

Original Article

Clinical application of small oblique view of thoracolumbar pedicle screws: a prospective study of new radiological assessment of pedicles screws

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Abstract: The study aimed to determine the accuracy of small oblique (SO) view in detecting the malposition of screws intraoperatively. Small oblique views are different from traditional oblique views. SO views are a projection method that form an enlightened lateral line of cranial joint (demonstrated in radiograph) consisted with the medial cortex of pedicle and inferior articular process to detect the wrongly inserted pedicle screws. Pedicle screws are widely utilized in the treatment of various spinal disorders caused by trauma or congenital deformity. Detecting malpositioned pedicle screw immediately after the insertion through C-arm is a challenge for surgeons intraoperatively. This study collected 20 patients to compare the accuracy of AP view and small oblique (SO) view which is different from traditional oblique views. AP radiograph was obtained immediately after the operation, SO radiograph was obtained from reexamination after discharge. The X-rays were grouped into two data files that were reviewed by 3 independent observers. Postoperative CT scans were used as the imaging gold standard to detect the malposition of pedicle screw. Specificity and sensitivity were calculated, negative predictive value and positive predictive value were also recorded. 126 thoracic and lumbar pedicle screws were inserted in 20 patients. CT demonstrated that the medial inserted pedicle screws were detected in 8 screws (6%), whereas the lateral ones were seen in 9 screws (7%). AP combined with lateral views demonstrated the accuracy of insertion, the sensitivity and specificity, other indicators such as PPV, NPV were 88%, 27%, 98%, 63%, 90%. SO combined with lateral views were 92%, 50%, 98%, 86%, 93%. The penetration rate of the pedicle was significantly different between AP and SO views ($P < 0.05$). In conclusion, SO view can decrease the rate of pedicle screw violations compared with AP views in patients with fractures. It can help to decrease the malposition combined with AP and lateral views.

Keywords: Pedicle screws, comparative study, observational study

Introduction

Pedicle screws have revolutionized spinal fixation, and have been shown to play a superior stability compared to traditional fixation methods. Pedicle screws are widely utilized to treat various degenerative, traumatic, and developmental spinal diseases because of their excellent biomechanical fixation and deformity correction [1]. However, complications such as malpositions are commonly seen in practice. Kosmopoulos et al reported that the rate of malposition reached to 10% maximally and varied due to the experience of the surgeons and other deformities [2].

Since its utilization in spine operations, how to decrease the rates of malpositioned pedicle screw remains to be a problem for orthopedics. In practical, due to radiopaque obstacles caused by screws head, the accuracy are not satisfactory through the anterior-posterior (AP), lateral views and traditional oblique views. Improper pedicle screw placement may results in the loss of fixation, or critical damage even lead to reinterventions and persistent pain. Moreover, another plan of operation may need to correct the failure, and the costs for patients increased. For these reasons, many unique techniques have been proposed to improve the accuracy of screw placement, such as comput-

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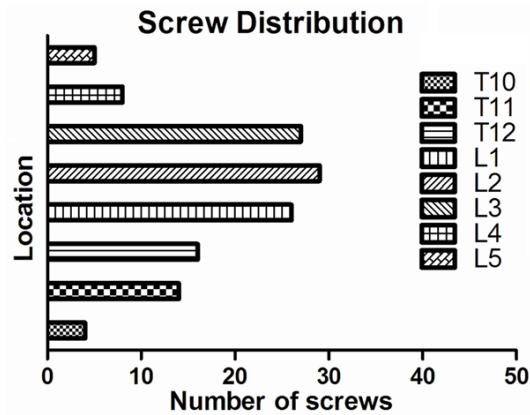


Figure 1. The distributions of pedicle screws, the most number of screws were inserted in L2.

ed tomography (CT) navigation and drill guide template. However, their high cost may limit the popularity of the technique.

To improve the accuracy of inserting pedicle screws, we proposed a new projection called small oblique (SO) views which are different from traditional oblique views. SO view is a projection method that forms an enlightened lateral line of cranial joint consisted with the medial cortex of pedicle and inferior articular process to assist the insertion of pedicle screws. This investigation was aimed to prove the hypothesis that the SO view may help to detect more breached screws postoperatively than that of traditional views. This research provides some essential information for this new view.

Materials and methods

Subjects

The study was approved by the Regional Ethics Board of the Third Hospital of Hebei Medical University. 20 patients who had an operation with thoracic and lumbar pedicle screws inserted were recorded retrospectively from 2012 to 2014, all the patients were known and consent with this clinical research. All 20 patients were provided with written consent to participate in the study before the enrollment. The exclusion criteria: the patients who have spinal operation, tumor, deformity, pedicle screws violating the cranial facet joint. There were 16 male and 4 female patients who were suffered from fracture injured by fall or traffic accident. The locations of 20 patients' fracture were distributed

as follows: (spinal segment level, number of patients) Th12, 5; L1, 5; L2, 8; L3, 1 and L4, 1 in each segment of vertebra respectively. The average age of the patients was 41 years (33-46 years). The inserted pedicle screws for fracture fixation were distributed as follows: (spinal segment level, number of screws) T10, 4; T11, 14; T12, 16; L1, 26; L2, 29; L3, 27; L4, 8; L5, 2 (**Figure 1**).

Retrospective methods

All surgeries were operated at Third Hospital of Hebei Medical University. All the patients were performed by one surgeon and the screws were provided by one manufacture. Postoperative CT scans, AP and lateral views were obtained regularly in our hospital at first examination, and SO view substituted AP view were obtained before discharge or routine clinical examination after one or two month after the operations at second routine examination. The AP view was abandoned if the SO view was taken in routine clinical examination, so the radiation to patients was not increased significantly. Postoperative CT scans were used as the imaging gold standard to detect the position of pedicle screw. Pedicle breaches were classified as medial and lateral ones, medial ones were classified: 0-2.0 mm, 2.1-4.0 mm, 4.1-6.0 mm, or 6.1-8.0 mm [3].

Projection technique

The actual SO views acquired during the procedures may have a slightly different from the true owl's eye and traditional oblique views [4]. It neglects the cranial/caudal inclination of pedicle screws in the sagittal plane. Firstly, the C-arm is positioned for an AP image and the laser of the fluoroscopic machine was positioned in the midline of the patients (**Figure 2**). The C-arm was rotated to find the SO view with the degrees begins with 10 bilaterally. And the superior vertebra of the injured ones was regarded as the references to project for SO views. The SO image was identified when an enlightened line consisted of the medial cortex of pedicle and the cortex of the inferior articular process surface was illustrated clearly in the target vertebra (**Figure 3**). Although SO view was not suffice for assessing screws at multiple levels (each of which presumably had different angles), the angles of adjacent vertebra may be familiar with each other, the SO views of target

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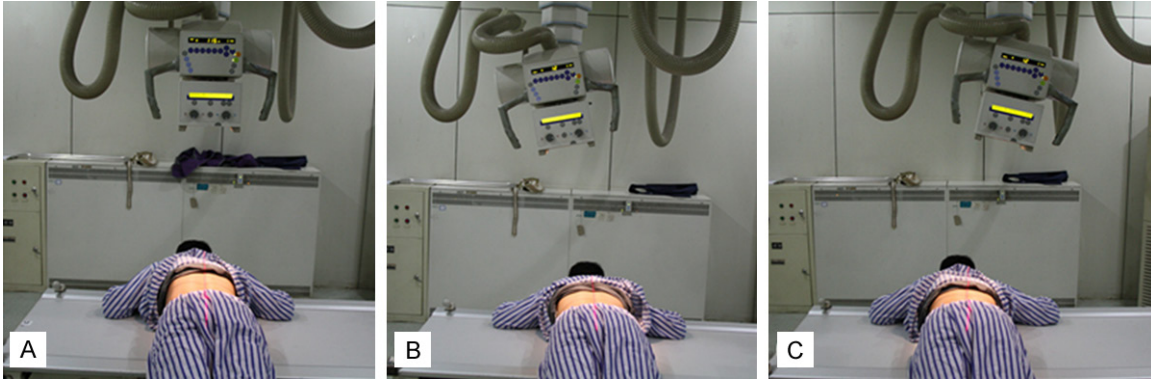


Figure 2. A. The AP view was obtained. B, C. Rotated the tube bilaterally until the desired image was obtained. The degrees of rotation begins with 10°.

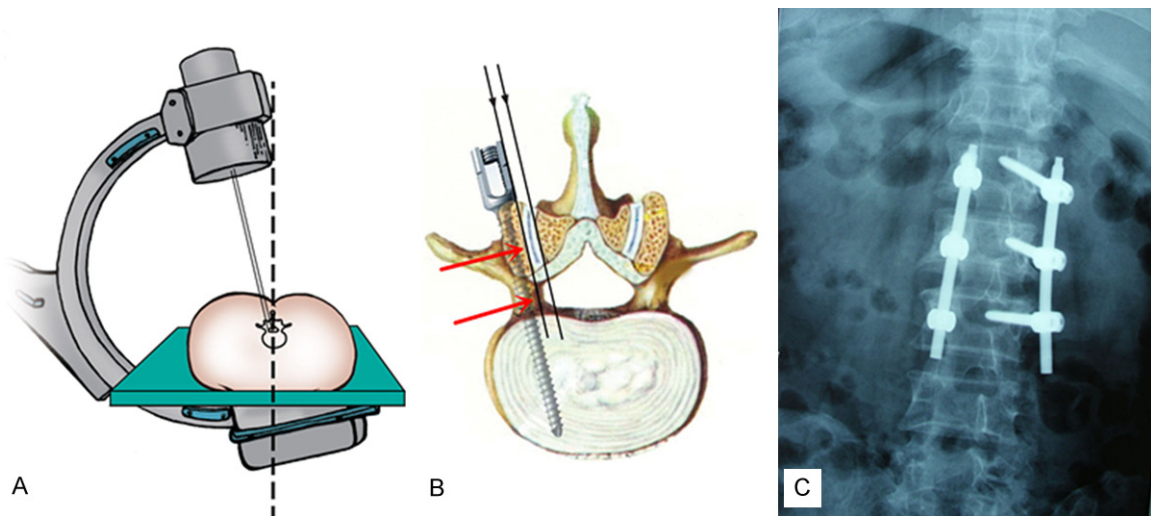


Figure 3. A. The C-arm position for SO view, the direction of tube was along to the cranial joint. B. The ideal trajectory of pedicle screw should tangents to medial cortex of pedicle (the inferior red line) and outer cortex of inferior articular process (the superior red line). C. The outer line of cranial joint was shown as a high density line on SO radiographs, and the line illustrates the relative position of the screws tip and cranial joint.

vertebra were excellent enough to assist the detection of screws. The C-arm only needs to be adjusted more or less if the SO images of adjacent vertebra were needed. Lateral views were obtained regularly (**Figure 4**).

Standard for judgment

The cortical perforation or out of pedicle should be judged based on the experience of surgeons through X rays and CT postoperative scan due to different insertion angles of pedicle screws (**Figure 5**). The enlightened lateral line of cranial joint in SO views was consisted with the medial cortex of pedicle and medial cortex of inferior articular process (**Figure 3**). The relative

location between the tip of pedicle screws and enlightened lateral line in SO views can help to detect the medial perforation of pedicle screws. If there is an overlap between the tip and enlightened lateral line of cranial joint views, the medial perforation can be determined (**Figure 6**). The rotation degrees of SO views were recorded respectively.

All data was classified as group A which contains AP, lateral views and B containing SO combined with the same lateral views. Radiological assessments were made by three independent observers (only surgeons) in group A and B. Before we take the assessment in group B after the assessment of AP views, the orders were

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Figure 4. Lateral views were obtained regularly.

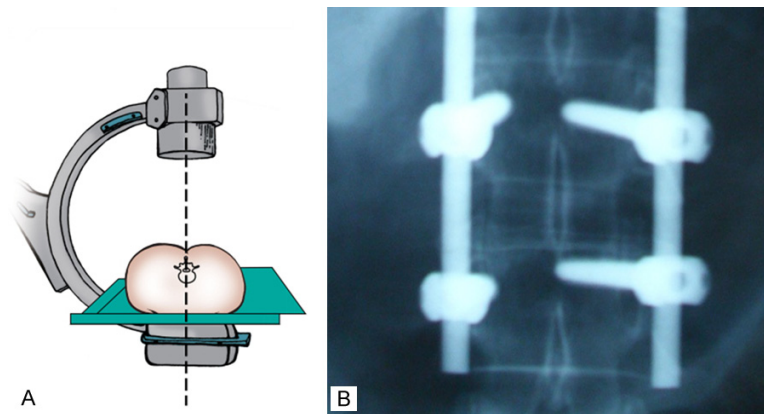
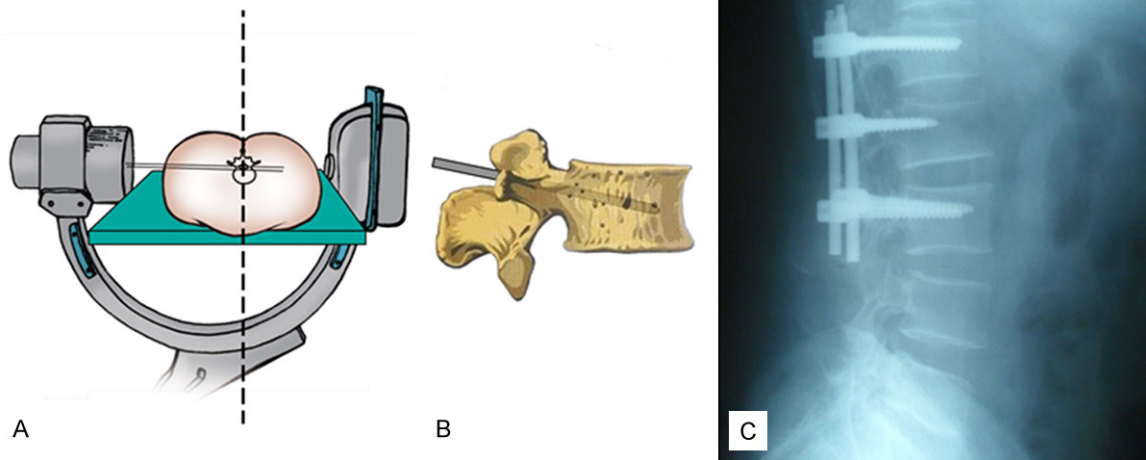


Figure 5. Anteroposterior radiographs exhibited improperly positioned screws (right). A. The projection of AP views. B. The cortical perforation or out of pedicle (right) should be judged based on the experience of surgeons.

disturbed randomly. The radiological assessment of the position based on the images was recorded respectively. Then the results were compared with the gold standard based on the CT postoperatively (**Figure 7**). The accuracy of inserted pedicles, and relevant PPV (positive predictive value), NPV (negative predictive value), or other indicators such as sensitivity, specificity was all calculated respectively.

Statistical analysis

The Chi-square test analysis and Fisher's (two-tailed) exact test were used to compare each observer's determination with CT scans. Values for $P < 0.05$ were regarded as significant statistically.

Results

There were no need to be revised among 126 screws, and no cases of neurovascular injury happened. All of the inserted screws were adequately imaged and none of them had an inferior or anterior breach. Among the 126 screws, 30 screws were inserted into the thoracic region, 96 in the lumbosacral spine. 109 screws were successfully inserted in the planned pathway in 126 pedicles screws (81%). Of 17 cortical breaches, 8 (6%) of the pedicle screws

were detected as medial breach, and 9 (7%) had a lateral perforation based on CT scans postoperatively. The breaches were distributed as follows (spinal segment level, number of screws) Th10, 1; Th11, 4; Th12, 1; L1, 4; L2, 3; L3, 1 and L4, 3 (**Figure 8**). The results of the reading compared with CT were demonstrated in **Table 1**.

The readers' radiological assessments of the pedicle insertion, and other indicators such as sensitivity, specificity, PPV, and NPV of the AP and SO views for the 3 observers were shown in **Tables 2-4**. The overall accuracy rate for the 3 observers was 88%. Mean sensitivity was 27%, with a range of 18% to 35% for the 3 observers.

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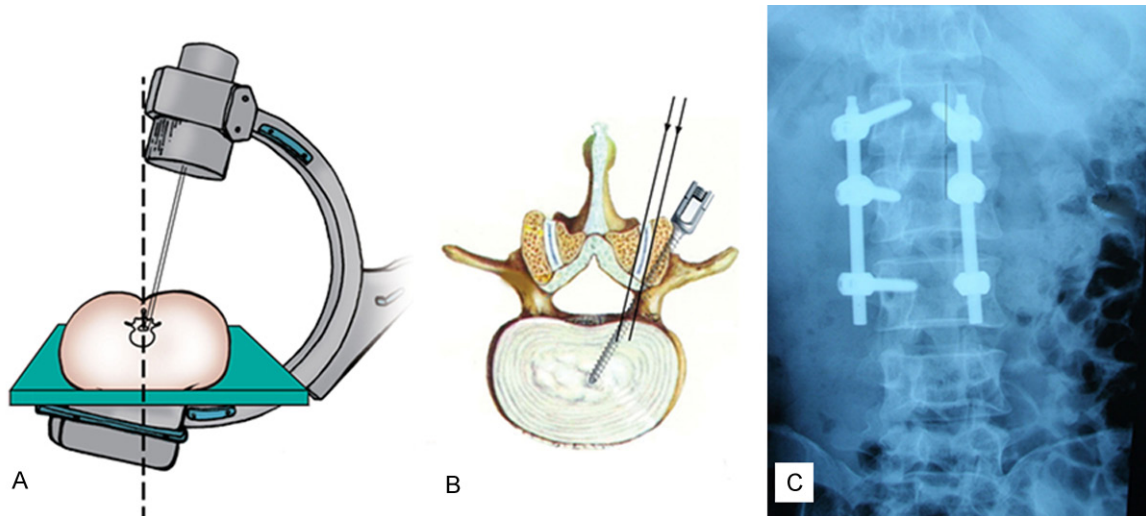


Figure 6. A. The projection of SO views. B. The relative position of the cranial joint and the pedicle screw, and the screw violate the medial cortex of pedicle. C. The screw tips across the high density line (formed by the cranial joint and the medial wall of pedicle) illustrated medial penetration screw on SO radiographs.

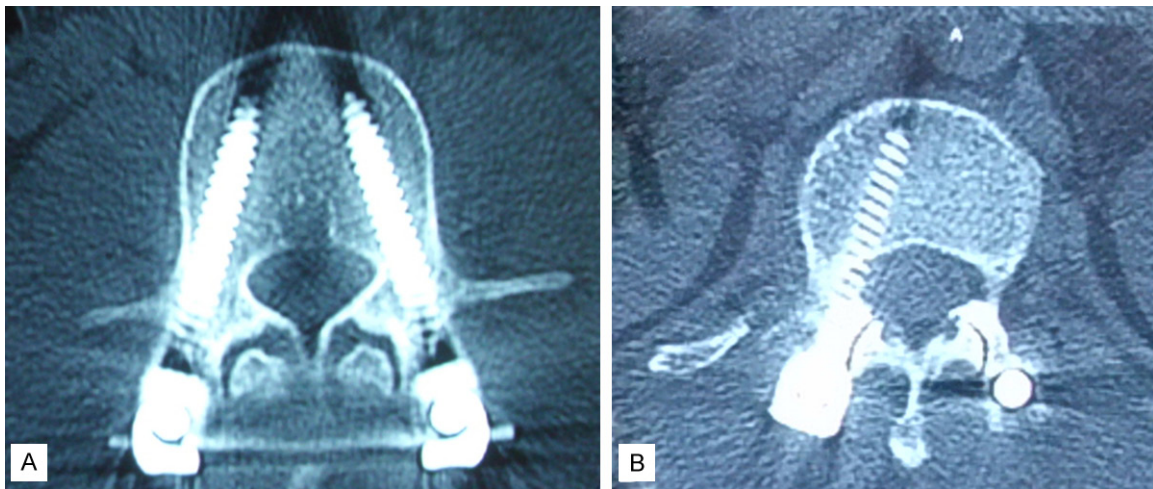


Figure 7. Postoperative CT scans are used as the imaging gold standard to detect the malposition of pedicle screw. A. The screws were inserted through the trajectory. B. The pedicle screw was medially inserted.

Mean specificity of three observers explained as the ability to identify a normal pedicle was 98% (97%-98%). Mean PPV and NPV was 63% and 90% respectively. With SO views, the accuracy, sensitivity, specificity, PPV, and NPV of pedicle screws were 92%, 50%, 98%, 86%, 93% respectively. When stratified according to direction of breach, the accuracy was higher in detecting medial breaches than lateral one with SO views.

There were 8 false-positive radiological assessment and 37 false-negative ones of the total

378 readings in group A. All observers agreed with the placement of 116 screws. The left L2 pedicle screw of tenth patient was detected as medial consistently by three observers in 17 wrongly inserted screws. However, the correct screws' insertion of left L2 pedicle was judged medial wrongly in tenth patient. So, only 115 screws were detected correctly in AP view.

In group B, the false positive, false negative readings were 5 and 25 respectively. All observers agreed on the positions of 120 screws. There were no screws which were in right posi-

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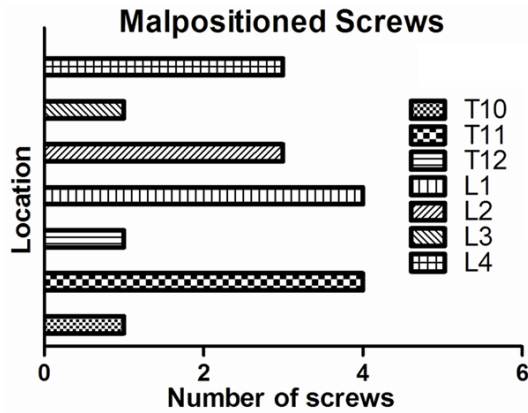


Figure 8. The distribution of malpositioned screws.

Table 1. Accordance with CT in three observers

	AP		SO	
	Malposition	Right	Malposition	Right
1	6	106	9	107
2	5	106	9	106
3	2	107	7	110

Table 2. Interpretation of images in AP and SO views

	Accuracy	Sensitivity	Specificity	PPV	NPV
AP	88%	27%	98%	63%	90%
SO	92%	50%	98%	86%	93%

Table 3. Interpretation of images in AP views of three observers

	Accuracy	Sensitivity	Specificity	PPV	NPV
1	88%	29%	97%	63%	90%
2	87%	18%	98%	60%	88%
3	89%	35%	97%	67%	91%

Table 4. Interpretation of images in SO views of three observers

	Accuracy	Sensitivity	Specificity	PPV	NPV
1	91%	53%	97%	75%	93%
2	93%	44%	100%	100%	92%
3	92%	53%	98%	82%	93%

tion determined by postoperative CT scans was judged wrongly inserted. The right L1 medial screw of the first patient, left T11 lateral screw of the fifth, right L1 medial screw of seventh

one, left T12 lateral screw of fifteenth patient, left T10 lateral, left L1 medial, left L2 lateral of the twentieth patient were detected by three observers consistently. All of the medial breaches that were missed were less than 2-mm breaches and would not need reoperation. No one had neural injuries caused by operations. The rotation degree of the 20 subjects was 11.75 ± 1.4 bilaterally.

Statistical analysis illustrated that there was clinically significant difference ($P < 0.05$) between this two radiographic methods, and the SO views was more accurate in detecting the malposition of the pedicle screws. In AP ($P = 0.267 > 0.05$) and SO ($P = 0.25 > 0.05$) views respectively, there was no significant difference about the result of identifications in three observers.

Discussion

The internal fixation with pedicle screws is the most used operations in spine surgery. As soon as it becomes an indispensable surgical technique, the problem we encountered most was the malposition of the screws, the wrongly located screw may cause potential alarming complications such as neural damage, infrequent vascular or visceral injuries and result to second spinal instability caused by surgery [5-10]. Although a safety zone which suggests that a breach of pedicle may not affect the surrounding tissue was proposed by Gertzbein and Belmont, spinal surgeons were unwilling to see the perforations which may endanger the adjacent structure [3, 11]. Clinical studies have shown that a distance which is less than 2 mm breach of the pedicle wall do not lead to serious complications [4, 9, 12-17]. However, anatomic fixations of the pedicle screws were still the ultimate goal for spine surgeons.

The violation of the facet joint might lead to degeneration of the adjacent vertebra or adjacent segment stenosis [18, 19]. The integrity of the facet joint was an important factor involving the development of adjacent segment after the fixation [20, 21]. The penetration of the cranial joint may disturb the evaluation of the comparative position of screws and the high density line which is an important reference for SO views, so the screws which penetrated the joint were excluded in this research. As the development of the percutaneous pedicle screw place-

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ment and minimal invasive approach, the problems should be paid more and more attention to.

Several techniques have been used to place pedicle screws, such as routine free-hand technique, CT-based navigation such as O-arm, drill guide template and robot-assisted surgical system. However, the rate of perforation of pedicle screws differ based on different technique [12, 22, 23]. O-arm was utilized in clinical operations because of immediate imaging feedback intraoperatively. Besides the additional radiation exposure and financial status, Santos et al shows that the O-arm images are not as reliable in the cervical spine as that in thoracic and lumbosacral segment [24]. Moreover, the O-arm is huge, space-demanding and matching fluoroscopic table, long preparations may be needed. As the development of rapid prototyping, Ma et al illustrated the template can decrease the rate of perforation compared with free-hand technique [25], but the soft tissue on the bone surface and spinous process should be stripped clean completely. The robot system was another developing technology accompanied with modern manufacture [26], but errors related to the reconstruction of the 3D coordinates with C-arm images, with the registration procedures and so on could not be avoided completely.

Based on AP views, the C-arm was adjusted with small scale to obtain the SO images. It was more accurate to detect malpositioned screws, and false-positive radiological assessment and false-negative ones were less compared with AP views in fracture patients. Although the accuracy of SO views may be lower than the CT navigation, it is more practical and feasible than those advanced machines. A slight adjustment of the C arm' projection pathway can make the accuracy improved obviously, SO views should be taken as an effective method to detect or review the pedicle screws. What we discuss here is not to replace the AP with SO views; the later can be made as an assisted method to decrease the rate of malpositioned screws. Traditional oblique views were obtained by tilting 45° bilaterally, and help to detect the deformity of the geometry projection of vertebral arch isthmus, but the detection of pedicles screws' location by traditional view was not reported before. The SO view is different from

the traditional ones. The entry point of operations was lies routinely lateral to the facet joint called nape of the neck of the superior articular facet. Although the rotated angle of SO views in axial plane was different from TSA (the screw angle in transverse plane) in AP view, the TSA provides a reference for our rotation degrees. The mean TSA for screws inserted within the pedicles correctly was 14.6° in thoracic vertebra [11]. The projection degree in SO views is smaller compared with TSA, so the initial rotation degrees of C-arm for SO views began from smaller degree, and 10° is chosen as the initial degree. We do not deny that fracture patients may be exposed to relative more radiation for the first time when targeting the vertebra with SO views, but wrongly inserted screws can be detected more easily combined with traditional AP and lateral views as long as the precise rotation degrees was obtained. To find the precise rotation degrees, the specimen and clinical trial will be conducted in future. This is the next step of our research, and may be completed as soon as possible.

Yukawa et al [27] utilized the axis view to give an assessment of the pedicle insertion. Compare with axial views, SO views do not need to rotate the C-arm ventrally or cephalad. Cranial/caudal inclination of pedicle screws can be detected by lateral views and medial malposition was more inclined to cause serious complications. The SO views are a simplified method to detect the medial or lateral malposition. The relative location between the tip of screws and enlightened line can be identified easier because of not rotating ventrally or cephalad, so the overlap status can be easily avoided. Radiopaque problems caused by metal screws were solved. As the problem of occupational irradiation was existed, the X-rays exposure to the patients and operators was minimized compared with other techniques if the clinical surgeons are familiar with the degrees of rotation. Compared with 8 false-positive assessments with AP views, there were only 5 false-positive assessments of 378 readings with this unique SO views. The misplaced screws can be repalpated removed as long as it was detected, and it avoided a return to operating room. The accuracy of insertion in AP views is 88%, which is in accordance with other relevant study [2].

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Although G-arm and O-arm are available, radiological assessment was still the routine way to detect the malpositions intraoperatively in Third Hospital of Hebei Medical University. The surgery cost can be the equivalent of 1 or 2 year's income for common families, and most of the patients have great expectations for the operation, meanwhile they hope to decrease the economic burden maximally. The SO view we proposed can assist traditional radiography examinations to improve the accuracy of screws placement by using the traditional C-arm to take assessment of the pedicle screws intraoperatively. What we recommend is not the most advanced technology, but the most beneficial ones which can be utilized in all the general hospital of China especially in the rural areas. The AP views may not be replaced easily, but SO views can assist traditional AP and lateral views to improve the accuracy for pedicle screws insertion in the premise of not increasing cost for patients.

A limitation of our study design is its retrospective nature and a clinical application in postoperative time. The definite degrees of rotation were still unable to be recognized, so the patients may be taken 2-3 times of pickups to find a reasonable image of SO views in our research. There is another limitation in detecting the misplaced screws if we take CT as the golden standard. Compare to dissection, the accuracy of CT is only 68% to 84% and the sensitivity can reach to 67%-94% [28, 29]. The SO views were applied to normal fracture patients in this research, for deformity ones more clinical research should be carried out.

In conclusion, SO view is more accurate in determining pedicle screw position in the lower thoracic and lumbosacral spine in fracture patients compared with that of AP views. SO views can assist traditional AP and lateral views to improve the accuracy for pedicle screws insertion without improving the economic burden on patients.

Disclosure of conflict of interest

None.

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References

- [1] Gaines RW Jr. The use of pedicle-screw internal fixation for the operative treatment of spinal disorders. *J Bone Joint Surg Am* 2000; 82-A: 1458-1476.
- [2] Kosmopoulos V and Schizas C. Pedicle screw placement accuracy: a meta-analysis. *Spine (Phila Pa 1976)* 2007; 32: E111-120.
- [3] Gertzbein SD and Robbins SE. Accuracy of pedicular screw placement in vivo. *Spine (Phila Pa 1976)* 1990; 15: 11-14.
- [4] Idler C, Rolfe KW and Gorek JE. Accuracy of percutaneous lumbar pedicle screw placement using the oblique or "owl's-eye" view and novel guidance technology. *J Neurosurg Spine* 2010; 13: 509-515.
- [5] Shin MH, Hur JW, Ryu KS and Park CK. Prospective comparison study between the fluoroscopy-guided and navigation coupled with O-arm-guided pedicle screw placement in the thoracic and lumbosacral spines. *J Spinal Disord Tech* 2015; 28: E347-351.
- [6] Parker SL, McGirt MJ, Farber SH, Amin AG, Rick AM, Suk I, Bydon A, Sciubba DM, Wolinsky JP, Gokaslan ZL and Witham TF. Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws. *Neurosurgery* 2011; 68: 170-178.
- [7] Yamagata M, Kitahara H, Minami S, Takahashi K, Isobe K, Moriya H and Tamaki T. Mechanical stability of the pedicle screw fixation systems for the lumbar spine. *Spine (Phila Pa 1976)* 1992; 17: S51-54.
- [8] Amato V, Giannachi L, Irace C and Corona C. Accuracy of pedicle screw placement in the lumbosacral spine using conventional technique: computed tomography postoperative assessment in 102 consecutive patients. *J Neurosurg Spine* 2010; 12: 306-313.
- [9] Acikbas SC, Arslan FY and Tuncer MR. The effect of transpedicular screw misplacement on late spinal stability. *Acta Neurochir (Wien)* 2003; 145: 949-954; discussion 954-945.
- [10] Kim YJ, Lenke LG, Bridwell KH, Cho YS and Riew KD. Free hand pedicle screw placement in the thoracic spine: is it safe? *Spine (Phila Pa 1976)* 2004; 29: 333-342.
- [11] Belmont PJ Jr, Klemme WR, Dhawan A and Polly DW Jr. In vivo accuracy of thoracic pedicle screws. *Spine (Phila Pa 1976)* 2001; 26: 2340-2346.
- [12] Gelalis ID, Paschos NK, Pakos EE, Politis AN, Arnaoutoglou CM, Karageorgos AC, Ploumis A and Xenakis TA. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. *Eur Spine J* 2012; 21: 247-255.

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- [13] Belmont PJ Jr, Klemme WR, Robinson M and Polly DW Jr. Accuracy of thoracic pedicle screws in patients with and without coronal plane spinal deformities. *Spine (Phila Pa 1976)* 2002; 27: 1558-1566.
- [14] Nottmeier EW, Seemer W and Young PM. Placement of thoracolumbar pedicle screws using three-dimensional image guidance: experience in a large patient cohort. *J Neurosurg Spine* 2009; 10: 33-39.
- [15] Fu TS, Wong CB, Tsai TT, Liang YC, Chen LH and Chen WJ. Pedicle screw insertion: computed tomography versus fluoroscopic image guidance. *Int Orthop* 2008; 32: 517-521.
- [16] Isaacs RE, Podichetty VK, Sandhu FA, Santiago P, Spears JD, Aaronson O, Kelly K, Hrubes M and Fessler RG. Thoracic microendoscopic discectomy: a human cadaver study. *Spine (Phila Pa 1976)* 2005; 30: 1226-1231.
- [17] Krag MH, Weaver DL, Beynon BD and Haugh LD. Morphometry of the thoracic and lumbar spine related to transpedicular screw placement for surgical spinal fixation. *Spine (Phila Pa 1976)* 1988; 13: 27-32.
- [18] Aota Y, Kumano K and Hirabayashi S. Postfusion instability at the adjacent segments after rigid pedicle screw fixation for degenerative lumbar spinal disorders. *J Spinal Disord* 1995; 8: 464-473.
- [19] Park P, Garton HJ, Gala VC, Hoff JT and McGillicuddy JE. Adjacent segment disease after lumbar or lumbosacral fusion: review of the literature. *Spine (Phila Pa 1976)* 2004; 29: 1938-1944.
- [20] Cardoso MJ, Dmitriev AE, Helgeson M, Lehman RA, Kuklo TR and Rosner MK. Does superior-segment facet violation or laminectomy destabilize the adjacent level in lumbar transpedicular fixation? An in vitro human cadaveric assessment. *Spine (Phila Pa 1976)* 2008; 33: 2868-2873.
- [21] Kim HJ, Chun HJ, Kang KT, Moon SH, Kim HS, Park JO, Moon ES, Kim BR, Sohn JS, Ko YN and Lee HM. The biomechanical effect of pedicle screws' insertion angle and position on the superior adjacent segment in 1 segment lumbar fusion. *Spine (Phila Pa 1976)* 2012; 37: 1637-1644.
- [22] Roy-Camille R, Saillant G and Mazel C. Internal fixation of the lumbar spine with pedicle screw plating. *Clin Orthop Relat Res* 1986; 7-17.
- [23] Weinstein JN, Spratt KF, Spengler D, Brick C and Reid S. Spinal pedicle fixation: reliability and validity of roentgenogram-based assessment and surgical factors on successful screw placement. *Spine (Phila Pa 1976)* 1988; 13: 1012-1018.
- [24] Santos ER, Ledonio CG, Castro CA, Truong WH and Sembrano JN. The accuracy of intraoperative O-arm images for the assessment of pedicle screw position. *Spine (Phila Pa 1976)* 2012; 37: E119-125.
- [25] Ma T, Xu YQ, Cheng YB, Jiang MY, Xu XM, Xie L and Lu S. A novel computer-assisted drill guide template for thoracic pedicle screw placement: a cadaveric study. *Arch Orthop Trauma Surg* 2012; 132: 65-72.
- [26] Tian W, Han X, Liu B, Liu Y, Hu Y, Han X, Xu Y, Fan M and Jin H. A robot-assisted surgical system using a force-image control method for pedicle screw insertion. *PLoS One* 2014; 9: e86346.
- [27] Yukawa Y, Kato F, Ito K, Horie Y, Hida T, Nakashima H and Machino M. Placement and complications of cervical pedicle screws in 144 cervical trauma patients using pedicle axis view techniques by fluoroscope. *Eur Spine J* 2009; 18: 1293-1299.
- [28] Learch TJ, Massie JB, Pathria MN, Ahlgren BA and Garfin SR. Assessment of pedicle screw placement utilizing conventional radiography and computed tomography: a proposed systematic approach to improve accuracy of interpretation. *Spine (Phila Pa 1976)* 2004; 29: 767-773.
- [29] Brooks D, Eskander M, Balsis S, Ordway N and Connolly P. Imaging assessment of lumbar pedicle screw placement: sensitivity and specificity of plain radiographs and computer axial tomography. *Spine (Phila Pa 1976)* 2007; 32: 1450-1453.