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Research Paper

Position and complications of pedicle screw insertion with or without image-navigation techniques in the thoracolumbar spine: a meta-analysis of comparative studies

Jinshan Tang, Ziqiang Zhu, Tao Sui, Dechao Kong, Xiaojian Cao✉

Department of Orthopedics, the First Affiliated Hospital of Nanjing Medical University, Nanjing, Jiangsu 210029, China.

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Abstract

Computer-navigated pedicle screw insertion is applied to the thoracic and lumbar spine to attain high insertion accuracy and a low rate of screw-related complications. However, some in vivo and in vitro studies have shown that no advantages are gained with the use of navigation techniques compared to conventional techniques. Additionally, inconsistent conclusions have been drawn in various studies due to different population characteristics and methods used to assess the accuracy of screw placement. Moreover, it is not clear whether pedicle screw insertion with navigation techniques decreases the incidence of screw-related complications. Therefore, this study was sought to perform a meta-analysis of all available prospective evidence regarding pedicle screw insertion with or without navigation techniques in human thoracic and lumbar spine. We considered in vivo comparative studies that assessed the results of pedicle screw placement with or without navigation techniques. PubMed, Ovid MEDLINE and EMBASE databases were searched. Three published randomized controlled trials (RCTs) and nine retrospective comparative studies met the inclusion criteria. These studies included a total of 732 patients in whom 4,953 screws were inserted. In conclusion, accuracy of the position of grade I, II, III and IV screws and complication rate related to pedicle screw placement were significantly increased when navigation techniques were used in comparison to conventional techniques. Future research in this area should include RCTs with well-planned methodology to limit bias and report on validated, patient-based outcome measures.

Keywords: meta-analysis, position, pedicle screw insertion, navigation, complication

INTRODUCTION

Pedicle screws, which perforate the pedicle cortex, increase the risk of dural tearing, neural damage and vascular or visceral complications, especially in the thoracic spine due to its complex anatomy and decreased pedicle dimensions[36,49]. Moreover, pedicle screw misplacement results in a loss of fixation, especially at the lower end of a construct, such as lumbar spine. Ideal pedicle screw should have a maximum diameter and length that do not breach the cortical layer of the pedicle or the vertebral body and should be converged[7]. The development of methods that improves the accuracy of pedicle screw insertion is an active area of research.

Pedicle screws are often inserted using conventional techniques that are based on anatomical landmarks of the vertebrae or assisted with any intraoperative imaging fluoroscopy, which is called fluoroscopic guided technique to localize the pedicle and evaluate the position of the pedicle screw[2,4,6,15,16,20,21,29,35,36,41,42,44,45,50,53].

✉Corresponding author: Xiaojian Cao, Department of Orthopedics, the First Affiliated Hospital of Nanjing Medical University, Nanjing, Jiangsu 210029, China. Tel/Fax: +86013002505801/+86-025-83724440, E-mail: xiaojiancao@gmail.com.

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With development of computer technology, image-navigated techniques now include computed tomography (CT)-based navigation and fluoroscopy-based navigation. Both provide 2- or 3-dimensional (2D or 3D) intraoperative imaging to assist screw insertion and have been applied extensively. Many studies reported that image-navigated techniques lead to a significant reduction in the rate of screw misplacement[1,3,9,17,24–26,28,31,37,39,42,43,51,55,56]. However, in vivo and in vitro studies found no advantages to using navigation techniques compared to conventional techniques, especially in the thoracic spine[18,28]. Additionally, it has been shown that experienced spine surgeons insert screws in the thoracolumbar region with a low incidence of screw misplacement using conventional techniques[22]. Furthermore, limitations of navigation systems relate to a lengthy learning curve, calibration errors, bending of instruments, occasional blocking of the surgical field with camera, inadvertently touching or hitting reference frames, and non-rigid connection between reference base and actual surgical site[8,12]. Although a few studies[17,24,44,57] reported that the accuracy of fluoroscopy-assisted pedicle screw insertion is comparable to that of CT navigation, differences in population characteristics and methods of assessing placement accuracy between studies have resulted in inconsistent conclusions.

The accuracy of pedicle screw insertion is determined according to the method performed to insert the pedicle and the tools (such as photography, CT, or magnetic resonance imaging (MRI)) performed to assess the position of the pedicle screw and the adoption of standard definitions of correct pedicle screw insertion. According to the relationship between the pedicle and screws, most surgeons consider pedicle violation as a safe zone of pedicle perforation smaller than 2 mm[11,22]. The grade of pedicle screw violation based on this definition is classified into four groups: screws fully contained within the pedicle; perforated screws with up to 2 mm of displacement (Grade A); perforated screws with 2–4 mm of displacement (Grade B); perforated screws with greater than 4 mm of displacement (Grade C)[15,33]. This classification has been used in the majority of studies. In addition, medial pedicle perforation greater than 4 mm may endanger the neural elements and result in neurological deficit[11,22]. However, no studies have compared all types of screw positions. The increased safety of inserting pedicle screws may be related to more accurate screw positioning and the fact that less violation of the lateral cortex is unlikely to cause neurological complications[14]. Although serious complications such as neurological, visceral, or vascular complications are very rare[30,34,52], the overall incidence of complications related to screw malposition is 0%–42%[19,32]. Moreover, it remains unclear that whether pedicle screw insertion using navigation techniques decreases the incidence of screw-related complications.

In this study, we performed a meta-analysis to compare the positioning of pedicle screws in the human thoracic and lumbar spine, and the screw-related complications with or without the assistance of navigation techniques.

MATERIALS AND METHODS

Inclusion criteria

Studies fulfilling the following criteria were eligible for inclusion. First, the report needed to be a comparative study and included randomized controlled trials (RCTs) or prospective or retrospective comparative studies, and the methods used to insert the pedicle screws were conventional techniques or image-navigated techniques. Second, the study was performed in vivo; cadaveric and animal studies as well as studies that used spine models and morphologic articles were excluded. Third, the study was published in English. Fourth, as fixing the cervical spine using the lateral mass and not the pedicle was the main technique used for the cervical spine because of its complicated anatomy, we excluded studies on pedicle screw insertion in the cervical spine. However, we accepted studies that included pedicle screws inserted into the S1 vertebrae, and we also accepted studies where the cervical spine was involved along with the thoracic and/or lumbar spine if separate results for the thoracolumbar spine were available. Fifth, the postoperative screw position must was assessed using CT or MRI.

Search strategy

The electronic databases of PubMed, Ovid MEDLINE (1950 to February, 2013), and EMBASE (1980 to February, 2013) were searched with the following search terms: "pedicle screw with navigation" or "navigated"; "computer assisted/assistance/aided"; and "image guided/guidance".

Screening and assessment of eligibility

Two of the authors (JT and ZZ) independently screened the titles and abstracts of the studies from the electronic search to identify all citations potentially containing the comparison of interest. They independently evaluated and identified these studies by searching references and abstracts from meetings to determine the final set of included articles. Disagreements were resolved by discussion and by further discussion with an independent colleague if necessary.

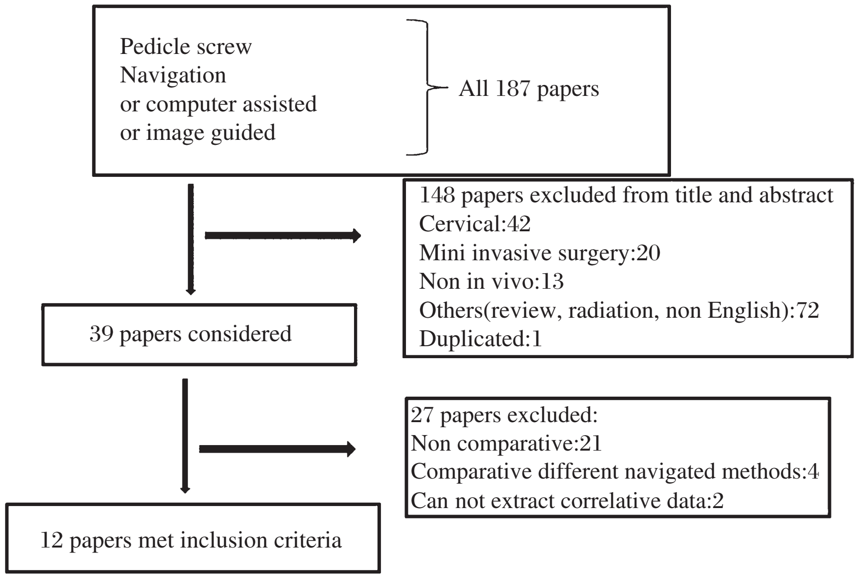

Fig. 1 **Study selection process.**

Some definitions and standardizations

Most surgeons consider a pedicle violation of less than 2 mm as a safe zone of pedicle perforation[24,38]. Although there is no strong evidence to support post–operative assessment, this was considered a criterion for inclusion in this meta-analysis[15,37]. The grade of pedicle screw violation was categorized into four groups (grade I, II, III and IV) based on published criteria. Grade I screws were those located inside the pedicle, which were defined as the ''perfect'' position for the screw; grade II screws were defined as ''safe'' zone screws; grade III screws were those in a ''potentially hazardous'' zone; and grade IV screws were defined as screws in a zone that was ''absolutely hazardous''. The screw-related complications included nerve root or spinal cord injury, vascular injury, cerebrospinal fluid leak, visceral injury and pedicle fracture[13].

Data extraction

For each eligible study, two of the authors (JT and ZZ extracted the relevant data independently for both the intervention and control groups. These data included demographic data (age and sex) and other types of data. The variables collected including type of study (RCT, prospective comparative study, or retrospective com–parative study), anatomic level, number of patients, indications, method of insertion, method of screw posi–tion assessment, accuracy of screw placement and cri–teria, pedicle screw position grades (I, II, III and IV) and screw-related complications.

Statistical analysis

Data concerning each grade of screw and screw-related complications from the included studies were pooled according to whether pedicle screw insertion was performed using conventional or navigation techni–ques. Dichotomous variables were pooled across stu–dies. The rate of pedicle violation and incidence of complications were summarized using odds ratios (OR) and 95% confidence intervals (CIs). $P < 0.05$ was considered statistical significant. Heterogeneity was evaluated by using the χ^2 test and I^2-statistics. $P < 0.1$ and $I^2 > 50\%$ were considered to be significant for heterogeneity. Fixed-effect models were used unless statistical heterogeneity was significant, in which case a random-effects model or sub-group analysis was used. Publication bias was assessed by visually examining the funnel plots based on each grade of pedicle screw and screw-related complications. All analyses were carried out in Review Manager 5.1 software (Cochrane IMS).

RESULTS

Search results

Fig. 1 shows the process for identifying eligible studies. There were 187 potentially relevant papers; after screening the title as well as reading the abstract and the entire article, we identified three published RCTs[17,25,37] and nine retrospective comparative stu–dies[1,3,9,24,26,31,39,42,43] that met all of the inclusion criteria (***Fig. 1***).

***Table 1* Characteristics of included studies**

Author and year	Type of study and class of evidence	Anatomic level	Patients	Indications	Methods of insertion	Tools and criteria for screw assessment
Allam/2013[1]	Retrospective comparative study (III)	Thoracic T1-T12	N=45 Nav n=27/Con n=18	Post-discectomy syndrome spondylolysis/ Spondylolisthesis osteochondritis	Free-hand/generic 3D-based	CT 3 mm
Shin/2012[42]	Retrospective comparative study (III)	Thoracolumbar T5-S1	N=69 Nav n=24/Con n=45	Degenerative spine diseases/metastatic spine tumors/ttraumas	C-arm/O-arm	CT 2 mm
Cui /2012[9]	Retrospective comparative study (III)	Thoracolumbar	N=59 Nav n=28/Con n=31	Scoliosis/kyphosis/scoliokyphosis	Free-hand/iCT	CT 2 mm
Sibermann/2011[43]	Retrospective comparative study (III)	Lumbosacral L1-S1	N=67 Nav n=37/Con n=30	Post-discectomy syndrome/spondylolysis/ Spondylolisthesis/osteochondritis	Free-hand/O-arm	CT 3 mm
Han/2010[17]	Randomized controlled trial (I)	Thoracic T1-T12	N=42 Nav n=20/Con n=22	Trauma/spinal stenosis, segmental instability, metastasis/spondylolisthesis	C-arm/I3D computer navigation	CT 2 mm
Sakai/2008[39]	Retrospective comparative study (III)	Thoracolumbar	N=40 Nav n= 20/Con n= 20	Scoliosis	C-arm/computer-assisted CT	CT 2 mm
Rajasekaran/2007[37]	Randomized controlled trial (I)	Thoracic	N=33 Nav n= 17/Con n= 16	Scoliosis/kyphosis	C-arm/Iso-C^{3D}	CT 2 mm
Merloz/2007[31]	Retrospective comparative study (III)	Thoracolumbar	N=52 Nav n= 26/Con n= 26	Fracture/degenerative instabilities/ spondylolithesis scoliosis	C-arm/Iso-C^{3D}	CT and X-ray 2 mm
Kotani/2007[24]	Retrospective comparative study (III)	Thoracolumbar	N=45 Nav n= 20/Con n= 25	Scoliosis	C-arm/Iso-C^{3D}	CT 1/4 diameter of a screw
Laine/2000[25]	Randomized controlled trial (I)	Thoracolumbar/lumbo–sacral	N=100 Nav n= 41/Con n= 50	Spinal stenosis/post-discectomy syndrome/ spondylolysis/spondylolisthesis/ disc degeneration/deformity	C-arm/computer-assisted CT	CT 2 mm
Amiot/2000[3]	Retrospective comparative study (III)	Thoracic lumbar sacral	N=150 Nav n= 50/Con n=100	Fracture/degenerative instabilities/ spondylolithesis/failed packsurgery/ lumbar metastasis	C-arm/computer-assisted CT	MRI 2 mm
Laine/1997[26]	Retrospective comparative study (III)	Lumbar	N=30	Post laminectomy instability/spinal stenosis/ painful disc degeneration/spondylolysis/ pseudarthrosis/post-traumatic kyphosis	C-arm/computer-assisted CT	CT 2 mm

*Nav, the navigation techniques group; Con, the conventional techniques group.

Extraction of data

A total of 732 patients and 4,953 screws were included in the 12 studies. There were 2,323 pedicle screws inserted using navigation techniques and 2,630 pedicle screws inserted using conventional tech– niques. ***Table 1*** shows a summary of these studies. CT[3,9,25,26,39] and 3D[1,17,24,31,37] imaging modalities were used to insert pedicle screws in five studies. An O-arm was used in two studies[42,43]. Eight[1,3,25,31,37,39,42,43] papers defined the number of screws in grade I, II, and III, and two papers[9,17] described cases of grade I and II. One[26] study defined only grade I screws, and another[24] study published only grade II screws (***Table 2***). Eight papers[3,9,17,25,31,37,39,42] used 2 mm as the criterion for pedi– cle screw violation, whereas two papers[1,43] used 3 mm and one[24] used 1/4 of the diameter of the screw as this criterion. With these different criteria, we pooled and analyzed the data according to sub-groups. One[3] study assessed the position of the pedicle screw using MRI, and the others used CT. Tohtz et al.[48] studied post– operative screw position using MRI or CT, and con–

Table 2 **Grade of screw and screw-related complications of included studies**

Author & year	Number of screws and criteria					Screw-related complications
		I*	II*	III*	IV*	
Allam/2013[1]	N=208	≤0 mm	<3 mm	3–6 mm	>6 mm	No screw-related complication
	Nav:100	90	99	1	1	
	Con:108	88	97	5	6	
Shin/2012[42]	N=310	≤0 mm	<2 mm	2–4 mm	>4 mm	Nav: 1, Con: 5 neurological deficit
	Nav:106	99	103	2	1	
	Con:204	186	192	8	4	
Cui /2012[9]	N=1,040	≤0 mm	<2 mm			Nav: 0, Con: 1 CSF leak
	Nav:483	458	474			
	Con:557	498	528			
Sibermann/2011[43]	N=339	≤0 mm	<3 mm	3–6 mm	>6 mm	Nav: 0, Con: 1 neurological deficit
	Nav:187	185	185	1	1	
	Con:152	127	143	4	5	
Han/2010[17]	N=176	≤0 mm	<2 mm			Nav: 0, Con: 1 pleura injury, 1 minor dura violation, 1, nerve root injury
	Nav: 92	88	92			
	Con: 84	70	81			
Sakai/2008[39]	N=478	≤0 mm	<2 mm	2–4 mm	>4 mm	No Screw-related complication
	Nav:264	205	234	27	3	
	Con:214	115	154	17	43	
Rajasekaran/2007[37]	N=478	≤0 mm	<2 mm	2–4 mm	>4 mm	No Screw-related complication
	Nav:242	237	238	4	0	
	Con:236	182	201	14	21	
Merloz/2007[31]	N=278	≤0 mm	<2 mm	2–4 mm	>4 mm	No Screw-related complication
	Nav:140	134	139	1	0	
	Con:138	120	120	18	0	
Kotani/2007[24]	N=138	≤0 mm	<1/4D			Nav: 0, Con:1 neurological deficit
	Nav:57	—	56			
	Con: 81	—	72			
Amiot/2000[3]	N=838	≤0 mm	<2 mm	2–4 mm	>4 mm	Nav:0, Con:1 neurological deficit
	Nav:294	278	294	0	0	
	Con:544	461	529	10	5	
Laine/2000[25]	N=496	≤0 mm	<2 mm	2–4 mm	>4 mm	Nav: 0, Con: 2 nerve root lesion
	Nav:219	209	217	2	0	
	Con:277	240	266	7	4	
Laine/1997[26]	N=174	≤0 mm				Nav: 0, Con: 1 pedicle fracture, 1 nerve root lesion
	Nav:139	133				
	Con: 35	30				

*Nav, the navigation techniques group; Con, the conventional techniques group; I, II, III and IV are grades of pedicle screws.

Study or subgroup	Nav Events	Nav Total	Nonnav Events	Nonnav Total	Weight	Odds ratio M–H, Random, 95% CI	Year
Laine 1997	133	139	30	35	5.5%	3.69 [1.06, 12.91]	1997
Amiot 2000	278	294	461	544	12.5%	3.13 [1.80, 5.45]	2000
Laine 2000	209	219	240	277	10.3%	3.22 [1.56, 6.64]	2000
Merloz 2007	134	140	120	138	7.7%	3.35 [1.29, 8.72]	2007
Rajasekaran 2007	237	242	182	236	7.9%	14.06 [5.51, 35.87]	2007
Saki 2008	205	264	115	214	14.8%	2.99 [2.02, 4.44]	2008
Han 2010	88	92	70	84	6.1%	4.40 [1.39, 13.96]	2010
Sibermann 2011	185	187	127	152	4.4%	18.21 [4.24, 78.24]	2011
Shin 2012	99	106	186	204	8.2%	1.37 [0.55, 3.39]	2012
Cui 2012	458	483	498	557	13.5%	2.17 [1.34, 3.52]	2012
Allam 2013	90	100	88	108	9.2%	2.05 [0.91, 4.62]	2013
Total (95% CI)		2,266		2,549	100.0%	3.36 [2.37, 4.77]	
Total events	2,116		2,117				

Heterogeneity: Tau^2 = 0.18; Chi^2 = 22.90, df = 10 (P = 0.01); I^2 = 56%
Test for overall effect: Z = 6.78 (P < 0.00001)

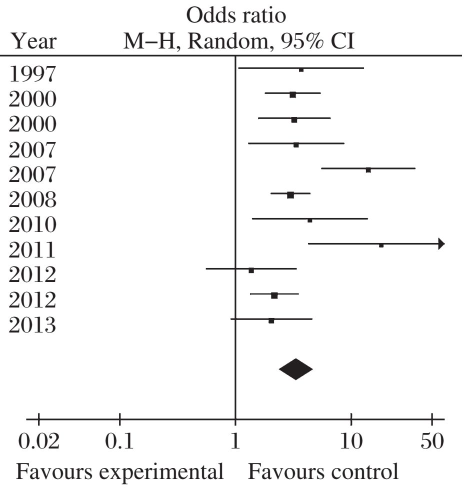

Fig. 2 **Forest plot comparing "perfect" screws (≤ 0 mm) between insertions performed with and without navigation.**

cluded that artifact-reduced MRI should be considered an alternative to the gold standard of CT for postoperative imaging after spinal fusion surgery. Therefore, we accepted data that were assessed using MRI.

Meta-analysis of each grade of pedicle screw

Eleven papers reported the number of perfect screws. The comparison of outcomes between placement with or without navigation is shown in ***Fig. 2***. Meta-analysis revealed a significant difference between image-guided and non-image-guided placement (OR: 3.36, 95%CI: 2.37, 4.77, I^2 = 56%, P < 0.00001).

Eleven papers provided the number of "safe zone" screws. As the different criteria used for perforation of the pedicle screw, such as 2 mm, 3 mm and 1/4 D, sub-group analysis was used. The comparison of outcomes with or without navigation is shown in ***Fig. 3***. Based on meta-analysis, there was a significant difference favoring procedures performed using navigation compared to those performed without navigation (OR: 4.72, 95%CI: 3.25–6.86, I^2 = 9%, P < 0.0001).

Seven papers provided the number of "potentially hazardous" screws. As different criteria were used for the perforation of the pedicle screws, including 2 mm and 3 mm, sub-group analysis was performed. The comparative outcomes for procedures performed with and without navigation are shown in ***Fig. 4***. Meta-analysis favored procedures performed with navigation compared to procedures performed without navigation (OR: 0.27, 95%CI: 0.10–0.77, I^2 = 69%, P = 0.01.)

Six papers provided the number of "absolutely hazardous" screws. As the different criteria were used for the perforation of the pedicle screw, including 2 mm and 3 mm, sub-group analysis was used. The comparison of absolutely hazardous screws between procedures with and without navigation is shown in ***Fig. 5***. Meta-analysis favored procedures performed with navigation compared to those without navigation for absolutely hazardous screws (OR: 0.09, 95%CI: 0.03–0.26, I^2 =40%, P < 0.00001).

Meta-analysis of screw-related complications

All papers included in the analysis provided rates of screw-related complications. Four papers reported no complications in two groups. The total incidence of complications was 0.22%, but only one complication occurred in the navigation group. There were 17 complications overall, including 13 neurological deficits, one cerebrospinal fluid leak, one pleural injury, one minor dura violation, and one pedicle fracture. Meta-analysis of these complications showed a significant difference favoring navigation compared to the conventional method (OR: 0.25, 95%CI: 0.09–0.70, I^2 = 0%, P = 0.008) (***Fig. 6***).

Publication bias

The funnel plot was based on each grade of pedicle screw and screw-related complications (***Fig. 7***). The graphical funnel plots based on screw-related complications of included studies appeared to be symmetrical, which suggested no publication bias, but the funnel plots based on each grade of pedicle screw of included studies appeared to be asymmetric, which suggested the presence of publication bias.

DISCUSSION

This meta-analysis has shown that for screws in the "perfect," "safe," "potentially hazardous", and "absolutely hazardous" zones, the accuracy of pedicle screw insertion was significantly improved with the aid of image-guided navigation. Based on the outcomes, screws inserted in the thoracic and lumbar spine with the use of navigation techniques exhibited a higher accuracy in pedicle screw placement than those placed with conventional techniques. The results is consistent with the report by Gelalis[14], who conducted a review to compare the free-hand, fluoroscopic-guided and navigation techniques, and found that the accuracy of screw positioning was improved when navigation assis–tance was used. However, this previous report used descriptive statistics to explain the findings. There have been four meta-analyses[23,46,47,52] published in the field of pedicle screw accuracy, and all of these reports included studies that performed retrospective analyses of screw placement and also included the cervical spine, which has a more complicated anatomy than other spinal seg–ments. These studies also showed that insertion with navigation techniques improves the accuracy of pedicle screw insertion. Tian et al.[46] also compared pedicle screw insertion accuracy with different navigation methods and found that CT and 2D and 3D navigation techniques presented few differences. However, these studies only compared the accuracy of ''safe zone'' screws with or without the use of navigation techniques, whereas the present study compared all of the different screw zones in the thoracic and lumbar spine, which suggests that the current report may provide more accu–rate evidence.

As pedicle screws were inserted in vivo, the assess–ment of pedicle screw positioning post operation must be performed using plain radiography, CT, or MRI, as opposed to dissection, which may influence the accu–racy of pedicle screw assessment. This is one possible reason why the accuracy of pedicle screw insertion in vitro is superior to that in vivo[23]. Assessment by plain radiography was not included in the present study due to its lower accuracy[5,54], whereas CT scans have been considered the ''gold standard'' for the assessment of pedicle screw placement[5,6,10,38]. The CT technique can reduce metal artifact significantly and provide 3D images that display all aspects of the position of

Study or subgroup	Nav Events	Nav Total	Nonnav Events	Nonnav Total	Weight	Odds ratio M–H, Random, 95% CI	Year
1.2.1 <2 mm							
Amiot 2000	294	294	529	544	1.7%	17.24 [1.03, 289.19]	2000
Laine 2000	217	219	266	277	5.7%	4.49 [0.98, 20.46]	2000
Merloz 2007	139	140	120	138	3.3%	20.85 [2.74, 158.50]	2007
Rajasekaran 2007	238	242	201	236	11.1%	10.36 [3.62, 29.65]	2007
Sakai 2008	234	264	154	214	36.4%	3.04 [1.87, 4.93]	2008
Han 2010	92	92	81	84	1.5%	7.94 [0.40, 156.12]	2010
Shin 2012	103	106	192	204	7.7%	2.15 [0.59, 7.78]	2012
Cui 2012	474	483	528	577	20.8%	4.89 [2.38, 10.06]	2012
Subtotal (95% CI)		1,840		2,274	88.3%	4.79 [2.96, 7.75]	
Total events	1,791		2,071				
Heterogeneity: Tau^2 = 0.12; Chi^2 = 9.83, df = 7 (P = 0.20); I^2 = 29%							
Test for overall effect: Z = 6.37 (P < 0.00001)							
1.2.2<3 mm							
Sibermann 2011	185	187	143	152	5.5%	5.82 [1.24, 27.36]	2011
Allam 2013	99	100	97	108	3.2%	11.23 [1.42, 88.63]	2013
Subtotal (95% CI)		287		260	8.6%	7.37 [2.14, 25.44]	
Total events	284		240				
Heterogeneity: Tau^2 = 0.00; Chi^2 = 0.25, df = 1 (P = 0.61); I^2 = 0%							
Test for overall effect: Z = 3.16 (P < 0.002)							
1.2.3<1/4D							
Kotani 2007	56	57	72	81	3.1%	7.00 [0.86, 56.89]	2007
Subtotal (95% CI)		57		81	3.1%	7.00 [0.86, 56.89]	
Total events	56		72				
Heterogeneity: not applicable							
Test for overall effect: Z = 1.82 (P = 0.07)							
Total (95% CI)		2,184		2,615	100.0%	4.72 [3.25, 6.86]	
Total events	2,131		2,383				
Heterogeneity: Tau^2 = 0.04; Chi^2 = 11.04, df = 10 (P = 0.35); I^2 = 9%							
Test for overall effect: Z = 8.15 (P < 0.00001)							
Test for subgrpou dofferences: Chi^2 = 0.49, df = 2 (P = 0.78); I^2 = 0%							

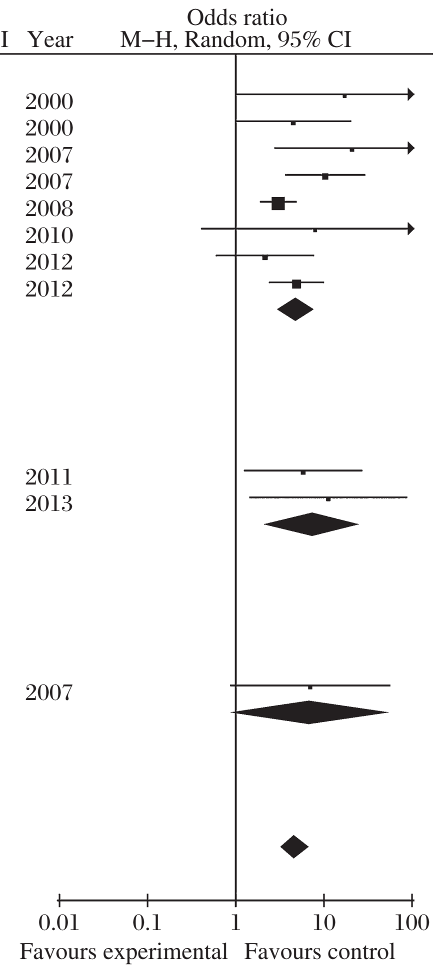

Fig. 3 **Forest plot of the comparison between ''safe zone'' screw procedures performed with and without navigation.**

	Nav		Nonnav			Odds ratio	
Study or subgroup	Events	Total	Events	Total	Weight	M–H, Random, 95% CI	Year
1.3.1 3–6 mm							
Sibermann 1997	1	187	4	152	11.5%	0.20 [0.02, 1.80]	2011
Allam 2013	1	100	5	108	11.7%	0.21 [0.02, 1.81]	2013
Subtotal (95% CI)		287		260	23.2%	0.20 [0.04, 0.95]	
Total events	2		9				
Heterogeneity: Tau² = 0.00; Chi² = 0.00, df = 1 (*P* = 0.98); I² = 0%							
Test for overall effect: Z = 2.02 (*P* = 0.04)							
1.3.2 2–4 mm							
Laine 2000	2	219	7	277	15.3%	0.36 [0.07, 1.73]	2000
Amiot 2000	0	294	10	544	8.6%	0.09[0.01, 1.48]	2000
Rajasekaran 2007	4	242	14	236	18.6%	0.27 [0.09, 0.82]	2007
Merloz 2007	1	140	18	138	12.5%	0.05 [0.01, 0.36]	2007
Sakai 2008	27	264	17	214	21.8%	1.32 [0.70, 2.49]	2008
Shin 2012	2	106	4	0		Not estimable	2012
Subtotal (95% CI)		1,265		1,409	76.8%	0.28 [0.08, 1.04]	
Total events	36		70				
Heterogeneity: Tau² = 1.51; Chi² = 17.35, df = 4 (*P* = 0.002); I² = 77%							
Test for overall effect: Z = 1.90 (P = 0.06)							
Total (95% CI)		1,552		1,669	100.0%	0.27 [0.10, 0.77]	
Total events	38		79				
Heterogeneity: Tau² = 1.19; Chi² = 19.10, df = 6 (*P* = 0.004); I² = 69%							
Test for overall effect: Z = 2.45 (P = 0.01)							
Test for subgrpou dofferences: Chi² = 0.11, df = 1 (*P* = 0.75); I² = 0%							

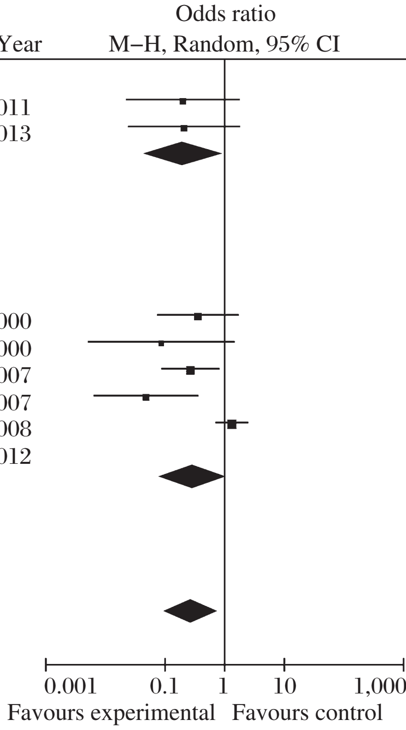

Fig. 4 **Forest plot of the outcomes for "potentially hazardous" screws compared between procedures performed with and without navigation.**

the pedicle screw. However, CT images cannot display the soft tissues clearly, especially the nerve root. In contrast, MRI provides excellent evaluation of the soft tissues, including the nerve root, although due to metal artifacts, MRI cannot display metal screws clearly. Recently, one study[48] has shown that artifact-reduced

	Nav		Nonnav			Odds ratio	
Study or subgroup	Events	Total	Events	Total	Weight	M–H, Random, 95% CI	Year
1.4.1>4 mm							
Amiot 2000	0	294	5	544	10.0%	0.17 [0.01, 3.02]	2000
Laine 2000	0	219	4	277	9.8%	0.14 [0.01, 2.59]	2000
Rajasekaran 2007	0	242	21	236	10.4%	0.02 [0.00, 0.34]	2007
Merloz 2007	0	140	0	138		Not estimable	2007
Sakai 2008	3	264	43	115	25.5%	0.02 [0.01, 0.06]	2008
Shin 2012	1	106	4	204	14.4%	0.48 [0.05, 4.31]	2012
Subtotal (95% CI)		1,265		1,514	70.2%	0.07 [0.02, 0.30]	
Total events	4		77				
Heterogeneity: Tau² = 1.27; Chi² = 7.98, df = 4 (*P* = 0.009); I² = 50%							
Test for overall effect: Z = 3.60 (*P* = 0.003)							
1.4.2>6 mm							
Sibermann 2011	1	187	5	152	14.8%	0.16 [0.02, 1.37]	2011
Allam 2013	1	100	6	108	15.0%	0.17 [0.02, 1.45]	2013
Subtotal (95% CI)		287		260	29.8%	0.16 [0.04, 0.75]	
Total events	2		11				
Heterogeneity: Tau² = 0.00; Chi² = 0.00, df = 1 (*P* = 0.96); I² = 0%							
Test for overall effect: Z = 2.33 (*P* = 0.02)							
Total (95% CI)		1,552		1,774	100.0%	0.09 [0.03, 0.26]	
Total events	6		88				
Heterogeneity: Tau² = 0.79; Chi² = 9.96, df = 6 (*P* = 0.013); I² = 40%							
Test for overall effect: Z = 4.46 (*P* = 0.00001)							
Test for subgroup differences: Chi² = 0.61, df = 1 (*P* = 0.44); I² = 0%							

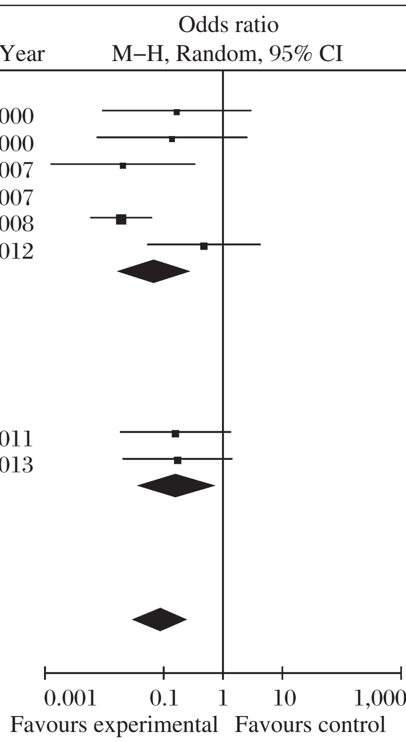

Fig. 5 **Forest plot comparing "absolutely hazardous" screws between procedures performed with and without navigation.**

Study or subgroup	Nav Events	Nav Total	Nonnav Events	Nonnav Total	Weight	Odds ratio M–H, Random, 95% CI	Year
Laine 1997	0	139	2	35	21.4%	0.05 [0.00, 1.02]	1997
Amiot 2000	0	294	1	544	5.7%	0.62 [0.02, 15.15]	2000
Laine 2000	0	219	2	277	11.9%	0.25 [0.01, 5.26]	2000
Kotani 2007	0	57	1	81	6.7%	0.47 [0.02, 11.66]	2007
Merloz 2007	0	140	0	138		Not estimable	2007
Rajasekaran 2007	0	242	0	236		Not estimable	2007
Sakai 2008	0	264	0	214		Not estimable	2008
Han 2010	0	92	3	84	19.6%	0.13 [0.01, 2.47]	2010
Sibermann 2011	0	187	1	152	8.9%	0.27 [0.01, 6.66]	2011
Cui 2011	0	483	1	557	7.5%	0.38 [0.02, 9.44]	2011
Shin 2012	1	106	5	204	18.3%	0.38 [0.04, 3.29]	2012
Allam 2013	0	100	0	108		Not estimable	2013
Total (95% CI)		2,323		2,630	100.0%	0.25 [0.09, 0.70]	
Total events	1		16				

Heterogeneity: $Tau^2 = 1.98$, df = 7 ($P = 0.96$); $I^2 = 0\%$
Test for overall effect: Z = 2.63, df = 1 ($P = 0.008$)

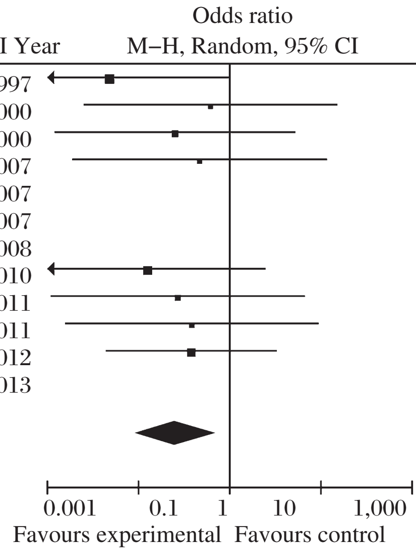

Fig. 6 **Forest plot comparing complications between procedures performed with and without navigation.**

MRI could be considered an alternative to the gold standard for postoperative imaging to assess the accuracy of pedicle screw insertion, as this technique can reveal the relationship of the pedicle screw to the nerve root after spinal fusion surgery. Thus, MRI will likely become a standard method to assess the position of pedicle screws in the future.

Malposition of a pedicle screw leads to many complications, such as dural lesions, nerve root irritation, vascular injury, cerebrospinal fluid leak, visceral injury and pedicle fracture. However, there are few symptomatic complications relative to the high rate of pedicle screw perforations[27,30,34,52]. Neurological complications while inserting pedicle screws are rare but serious. In our study, 12 papers reported that 94 screws perforated the pedicle by more than 4 mm, but only 17 screw-related complications were reported, with a mean incidence of 18%. The results of our study show that dural lesions and irritation of nerve roots occurred in a mean of 0.06% and 0.15% of pedicle screws, respectively. In all 12 papers, only one complication was reported in the group using navigation techniques. However, Schulze et al.[40] reported that experienced surgeons could accurately place pedicle screws in 80% of cases with conventional techniques and that neurological symptoms are rarely affected by an inaccurate pedicle screw placement, even if the penetration of the pedicle wall is greater than 6 mm. Gelalis et al.[14] showed in a review that the neurological complication rate was similar between studies using CT navigation, the free-hand technique and fluoroscopy. In our meta-analysis, pedicle screw insertion using navigational techniques led to a significantly lower incidence of screw-related complications compared to conventional methods ($P = 0.008$).

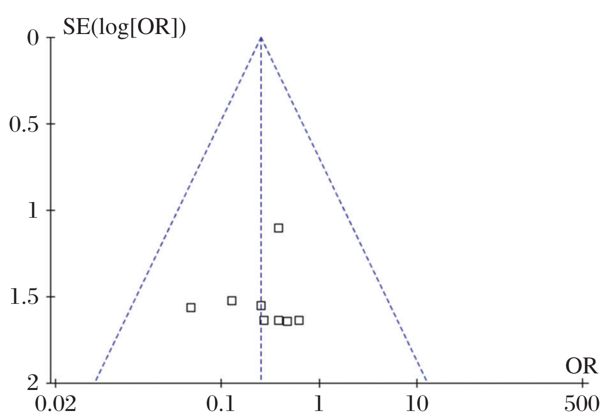

Fig. 7 **Funnel plot checking the publication bias based on screw-related complications.**

The results of this meta-analysis should be interpreted with caution due to several limitations. First, only three studies were RCTs, and most data included in the present study were reported from nonrandomized, controlled trials. A meta-analysis of such data leads to less powerful results compared to those obtained purely from randomized studies. However, it is difficult to conduct a prospective randomized trial to answer these types of questions due to poor patient compliance, different patient demographic characteristics and different indications for surgery. Second, methods and tools used to assess postoperative screw position vary across studies, and these differences are usually associated with heterogeneity among studies. Furthermore, technical issues, such as differences in surgeons′ skills, varying complexity of the surgery, and screw/pedicle dimensions could be responsible for this reported heterogeneity. Other limitations include the heterogeneity of different navigation techniques and the different spine levels instrumented. Although the outcome of the current study indicated a significant difference, the funnel plots based on each grade of screw showed obvious publication bias as authors are more likely to report positive outcomes. We also only included papers written in English.

In conclusion, our study showed that the accuracy and complication rate of pedicle screw insertion using navigation techniques was superior to those obtained using conventional techniques. Furthermore, research in this area should include RCTs with well-planned methodologies to limit bias and report on validated patient-based outcome measures.

The outcome of this meta-analysis found that the accuracy and complication rate of pedicle screw insertion using navigation techniques was superior to those obtained using conventional techniques. More RCTs of high quality are needed to strengthen the quality of evidence.

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Retraction: Physical and degradation properties of PLGA scaffolds fabricated by salt fusion technique.

The paper entitled "Physical and degradation properties of PLGA scaffolds fabricated by salt fusion technique. *J Biomed Res* 27(4), 318–325 (**DOI**: 10.7555/JBR.27.20130001)" has been retracted. The paper is withdrawn at the request of the editor as it contains plagiarized materials from Murphy, William L., *et al*. "Salt fusion: an approach to improve pore interconnectivity within tissue engineering scaffolds." *Tissue engineering* 8.1 (2002): 43–52. The Publisher apologizes for any inconvenience this may cause.