. The coronal line *C* represents coronal sectioning of the image. **b** The vertical plane represented by line *V* on this cross-sectional image has been positioned parallel to and bisecting the pedicle. The coronal line *C* represents coronal sectioning of the image. **c** *R* shows the intersection of transverse and vertical planes as represented by lines *T* and *V* on the dorsal *VR* image and represents the entry point of pedicle. **d** This image shows a dorsal overview of spine. The current segment (Fig. 1c) was T7 coronal line on the cross-sectional image was moved to intersect the vertical line on this image at the posterior border of the vertebra (Fig. 1b). The intersection (R) of lines T and V as displayed on the dorsal VR image was the ideal entry point of the pedicle as determined by CT 3D reconstruction (Fig. 1c). The location of the entry point was then mapped onto a grid drawn on the pedicle surface on the CT scan, using the following process. The transverse process was transversally divided into three parts by the upper edge and bisected axis of transverse process, and the superior facet was vertically divided into three parts by the trisected axis of superior facet. Because the entry point was determined by the invariant vertebral skeletal structure, the entry point would not vary whether patient was lying supine or prone on the table. The entry point decided by preoperative CT scan could then be marked in one of the nine areas (A1 ~ C3) (Fig. 2a, b). In this way, observation error could be minimized.

Pedicle morphological measurement

The width and length of the pedicle isthmus were measured on the sagittal and cross-sectional images, with a precision of 0.01 cm. Width was defined as the distance between the bilateral outer edges of the cortex at the isthmus on the sagittal and cross-sectional planes (Fig. 3). The lesser of the two values was considered the minimum diameter of the pedicle. At the same time, the length of pedicle trajectory was measured and used to determine the appropriate screw length.

Clinical application

The spine was exposed to the tips of the transverse processes bilaterally. The facet joints were thoroughly cleaned of soft tissue. The inferior facet was removed after identifying the entry point, if necessary. The entry points were

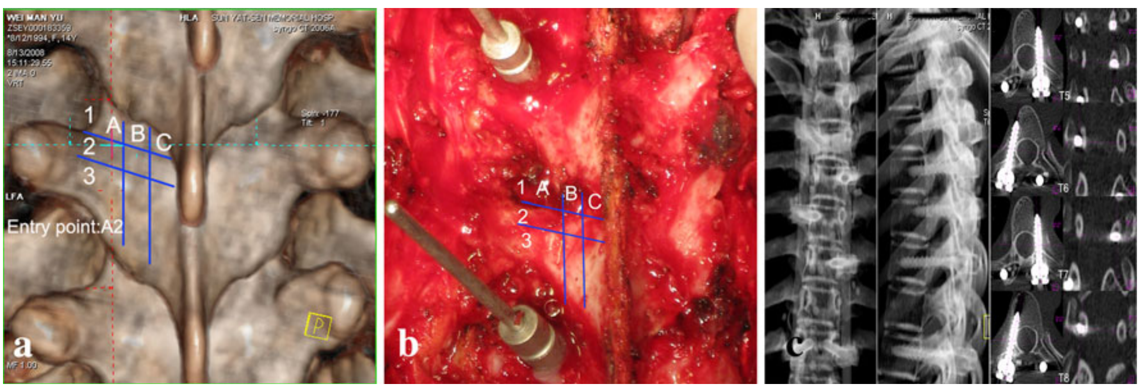

Fig. 2 The nine areas system was used to help locating the reconstructional entry point. **a** The entry point was decided preoperatively locating at A2 area. **b** The A2 area of the in vivo spine was identified as the entry point. **c** The evaluation of screw placement using MPR with CT scan

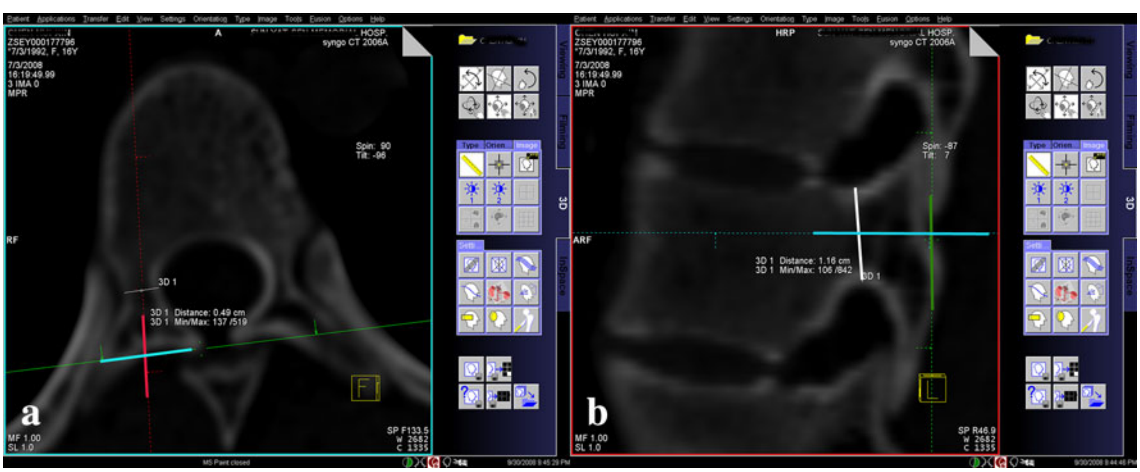

Fig. 3 The pedicle width and height were defined, respectively, as the distance between the outer edge of the cortex at the isthmus on the cross-sectional and sagittal plane. **a** The measurement of the pedicle width on the cross sectional plane. Since a hollowed-out cortex appears, we take the proximal pedicle into concern. Width = 0.60 cm. **b** The measurement of the pedicle height on sagittal plane. Height = 0.85 cm. The smaller of the two values (0.60 cm) would be defined as the minimum diameter of the pedicle

burred starting from the neutrally rotated and most distally instrumented vertebra. After the burring of entry point, a gearshift pedicle probe was used to make the entrance trajectory into the cancellous bone at the base of the pedicle. A probe was used to palpate the pedicle tract to make sure that the five osseous borders were intact. The pedicle tract was under tapped using a tap with a diameter 0.5 mm smaller than that of the intended screw. After tapping and re-palpation, screws of appropriate size were placed in predetermined segments (Fig. 2b). After surgery, all patients received a postoperative CT scan of the treated segment, using the same dose protocol as that used in the preoperative scan. MPR images were obtained to evaluate the placement accuracy.

Statistical analysis

Statistical analysis was performed by a statistician with SPSS for Windows, version 16 (SPSS Inc., Chicago, IL, USA), and Microsoft Office Excel 2003 (Microsoft Corp., Redmond, WA, USA) to evaluate the accuracy of screw placement. To simplify the analysis of screw placement accuracy, we neglected the diameter discrepancy of the screws. Breach was defined as the axis of pedicle screw penetrating the outer cortex of the pedicle or vertebrae (Fig. 2c).

Results

In total, there were 169 screws placed in the two groups, without the occurrence of any anterior breach. Twenty-three screws breached the pedicle in “Free Hand” group: 8 in the thoracic convexity, 12 in the thoracic concavity, 2 in the lumbar convexity, and 1 in the lumbar concavity. In the “Assisted Free Hand” group, ten screws breached the pedicle: four in the thoracic convexity, four in the thoracic concavity, one in the lumbar convexity, and one in the lumbar concavity (Table 1). Seven patients in the “Free Hand” group and four patients in the “Assisted Free Hand” group had screw breaching, and the amount of breaching was measured (Table 2). No complication was observed from misplaced screws in either group, and no patient returned to the operating room. The accuracy of placement was 88.2% in convexity and 84.5% in concavity for the “Free Hand” group, and 94.1% in convexity and 94% in concavity for the “Assisted Free Hand” group (Fig. 4a, b). It seemed that the “Assisted Free Hand” group had higher accuracy (93.2, 93.1%) in the thoracic segment than the “Free Hand” group (8.7, 80%). According to the chi-square test, the “Assisted Free Hand” group had significantly higher accuracy ($P = 0.01$) in general. No significant difference was found with the accuracy of screws placed in different curve sides. Evidence showed that the “Assisted Free Hand” group had higher accuracy when inserting screws in thoracic spine ($P = 0.02$), and no significant difference when inserting in the lumbar spine ($P = 0.47$).

Table 1 Accuracy of screw placement in both groups. (intact/violation)

Groups	“Free Hand” group		“Assisted Free Hand” group	
Sides	Convexity	Concavity	Convexity	Concavity
Thoracic	52/8 (M2, L6)	48/12 (M10, L2)	55/4 (M2, L2)	54/4 (M3, L1)
Lumbar	23/2 (M1, L1)	23/1 (M1)	25/1 (L1)	25/1 (L1)
Sum of sides	75/10	71/13	80/5	79/5
Sum of group	146/23 (M14, L9)		159/10 (M5, L5)	

M medial breach, *L* lateral breach

Discussion

Pedicle screw fixation can be dangerous because of the maximum permissible translational error of less than 1 mm and rotational error of less than 5° [16] in the scoliotic spine, especially the mid-thoracic spine because of the small pedicle diameter, limited space between the spinal cord and the medial pedicle, and the morphological deformity of the pedicle [17]. A freehand thoracic pedicle screw insertion technique with no radiographic guidance or intraoperative tracking devices has been reported to be safe and reliable [15]. In patients with severe scoliosis, however, the ideal entry point of the pedicle screw may vary among patients, possibly resulting in screw malposition due to severe vertebral rotation, pedicle deformation, and transverse process dysplasia [18]. Therefore, individual determination of each entry point is necessary to overcome the difficulties of pedicle screw placement caused by the complexity and variability of spinal anatomy deformation.

Preoperative CT scanning is increasingly used for patients with moderate to severe scoliosis to evaluate vertebral dysplasia and rotation. Advances in equipment and settings of scanning parameters have allowed single-dose radiation to reach an acceptable range [13]. In our study, the tallest patient who received the axis length of scanning was 52.29 cm. The dose-length product (DLP) was $4.59 \times 52.29 = 240$ mGycm during the scanning. When the same patient had a lung CT scan in routine power setting with the axis length of 34 cm, the DLP was $13.78 \times 34 = 469$ mGycm. In our groups, the radiation

Table 2 Screw breaching in 20 patients (Breach in mm)

Patient no.	Thoracic				Lumbar			
	Convexity		Concavity		Convexity		Concavity	
	Medial	Lateral	Medial	Lateral	Medial	Lateral	Medial	Lateral
"Free Hand" group								
1	1 (2.8)	1 (1.6)	1 (2.5)	0	0	0	0	0
2	1 (2.0)	1 (1.5)	1 (1.9)	1 (2.1)	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	1 (1.6)	2 (2.2, 1.7)	0	0	0	1 (1.3)	0
5	0	0	0	0	0	0	0	0
6	0	2 (2.7, 1.4)	1 (2.5)	1 (2.0)	0	1 (1.7)	0	0
7	0	0	2 (1.3, 1.8)	0	1 (1.3)	0	0	0
8	0	0	0	0	0	0	0	0
9	0	1 (1.3)	2 (1.8, 1.6)	0	0	0	0	0
10	0	0	1 (1.7)	0	0	0	0	0
"Assisted Free Hand" group								
1	0	0	0	0	0	0	0	0
2	0	0	2 (1.0, 0.8)	0	0	0	0	0
3	2 (2.0, 1.8)	0	1 (0.9)	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	1 (1.1)	0	1 (1.6)	0	0	0	1 (0.6)
6	0	1 (1.2)	0	0	0	1 (2.0)	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0

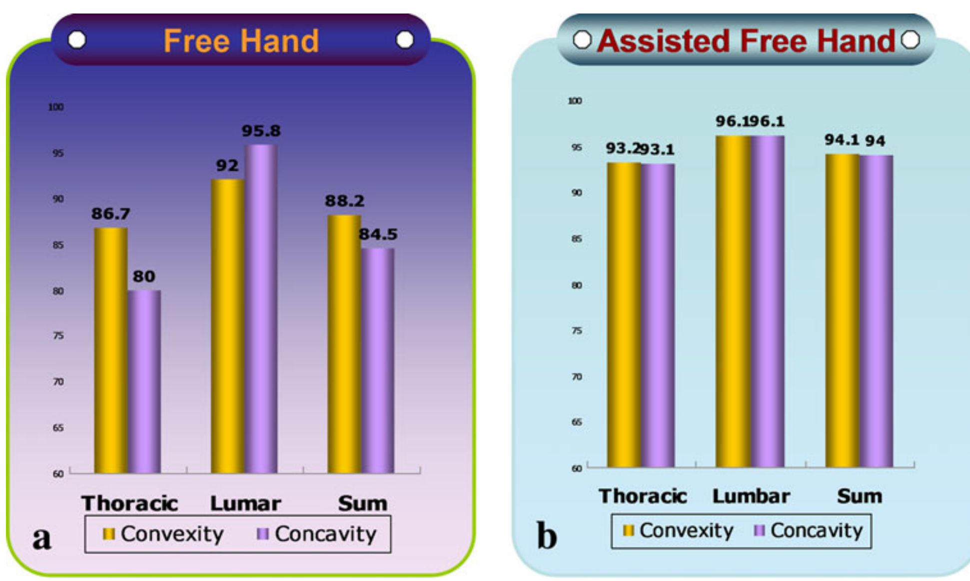

Fig. 4 Accuracy of screw placement in scoliosis patients, classified by different techniques, segments and curvature sides. **a** Accuracy of screw placement in "Free Hand" group. **b** Accuracy of screw placement in "Assisted Free Hand" group

exposure was only one half of a lung scan. Due to the underdevelopment of the spinal bone cortex, MRI is not an appropriate option for measurement and mapping. Although recently developed, image-guided techniques have been associated with increased accuracy. Screw placement guided by CT-based navigation has been reported to have an accuracy rate of up to 96.1% [19]. This technique, however, requires expensive equipment and is associated with prolonged operative time and potential navigational failure due to image drift [20].

The results of this study indicate that the use of fixed criteria to guide screw placement, as in conventional methods, may lead to deviation in the determination of the entry point at different pedicles. The result may be a higher risk of breach in the concave side and in the mid-thoracic section, where severe vertebral rotation and dysplasia often occur [21]. The efficacy of determination of ideal entry points varies among the surgeons, indicating not only the instability of the conventional methods but also the need for continuous education. Because the entry point determined by CT reconstruction is the point of intersection of three fixed planes, it can easily be identified preoperatively and intraoperatively. Moreover, it does not change while rotating VR image or the patient's posture. The inferior facetectomy can help identifying the entry point especially when there is no guidance facility. In the study, no matter whether the entry point is located on the inferior facet or not, it is already established according to the reconstruction image. The CT reconstruction point can help reduce the risk of screw malposition due to vertebral rotation and deformation. Considering the X-ray exposure, we recommend the routine preoperative CT scanning and reconstruction for the entry point in severely deformed cases.

The transverse angle of the pedicle is another major factor affecting the screw placement [22]. Many reports have been published achieving a reliable transverse angle as a result of CT-based measurement [23]. This study shows that auxiliary transverse angles corresponding to the established entry points can be measured by CT during reconstruction, which can facilitate screw placement. In a Free Hand technique, the entry points established by our method are located at the central axis line of individual pedicles so that the ideal trajectory can be more easily achieved and the largest safe range obtained with screw insertion at different transverse angles. When the pedicles are not large enough to allow a true intraosseous position, which means the screw breaching could not be avoided, an "in–out–in" trajectory or a juxta pedicular technique may be necessary. The ideal entry point and trajectory can be determined preoperatively by the radiologist during reconstruction. This can increase the surgeon's level of confidence and avoid repeated determination of entry points, as well as lowering the rupture rate and reducing the operative time.

High accuracy rates have been reported for the method proposed by Lenke and Magerl for guidance of pedicle screw placement [5, 10]. Our clinical experience has yielded the same conclusion but has also revealed the need for continuous education and the risk of screw malposition in severely rotated regions, especially on the concave side. In patients with severe scoliosis, placing screws in these regions may carry a significantly higher risk of breach. The results of the present study show that the two techniques for determining the entry point are comparable with respect to the accuracy of screw placement and the feasibility of the procedure. Assisted technique is recommended for the purpose of safety and shortening the learning curve.

According to the result, screw breaching was more often observed in the thoracic concavity of the "Free Hand" group, particularly with respect to breaching of the inner wall; while breaching of the outer wall often tended to occur at the thoracic convexity. In the "Assisted Free Hand" group, the incidence of both inner and outer wall screw breaching was significantly lower than in the "Free Hand Group", and the positions of the breaches were more evenly distributed. We found that the entry point usually lies more lateral in the concavity side and more medial in the convexity side in mid-severe scoliosis. Although no significant difference was found with the accuracy of screws in different curve sides, we found that more screws in thoracic concavity breached the pedicle in "Free Hand" group in this study (12 versus. 8). More data about specific differences between the two methods and segments are being collected to explain the variance. Additional clinical studies are needed to improve the accuracy of this technique, determine the best insertion trajectory, and evaluate the efficacy and feasibility of the procedure in various clinical situations. In our clinical treatment, with the help of preoperative planning, the technique evaluated is reproducible and predictable.

Conclusion

Since pedicle dysplasia often occurs in the patients with severe scoliosis, placing screws in guidance with the same criteria is unreliable and would possibly result in misplacement. Spiral CT scanning and 3D reconstruction can be used preoperatively to increase the precision of the screw placement and decrease the risk of screw malposition in severely deformed vertebrae.

Ethical Board Review statement Each author certifies that his or her institution has approved the human protocol for this investigation that all investigations were conducted in conformity with ethical principles of research, and that informed consent was obtained.

Acknowledgments This research has received funding from The National Natural Science Foundation of China (Grant No. 30700456), Natural Science Foundation of Guangdong Province (Grant No. 8151008901000141) and Fundamental Research funds for the Central Universities (Grant No. 09 ykpy 30). One or more of the authors (DH, PS) have received funding from grants provided by Research Fund of National Natural Science Funds of China (30700456) and Yat-Sen Scholarship for Young Scientist. Foundation funds were received in support of this work. We wish to thank Heran Deng who served as the radiologist in this study.

Conflict of interest We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of the manuscript entitled.

References

1. Liljenqvist UR, Halm HF, Link TM (1997) Pedicle screw instrumentation of the thoracic spine in idiopathic scoliosis. Spine 22:2239–2245
2. Suk SI, Lee CK, Min HJ, Cho KH, Oh JH (1994) Comparison of Cotrel-Dubousset pedicle screws and hooks in the treatment of idiopathic scoliosis. Int Orthop 18:341–346
3. Katonis P, Christoforakis J, Kontakis G, Aligizakis AC, Papadopoulos C, Sapkas G, Hadjipavlou A (2003) Complications and problems related to pedicle screw fixation of the spine. Clin Orthop Relat Res 411:86–94
4. Lonstein JE, Denis F, Perra JH, Pinto MR, Smith MD, Winter RB (1999) Complications associated with pedicle screws. J Bone Joint Surg Am 81:1519–1528
5. Viau M, Tarbox BB, Wonglertsiri S, Karaikovic EE, Yingsakmongkol W, Gaines RW (2002) Thoracic pedicle screw instrumentation using the "Funnel Technique": part 2: clinical experience. J Spinal Disord Tech 15:450–453
6. Elliott MJ, Slakey CJ (2007) Thoracic pedicle screw placement: analysis using anatomical landmarks without image guidance. J Pediatr Orthop 27:582–586
7. Arand M, Hartwig E, Hebold D, Kinzl L, Gebhard F (2001) Precision analysis of navigation-assisted implanted thoracic and lumbar pedicled screws: a prospective clinical study. Unfallchirurg 104:1076–1081
8. Fu TS, Chen LH, Wong CB, Lai PL, Tsai TT, Niu CC, Chen WJ (2004) Computer-assisted fluoroscopic navigation of pedicle screw insertion: an in vivo feasibility study. Acta Orthop Scand 75:730–735
9. Kim YJ, Lenke LG, Bridwell KH, Cho YS, Riew KD (2004) Free hand pedicle screw placement in the thoracic spine: is it safe? Spine 29:333–342
10. Magerl FP (1984) Stabilization of the lower thoracic and lumbar spine with external skeletal fixation. Clin Orthop Relat Res 189:125–141
11. Abul-Kasim K, Strombeck A, Ohlin A, Maly P, Sundgren PC (2009) Reliability of low-radiation dose CT in the assessment of screw placement after posterior scoliosis surgery, evaluated with a new grading system. Spine 34:8–941
12. Abul-Kasim K, Ohlin A, Strombeck A, Maly P, Sundgren PC (2010) Radiological and clinical outcome of screw placement in adolescent idiopathic scoliosis: evaluation with low-dose computed tomography. Eur Spine J 19:96–104
13. Kalra MK, Maher MM, Rizzo S, Saini S (2004) Radiation exposure and projected risks with multidetector-row computed tomography scanning: clinical strategies and technologic developments for dose reduction. J Comput Assist Tomogr 28(Suppl 1):S46–S49
14. Su P, Ma R, Li C, Liu S, Huang D (2007) Pedicle screw fixation of the cervical spine: guidance by computed tomography. Clin Orthop Relat Res 462:99–104
15. Kim YJ, Lenke LG (2005) Thoracic pedicle screw placement: free-hand technique. Neurol India 53:512–519
16. Rampersaud YR, Simon DA, Foley KT (2001) Accuracy requirements for image-guided spinal pedicle screw placement. Spine 26:352–359
17. Liljenqvist UR, Link TM, Halm HF (2000) Morphometric analysis of thoracic and lumbar vertebrae in idiopathic scoliosis. Spine 25:1247–1253
18. Gilbert TJ, Winter RB (2005) Pedicle anatomy in a patient with severe early-onset scoliosis: can pedicle screws be safely inserted? J Spinal Disord Tech 18:360–363
19. Fu TS, Wong CB, Tsai TT, Liang YC, Chen LH, Chen WJ (2008) Pedicle screw insertion: computed tomography versus fluoroscopic image guidance. Int Orthop 32:517–521
20. Grutzner PA, Beutler T, Wendl K, Von RJ, Wentzensen A, Nolte LP (2004) Intraoperative three-dimensional navigation for pedicle screw placement. Chirurg 75:967–975
21. Lehman RA, Lenke LG, Keeler KA, Kim YJ, Cheh G (2007) Computed tomography evaluation of pedicle screws placed in the pediatric deformed spine over an 8 year period. Spine 32:2679–2684
22. Lien SB, Liou NH, Wu SS (2007) Analysis of anatomic morphometry of the pedicles and the safe zone for through-pedicle procedures in the thoracic and lumbar spine. Eur Spine J 16:1215–1222
23. Ebraheim NA, Xu R, Ahmad M, Yeasting RA (1997) Projection of the thoracic pedicle and its morphometric analysis. Spine 22:233–238