Image-guided pedicle screw insertion accuracy: a meta-analysis

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Abstract Improved pedicle screw insertion accuracy has been reported with the assistance of computer tomography-based navigation. Studies also indicated that fluoroscopy-based navigation offers high accuracy and is comparable to CT-based assistance. However, different population characteristics and assessment methods resulted in inconsistent conclusions. We searched OVID, Springer, and MEDLINE databases to conduct a meta-analysis of the published literature specifically looking at accuracy of pedicle screw placement with different navigation methods. Subgroups and descriptive statistics were determined based on the subject type (in vivo or cadaveric), navigational method, and spinal level. A total number of 7,533 pedicle screws were summarised in our database with 6,721 screws accurately inserted into the pedicles (89.22%). Overall, the median placement accuracy for the in vivo CT-based navigation subgroup (90.76%) was higher than that with the use of two-dimensional (2D) fluoroscopy-based navigation (85.48%). We concluded that CT-based navigation could provide a higher accuracy in the placement of pedicle screws for all subgroups presented. In the lumbar level, 2D fluoroscopy-based navigation was comparable with CT-based navigation. Discrepancy between the two navigation types increased in the thoracic level for the in vivo populations, where there was less potential in the use of 2D fluoroscopy-based navigation than CT-based navigation.

Introduction

Transpedicle screw fixation has been accepted worldwide since Harrington et al. first placed pedicle screws through the isthmus [1]. Studies have reported that transpedicle screw fixation has gained an advantage over other forms of spinal instrumentation [2, 3]. Safety concerns on the violation of the spinal canal leading to potential harm to vascular, neural, and other vital structures have been encouraging surgeons to improve the accuracy of pedicle screw placement by trying various approaches [2, 3, 7–60]. Through many conventional methods, usually relying on anatomical landmarks, pedicle screws were inserted with or without fluoroscopy to localise the pedicle. However, studies have reported high rates of cortical perforation [13, 24, 27, 53].

Image-guided technology has greatly broadened the scope of modern surgery and has improved the clinical results of various non-spinal orthopaedic operations [4–6]. In vivo and in vitro studies indicated that pedicle screw insertion accuracy could be significantly improved with image-assisted systems compared with conventional approaches [10, 15, 21, 22, 24, 25, 27, 32, 36, 44]. Among them, computed tomography-based navigation (CT Nav) was the most popular. CT Nav could provide precise anatomy of the pedicle as well as reduced radiation exposure. However, new concerns about the system arose with a steep learning curve and excessive preoperative preparation including computed tomography with a specific protocol, data acquisition and transfer, and patient registration [23, 45]. The development of intraoperative two dimensional and three dimensional fluoroscopy-based navigation (2D FluoroNav and 3D FluoroNav) appeared to tackle such issues [7, 23, 25, 34, 38, 39, 45, 52]. The equipment did not require registration, it reduced imaging time and radiation dosage, and avoided repeated C-arm

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movements during surgery because visualisation of the surgical instruments in relation to the patient's anatomy in all the desired image planes was determined from the beginning. Though a few studies implied that accuracy of fluoroscopy-assisted pedicle screw insertion was comparable with that of CT Nav [23, 43, 45], different population characteristics and assessment methods of placement accuracy in various studies resulted in inconsistent conclusions.

To investigate these issues, the authors conducted a systematic meta-analysis of the published literature which looked at the accuracy of pedicle screw placement with the image-guided systems in the human spine. Postoperative methods used for pedicle screw placement assessment were identified, and we used a uniform method to assess the insertion accuracy in this study. A meta-analysis combining the results of numerous studies could obtain more value for clinical reference than a single study.

Materials and methods

Literature search

A literature search was conducted covering the span from 1990 until March 7, 2009 using OVID, Springer, and MEDLINE databases. Screening included titles, subtitles, and abstracts by combining the term pedicle screw with each of the following keywords: computer assisted/assistance/aided, image guided/guiding/guidance, navigation, and navigated. No language restriction was used. Additionally, a review of all references from the identified papers was performed.

The following inclusion criteria were used: (1) the study should have a design in which the pedicle screw was inserted with one of the navigation methods (studies without an image-assisted study design were excluded), (2) the study should include living or cadaveric human spine (studies with only animal or artificial models were excluded), and (3) postoperative assessment of the pedicle screw placement was conducted.

Meta-database construction

To construct the meta-database, the fields and parameters as defined below, when available, were recorded for each study. Categories were developed to classify studies as either clinical and/or cadaveric. The demographics of each study population were recorded when available and applicable. Navigation types and methods for postoperative assessment of the pedicle screw placement of each study were discriminated. The range of vertebral segments instrumented with pedicle screws was recorded for single

spinal level (e.g. the cervical, thoracic, lumbar [including S1]), multi-spinal levels (e.g. cervical and thoracic, thoracic and lumbar, the whole spine) and spinal level unstated for each study. The total number of pedicle screws and misplaced screws were noted. Data of studies including multi-spinal levels were extracted and recorded according to detailed spinal level if they were available, and were used for further subgroup analysis. Figure 1 depicts how the studies were classified. In this study, a unified way was used for assessing pedicle screw accuracy. Pedicles without any perforation after screw insertion were extracted from the total screws placed and were defined as nonbiased screws. Studies comparing two or more navigation techniques or different populations (e.g. in vivo patient vs cadaveric, scoliosis vs non-scoliosis) were divided into sub-studies.

After setting up the meta-database, subgroups were analysed according to the filtering of results. The meta-database was first divided based on the subject type (in vivo patient or cadaveric population) and then separated based on the spinal levels. If multiple examiners and/or multiple postoperative assessing methods were applied in the paper, the most accurate way was retained (e.g. results stored radiologist over those of the surgeon, and direct dissection results over CT and CT over radiographic assessments).

Meta-analysis

The descriptive statistics in this study summarise the data using SPSS 10.0 software (SPSS Inc., Chicago, IL, USA). The descriptive statistics included 5% trimmed mean, the median, standard deviation, minimum and maximum, and interquartile range. The 5% trimmed mean was calculated by excluding the lowest and highest 2.5% of the data (possible outliers). The median is used to calculate the central tendency for both normal and skewed distributed data. The box plots display the 25th and 75th percentiles (interquartile range) of the data set, the median accuracy, and possible outliers.

Results

Literature search

The search resulted in 131 references from the database. Seventy-seven studies (58.8%) were omitted in accordance with our predefined exclusion criteria. Thirty-five papers were removed because they were unrelated to image-guided pedicle screw insertion. Eighteen of the excluded studies were the review papers. Four surveys were conducted on either animal or artificial models. Two technical note papers and four studies merely addressing radiation dose or

Fig. 1 Schematic showing the subgroups developed from the meta-database based on subject type and spinal level

registration issues were also omitted. Two experiments on robot-assisted navigation were not taken into the final review. Twelve clinical articles were removed because pedicle screws were placed but no information could be used for accuracy assessment. Thus, data of 54 [7–60] remaining studies were extracted for further analysis.

Meta-database characteristics

The remaining 54 studies (48 English, four German, one French, and one Chinese) could be classified into 35 clinical [7–41] and 20 cadaveric [41–60] articles. One study [41] was labelled into two categories. In the clinical group, all studies used postoperative CT for their analysis of pedicle screw placement. Two of them used CT and radiographs, and one study applied CT and EMG along with intraoperative visualisation. In the cadaveric group, six researches (30.0%) used dissection-based approaches, four (20.0%) used CT, seven (35.0%) used CT and dissection, and three studies used CT and radiographs (15.0%) for assessment. In the in vivo studies, the most common assessment method for pedicle placing accuracy was the 2-mm increment deviation classification. Twenty-five studies (71.4%) used this classification along with the screw direction when deviation was present. However, in the in vitro tests, various assessments were identified based on the authors' own definitions.

According to navigation type, all 54 studies could also be classified into 40 CT navigated, 20 2D fluoroscopy navigated, and six 3D fluoroscopy navigated sub-studies.

Five studies (two with CT Nav and three with 2D FluoroNav) were divided because each of them contains two populations with remarkably different characteristics. Seven studies could be classified into two categories because they used two navigation methods in their experiments.

Based on spinal level, 30 studies (55.6%) included a single spinal level and 20 studies (37.0%) contained two spinal levels. The spinal levels of the remaining four studies (7.4%) were unstated. Of the 20 studies containing two spinal levels, twelve studies were further divided into sub-studies based on extracted single spinal level because they provided enough information about the pedicle screw number in the specific spinal level.

In our review, two cadaveric studies [43, 45] compared screw insertion accuracy between the CT and 2D fluoroscopy-guided methods. In three retrospective in vivo studies [7, 23, 38], two navigation methods were compared (2D vs 3D FluoroNav, 2D FluoroNav vs CT Nav, and 3D FluoroNav vs CT Nav, respectively).

A total number of 7,533 pedicle screws were summarised in our database with 6,721 screws accurately inserted into the pedicles (89.22% weighted mean accuracy). A total of 6,063 were placed in vivo, with a weighted mean accuracy of 90.21% (median 91.14%), and 1,470 were placed in vitro, with a weighted mean accuracy of 85.10% (median 90.83%).

In vivo population filter and descriptive statistics

In 42 in vivo studies or sub-studies, there were 27 CT navigated, ten 2D fluoroscopy navigated, and five 3D

Table 1 Descriptive statistics of the pedicle screw insertion accuracy in the in vivo and cadaveric populations at all spinal levels with the assistance of different navigation systems

Descriptive statistic	In vivo			Cadaveric		
	CT Nav	2D FluoroNav	3D FluoroNav	CT Nav	2D FluoroNav	3D FluoroNav
5% trimmed mean accuracy	89.59%	86.96%	94.13%	87.06%	83.81%	*
Median accuracy	90.76%	85.48%	97.16%	94.59%	90.12%	*
Minimum accuracy	72.03%	72.73%	80.85%	50.00%	43.33%	*
Maximum accuracy	98.25%	96.05%	99.29%	100.00%	98.37%	*
Accuracy range	26.22%	23.32%	18.44%	50.00%	50.04%	*
Interquartile accuracy range	10.36%	11.64%	11.48%	21.49%	17.61%	*
Standard deviation	7.02%	7.44%	7.52%	16.13%	17.79%	*
Total screws	3,554	1,219	1,290	801	663	6
Perfect screws	3,191	1,060	1,219	678	568	5

* Indicates number of studies too few to calculate statistic

CT Nav computed tomography-based navigation, 2D FluoroNav and 3D FluoroNav two dimensional and three dimensional fluoroscopy-based navigation

fluoroscopy navigated articles. For the CT Nav subgroup, 3,554 screws were placed and the range in placement accuracy was 26.22% (minimum 72.03%, maximum 98.25%) with a median accuracy of 90.76%. In the 2D FluoroNav subgroup, a total of 1,219 pedicle screws were inserted. The median accuracy and range were 85.48% and 23.32% (minimum 72.73%, maximum 96.05%), respectively. For the 3D-fluoroscopy navigated subgroup, the range in placement accuracy was 18.44% (minimum 80.85%, maximum 99.29%) with a median accuracy of 97.16%. Further descriptive statistics and a box plot comparing these three subgroups can be found in Table 1 and Fig. 2.

Fig. 2 Box plots showing the accuracy of pedicle screw insertion assisted by computed tomography (CT), 2D fluoroscopy, and 3D fluoroscopy-based navigation for all spinal levels of the in vivo patient

Based on pure studies (studies with two spinal levels were not divided), the CT navigated subgroup only at the lumbar and/or thoracic spine levels included 16 papers and a total of 2,333 pedicle screws placed. Using the same filtering for the 2D fluoroscopy navigated subgroup resulted in eight papers and a total of 1,156 pedicle screws placed with a lower median accuracy (86.51%) than the CT-assisted subgroup (91.14%). Descriptive statistics and a box plot for these subgroups can be found in Table 2 and Fig. 3, respectively.

Based on pure and spinal level extracted studies and filtering by spine level resulted in three pure thoracic, six extracted thoracic, six pure lumbar and four extracted lumbar papers for the in vivo subgroup with the use of CT navigation. Using the same filtering for the 2D fluoroscopy navigated group resulted in two pure thoracic, five extracted thoracic, one pure lumbar and four extracted lumbar papers. In the lumbar level, CT Nav obtained a median accuracy of 90.32% compared with 86.96% for the 2D FluoroNav subgroup. However, the discrepancy of median accuracy between the two navigational methods increased at the thoracic level (91.52% vs 82.51%). Further descriptive statistics can be found in Table 3.

Cadaveric population filter and descriptive statistics

In 24 in vitro studies or sub-studies, there were 13 CT navigated, ten 2D fluoroscopy navigated, and one 3D fluoroscopy navigated articles. For the CT Nav subgroup, 801 screws were placed and the range in placement accuracy was 50.00% (minimum 50.00%, maximum 100.00%) with a median accuracy of 94.59%. In the 2D fluoroscopy navigated subgroup, a total of 663 pedicle

Table 2 Descriptive statistics comparing the in vivo and cadaveric subgroups only at the lumbar and/or thoracic spine levels with the assistance of CT and 2D fluoroscopy-based navigation

Descriptive statistic	In vivo		Cadaveric	
	CT Nav	2D FluoroNav	CT Nav	2D FluoroNav
5% trimmed mean accuracy	89.93%	87.48%	90.51%	87.81%
Median accuracy	91.14%	86.51%	94.65%	91.67%
Minimum accuracy	72.03%	72.73%	59.38%	58.33%
Maximum accuracy	98.25%	96.05%	100.00%	98.37%
Accuracy range	26.22%	23.32%	40.63%	40.04%
Interquartile accuracy range	9.82%	12.30%	13.93%	11.74%
Standard deviation	6.83%	7.74%	12.91%	11.95%
Total screws	2,333	1,156	660	633
Perfect screws	2,110	1,008	574	555

CT Nav computed tomography-based navigation, 2D FluoroNav two dimensional-based navigation

screws were inserted. The median accuracy and range were 90.12% and 50.04% (minimum 43.33%, maximum 98.37%), respectively. Further descriptive statistics and a box plot comparing these three subgroups can be found in Table 1 and Fig. 4.

Based on pure studies (studies with two spinal levels were not divided), there were ten papers and a total of 660 pedicle screws inserted in the CT navigated subgroup only with the lumbar and/or thoracic spine levels included. Using the same filter for the 2D fluoroscopy navigation group resulted in nine studies and a total of 633 pedicle screws placed with a lower median accuracy (91.67%) than the CT-based navigation group (94.65%). Descriptive statistics and a box plot for these subgroups can be found in Table 2 and Fig. 5, respectively.

Based on pure and extracted studies and filtering by spine level resulted in five pure thoracic, two extracted thoracic, one pure lumbar and two extracted lumbar papers

for the in vivo subgroup with the use of CT navigation. Using the same filter for the 2D fluoroscopy navigated subgroup resulted in two pure thoracic, one extracted thoracic, three pure lumbar and one extracted lumbar papers. In the thoracic level, CT Nav obtained a median accuracy of 92.50% compared with 88.57% for the 2D FluoroNav subgroup. In the lumbar level, three studies with CT navigation obtained pedicles all accurately placed into the pedicle (100.00%) and the median accuracy was 94.17% for the 2D fluoroscopy navigation group. Further descriptive statistics can be found in Table 4.

Discussion

Although the transpedicle screw fixation is commonplace in spinal surgery, it is still a technically demanding procedure. Various conventional methods were developed to assist with screw insertion. However, the high pedicle malposition rate encouraged surgeons to search for the perfect method for screw placement [13, 24, 27, 53]. Image guided systems appeared to improve the surgical accuracy for pedicle screw placement. Kosmopoulos et al. [61] pooled previous studies on pedicle screw placement accuracy and used a descriptive method to assess the accuracy between conventional and navigated methods. The study indicated that navigation does provide a higher accuracy in the placement of pedicle screws except at the thoracic levels. In the studies of our search, a total of 13 in vivo [10, 12, 13, 15, 18, 21, 22, 24, 25, 27, 32, 35, 36] and nine in vitro [42, 44, 48–51, 53, 55] studies or sub-studies were detected to compare the pedicle screw insertion accuracy between the conventional and navigational methods. We further analysed the relative risk of malposition rate of the image-guided over the conventional method and found most of them indicated that navigation groups were associated with a smaller risk of screw malposition compared with non navigation groups with statistically significant RR values in one in vitro [44]

Fig. 3 Box plots comparing pedicle screw insertion accuracy with computed tomography (CT) and 2D fluoroscopy-based navigation for only the thoracic and/or lumbar spinal levels of the in vivo patient

Table 3 Descriptive statistics comparing only the in vivo subgroups at the lumbar or thoracic spinal level with the assistance of CT and 2D fluoroscopy-based navigation

Descriptive statistic	Thoracic		Lumbar	
	CT Nav	2D FluoroNav	CT Nav	2D FluoroNav
5% trimmed mean accuracy	91.41%	77.94%	89.21%	85.02%
Median accuracy	91.52%	82.51%	90.32%	86.96%
Minimum accuracy	80.00%	60.00%	72.03%	72.73%
Maximum accuracy	100.00%	100.00%	95.68%	90.74%
Accuracy range	20.00%	40.00%	23.65%	18.01%
Interquartile accuracy range	13.19%	30.91%	11.37%	11.82%
Standard deviation	7.08%	15.87%	7.50%	7.20%
Total screws	646	453	1,281	530
Perfect screws	574	367	1,164	465

CT Nav computed tomography-based navigation, 2D FluoroNav two dimensional-based navigation

and nine in vivo [10, 15, 21, 22, 24, 25, 27, 32, 36] studies. Overall, pedicle screw insertion with navigation assistance does improve accuracy especially in the in vivo studies.

The first generation of navigation applied to spinal surgery was the computer tomography-assisted system. Many researches indicated that CT Nav could improve pedicle screw placement accuracy [10, 15, 22, 24, 27, 32, 36, 44]. However, concerns about the system with a steep learning curve and excessive preoperative preparation prevented this technique from being widely adopted [23, 45]. The 2D and 3D FluoroNav systems appeared to solve the above problem by eliminating or minimising steps such as preoperative scanning, data acquisition and transfer, and intraoperative registration [23, 45]. In our searched studies, one in vivo retrospective study [23] compared pedicle screw insertion accuracy between 2D FluoroNav and CT Nav. CT Nav obtained a lesser but insignificant risk compared with the 2D FluoroNav ($P=0.45$, $RR=0.58$,

95% $CI=0.14$ – 2.36). Two in vitro studies [43, 45] also compared the accuracy between 2D FluoroNav and CT Nav. The pooled estimate of effect size from the two studies demonstrated that the CT-based navigation group was associated with a lesser (but insignificantly so) risk of screw malposition rate compared with 2D FluoroNav group ($P=0.12$, $RR=0.64$, 95% $CI=0.36$ – 1.12). Another in vivo retrospective study [38] compared accuracy between 3D fluoroscopy and CT-based navigation. 3D FluoroNav obtained a lesser (but insignificantly so) risk compared with the CT assistance ($P=0.15$, $RR=0.71$, 95% $CI=0.45$ – 1.12). The statistically insignificant differences might be attributed to the small number of pedicle screws in these studies. As a result, it became necessary to perform a meta-analysis combining the results of numerous previous studies to draw more confident and acceptable conclusions, thus resulting in our study.

After reviewing the searched papers, we found only six studies [7, 25, 34, 38, 39, 45, 52] which assessed accuracy of the 3D fluoroscopy assisted pedicle screw insertion (five in vivo and one in vitro). Due to the lack studies with such assistance, the authors did not make much descriptive analysis for 3D FluoroNav. The main part of this survey focussed on 2D fluoroscopy and CT-based navigation and we tried to compare the screw insertion accuracy between them. Based on subject type, we found that the median placement accuracy for both the in vivo and in vitro subgroups with CT assisted navigation (in vivo=90.76%, in vitro=94.59%) was higher than that of the corresponding subgroup with 2D FluoroNav (in vivo=85.48%, in vitro=90.12%) when only pure studies with any spinal level were considered (Table 1, Figs. 2 and 4). It was also interesting to note that the results were found to be consistent when only thoracic and/or lumbar segments were considered (Table 2, Figs. 3 and 5). Moreover, when we further extracted single spinal level data from studies with multi-spinal levels and re-analysed the database based on one spinal level (thoracic or lumbar), the same conclusion was

Fig. 4 Box plots comparing pedicle screw insertion accuracy with computed tomography (CT) and 2D fluoroscopy-based navigation for all spinal levels of the cadaveric population

Fig. 5 Box plots comparing pedicle screw insertion accuracy with computed tomography (CT) and 2D fluoroscopy-based navigation for only the thoracic and/or lumbar spinal levels of the cadaveric population

made, namely, that CT Nav provided a higher accuracy compared with 2D FluoroNav (Tables 3 and 4). It was noteworthy that discrepancy between the two navigation methods became larger after extracting single spinal level data from multi-spinal level studies, especially at the in vivo thoracic level (CT Nav=91.52%, 2D FluoroNav=82.51%) (Table 3), which meant there was less potential in the use of 2D FluoroNav than CT Nav in this spinal segment. However, the smaller difference between the two at the lumbar level implied a similar advantage in the use of both navigation methods.

Kosmopoulos et al. [61] discussed the importance of clearly defining the pedicle screw placement assessment method. Take the common assessment of “in” or “out” for example; a screw “in” the pedicle could be interpreted as a screw completely in the pedicle without any violation and also could be regarded as a screw safely placed in, allowing

perforation to certain extent, which was mainly determined by the evaluator’s opinion. In our study, various kinds of assessment methods were identified from the reviewed papers and most studies provided detailed information about the magnitude and direction of misplacement. The author carefully reviewed the papers and extracted the information of screws perfectly in the pedicle without any deviation to build a comparable database allowing for synthesis of the results. Though simple, such gauging provided a unified method used to synthesise numerous published studies and draw a more acceptable result.

In this study we mainly used the median to describe the central tendency rather than the arithmetic mean, weight or geometric mean. For one thing, the database in our study does not represent results of one experiment or the conclusion of homogenous researches, and it’s better to “describe” rather than to “calculate”. As a result, we used the median along with box plots for our study. Another reason is that the median could be used to describe the central tendency for both normal and skewed distributed data, and it was possible to detect the difference between a group of normal data and another one of skewed data. The other information we provided in the study, such as 5% trimmed mean, was for the purpose of providing convenience for comparisons when other authors reported results with a similar form.

Theoretically, it is of convenience to control the variates in the cadaveric study which could provide confident results. However, such results were questioned on account of the difference between in vivo and in vitro conditions. As a result, RCTs comparing two medical treatments might provide more powerful evidence than other kinds of research for clinical studies. Though three retrospective studies [7, 23, 38] were identified, no RCTs were found comparing two navigation methods after our search, which might not lead to a powerful conclusion. As a result, the current meta-analysis might obtain clinical reference, for

Table 4 Descriptive statistics comparing only the in vitro subgroups at the lumbar or thoracic spinal level with the assistance of CT and 2D fluoroscopy-based navigation

Descriptive statistic	Thoracic		Lumbar	
	CT Nav	2D FluoroNav	CT Nav	2D FluoroNav
5% trimmed mean accuracy	86.98%	*	*	92.40%
Median accuracy	92.50%	88.57%	100.00%	94.17%
Minimum accuracy	59.38%	58.33%	100.00%	82.79%
Maximum accuracy	95.83%	99.01%	100.00%	97.59%
Accuracy range	36.46%	40.68%	0.00%	14.80%
Interquartile accuracy range	20.00%	*	*	11.52%
Standard deviation	13.78%	21.13%	*	6.50%
Total screws	442	219	92	260
Perfect screws	369	190	92	234

* Indicates number of studies too few to calculate statistic
CT Nav computed tomography-based navigation, 2D FluoroNav two dimensional-based navigation

cumulative studies taken into the analysis with a uniform assessing method.

There are limitations to this study. The best evidence should be a meta-analysis of numerous RCTs with high quality. Our research is a descriptive research on various studies with different population characteristics and methods. Heterogeneities might result from differences in surgeons' skill, screw dimension/accuracy assessment method, and publication bias. Furthermore, it might not be proper to extract single spinal level data from multi-spinal level studies to make a data pool. However, we conducted an extensive search with no language limitation and a uniform method to obtain the data and pool an acceptable and comparable database. Detailed information provided by the studies made it possible to explore more potential information about the screws in the specific spinal level, and cumulative findings resulting from a meta-analysis with a specific spinal level can provide more value for clinical reference. It was noteworthy that the difference in pedicle placing accuracy between 2D fluoroscopy and CT-assisted navigation remained consistent when compared with each other based on different classifications.

References

- Harrington PR, Tullos HS (1969) Reduction of severe spondylolisthesis in children. *South Med J* 62:1–7
- 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
- Karatoprak O, Unay K, Tezer M, Ozturk C, Aydogan M, Mirzanli C (2008) Comparative analysis of pedicle screw versus hybrid instrumentation in adolescent idiopathic scoliosis surgery. *Int Orthop* 32:523–528
- Luring C, Oczipka F, Grifka J, Perlick L (2008) The computer-assisted sequential lateral soft-tissue release in total knee arthroplasty for valgus knees. *Int Orthop* 32:229–235
- Ybinger T, Kumpan W (2007) Enhanced acetabular component positioning through computer-assisted navigation. *Int Orthop* 31: S35–S38
- Seon JK, Song EK, Yoon TR, Bae BH, Park SJ, Cho SG (2007) In vivo stability of total knee arthroplasty using a navigation system. *Int Orthop* 31:45–48
- Lekovic GP, Potts EA, Karahalios DG, Hall G (2007) A comparison of two techniques in image-guided thoracic pedicle screw placement: a retrospective study of 37 patients and 277 pedicle screws. *J Neurosurg Spine* 7:393–398
- Kotani Y, Abumi K, Ito M, Takahata M, Sudo H, Ohshima S, Minami A (2007) Accuracy analysis of pedicle screw placement in posterior scoliosis surgery: comparison between conventional fluoroscopic and computer-assisted technique. *Spine* 32:1543–1550
- Lim MR, Girardi FP, Yoon SC, Huang RC, Cammisa FP (2005) Accuracy of computerized frameless stereotactic image-guided pedicle screw placement into previously fused lumbar spines. *Spine* 30:1793–1898
- Laine T, Lund T, Ylikoski M, Lohikoski J, Schlenszka D (2000) Accuracy of pedicle screw insertion with and without computer assistance: a randomised controlled clinical study in 100 consecutive patients. *Eur Spine J* 9:235–240
- Papadopoulos EC, Girardi FP, Sama A, Sandhu HS, Cammisa FP Jr (2005) Accuracy of single-time, multilevel registration in image-guided spinal surgery. *Spine J* 15:263–267
- Richter M, Cakir B, Schmidt R (2005) Cervical pedicle screws: conventional versus computer-assisted placement of cannulated screws. *Spine* 30:2280–2287
- Lee GY, Massicotte EM, Rampersaud YR (2007) Clinical accuracy of cervicothoracic pedicle screw placement: a comparison of the "open" lamino-foraminotomy and computer-assisted techniques. *J Spinal Disord Tech* 20:25–32
- Rampersaud YR, Pik JH, Salonen D, Farooq S (2005) Clinical accuracy of fluoroscopic computer-assisted pedicle screw fixation: a CT analysis. *Spine* 30:E183–E190
- Amiot LP, Lang K, Putzier M, Zippel H, Labelle H (2000) Comparative results between conventional and computer-assisted pedicle screw installation in the thoracic, lumbar, and sacral spine. *Spine* 25:606–614
- 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
- Richter M, Mattes T, Cakir B (2004) Computer-assisted posterior instrumentation of the cervical and cervico-thoracic spine. *Eur Spine J* 13:50–59
- Ito H, Neo M, Yoshida M, Fujibayashi S, Yoshitomi H, Nakamura T (2007) Efficacy of computer-assisted pedicle screw insertion for cervical instability in RA patients. *Rheumatol Int* 27:567–574
- Rampersaud YR, Lee KS (2007) Fluoroscopic computer-assisted pedicle screw placement through a mature fusion mass: an assessment of 24 consecutive cases with independent analysis of computed tomography and clinical data. *Spine* 32:217–222
- Carbone JJ, Tortolani PJ, Quartararo LG (2003) Fluoroscopically assisted pedicle screw fixation for thoracic and thoracolumbar injuries: technique and short-term complications. *Spine* 28:91–97
- Merloz P, Troccaz J, Vouaillat H, Vasile C, Tonetti J, Eid A, Plaweski S (2007) Fluoroscopy-based navigation system in spine surgery. *Proc Inst Mech Eng [H]* 221:813–820
- Laine T, Schlenszka D, Mäkitalo K, Tallroth K, Nolte LP, Visarius H (1997) Improved accuracy of pedicle screw insertion with computer-assisted surgery. A prospective clinical trial of 30 patients. *Spine* 22:1254–1258
- 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
- Merloz P, Tonetti J, Pittet L, Coulomb M, Lavalée S, Sautot P (1998) Pedicle screw placement using image guided techniques. *Clin Orthop Relat Res* 354:39–48
- Rajasekaran S, Vidyadhara S, Ramesh P, Shetty AP (2007) Randomized clinical study to compare the accuracy of navigated and non-navigated thoracic pedicle screws in deformity correction surgeries. *Spine* 32:E56–E64
- Seichi A, Takeshita K, Nakajima S, Akune T, Kawaguchi H, Nakamura K (2005) Revision cervical spine surgery using transarticular or pedicle screws under a computer-assisted image-guidance system. *J Orthop Sci* 10:385–390
- Sakai Y, Matsuyama Y, Nakamura H, Katayama Y, Imagama S, Ito Z, Ishiguro N (2008) Segmental pedicle screwing for idiopathic scoliosis using computer-assisted surgery. *J Spinal Disord Tech* 21:181–186
- Lee TC, Yang LC, Liliang PC, Su TM, Rau CS, Chen HJ (2004) Single versus separate registration for computer-assisted lumbar pedicle screw placement. *Spine* 29:1585–1589

29. Arand M, Hartwig E, Kinzl L, Gebhard F (2002) Spinal navigation in tumor surgery of the thoracic spine: first clinical results. *Clin Orthop Relat Res* 399:211–218
30. Youkilis AS, Quint DJ, McGillicuddy JE, Papadopoulos SM (2001) Stereotactic navigation for placement of pedicle screws in the thoracic spine. *Neurosurgery* 48:771–778
31. Nakanishi K, Tanaka M, Misawa H, Sugimoto Y, Takigawa T, Ozaki T (2009) Usefulness of a navigation system in surgery for scoliosis: segmental pedicle screw fixation in the treatment. *Arch Orthop Trauma Surg*. Published Online January 29, 2009
32. Liu YJ, Tian W, Liu B, Li Q, Hu L, Li ZY, Yuan Q, Xing YG, Wang YQ, Sun YZ (2005) Accuracy of CT-based navigation of pedicle screws implantation in the cervical spine compared with X-ray fluoroscopy technique. *Chin J Surg* 43:1328–1330
33. 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
34. Wendl K, von Recum J, Wentzensen A, Grützner PA (2003) Iso-C (3D0-assisted) navigated implantation of pedicle screws in thoracic lumbar vertebrae. *Unfallchirurg* 106:907–913
35. Sella K, Wild A, Urselmann L, Krauspe R (2005) Prospective screw misplacement analysis after conventional and navigated pedicle screw implantation. *Biomed Tech (Berl)* 50:287–292
36. Schnake KJ, König B, Berth U, Schroeder RJ, Kandziora F, Stöckle U, Raschke M, Haas NP (2004) Accuracy of CT-based navigation of pedicle screws in the thoracic spine compared with conventional technique. *Unfallchirurg* 107:104–112
37. Schwarzenbach O, Berlemann U, Jost B, Visarius H, Arm E, Langlotz F, Nolte LP, Ozdoba C (1997) Accuracy of computer-assisted pedicle screw placement. An in vivo computed tomography analysis. *Spine* 22:452–458
38. Nottmeier EW, Seemer W, Young PM (2009) Placement of thoracolumbar pedicle screws using three-dimensional image guidance: experience in a large patient cohort. *J Neurosurg Spine* 10:33–39
39. Ito Y, Sugimoto Y, Tomioka M, Hasegawa Y, Nakago K, Yagata Y (2008) Clinical accuracy of 3D fluoroscopy-assisted cervical pedicle screw insertion. *J Neurosurg Spine* 9:450–453
40. Rath SA, Moszko S, Schäffner PM, Cantone G, Braun V, Richter HP, Antoniadis G (2008) Accuracy of pedicle screw insertion in the cervical spine for internal fixation using frameless stereotactic guidance. *J Neurosurg Spine* 8:237–245
41. Nolte LP, Slomczykowski MA, Berlemann U, Strauss MJ, Hofstetter R, Schlenzka D, Laine T, Lund T (2000) A new approach to computer-aided spine surgery: fluoroscopy-based surgical navigation. *Eur Spine J* 9:S78–S88
42. John PS, James C, Antony J, Tessamma T, Ananda R, Dinesh K (2007) A novel computer-assisted technique for pedicle screw insertion. *Int J Med Robot* 3:59–63
43. Mirza SK, Wiggins GC, Kuntz C 4th, York JE, Bellabarba C, Konodi MA, Chapman JR, Shaffrey CI (2003) Accuracy of thoracic vertebral body screw placement using standard fluoroscopy, fluoroscopic image guidance, and computed tomographic image guidance: a cadaver study. *Spine* 28:402–413
44. Ludwig SC, Kowalski JM, Edwards CC 2nd, Heller JG (2000) Cervical pedicle screws: comparative accuracy of two insertion techniques. *Spine* 25:2675–2681
45. Choi WW, Green BA, Levi AD (2000) Computer-assisted fluoroscopic targeting system for pedicle screw insertion. *Neurosurgery* 47:872–878
46. Richter M, Amiot LP, Neller S, Kluger P, Puhl W (2000) Computer-assisted surgery in posterior instrumentation of the cervical spine: an in-vitro feasibility study. *Eur Spine J* 9:S65–S70
47. Kim KD, Patrick Johnson J, Bloch BSO, Masciopinto JE (2001) Computer-assisted thoracic pedicle screw placement: an in vitro feasibility study. *Spine* 26:360–364
48. Sagi HC, Manos R, Park SC, Von Jako R, Ordway NR, Connolly PJ (2003) Electromagnetic field-based image-guided spine surgery part two: results of a cadaveric study evaluating thoracic pedicle screw placement. *Spine* 28:E351–E354
49. Sagi HC, Manos R, Benz R, Ordway NR, Connolly PJ (2003) Electromagnetic field-based image-guided spine surgery part one: results of a cadaveric study evaluating lumbar pedicle screw placement. *Spine* 28:2013–2018
50. Austin MS, Vaccaro AR, Brislin B, Nachwalter R, Hilibrand AS, Albert TJ (2002) Image-guided spine surgery: a cadaver study comparing conventional open laminoforaminotomy and two image-guided techniques for pedicle screw placement in posterolateral fusion and nonfusion models. *Spine* 27:2503–2508
51. Hart RA, Hansen BL, Shea M, Hsu F, Anderson GJ (2005) Pedicle screw placement in the thoracic spine: a comparison of image-guided and manual techniques in cadavers. *Spine* 30:E326–E331
52. Holly LT, Foley KT (2006) Percutaneous placement of posterior cervical screws using three-dimensional fluoroscopy. *Spine* 31:536–540
53. Ludwig SC, Kramer DL, Balderston RA, Vaccaro AR, Foley KF, Albert TJ (2000) Placement of pedicle screws in the human cadaveric cervical spine: comparative accuracy of three techniques. *Spine* 25:1655–1667
54. Schwend RM, Dewire PJ, Kowalski TM (2000) Accuracy of fluoroscopically assisted laser targeting of the cadaveric thoracic and lumbar spine to place transpedicular screws. *J Spinal Disord* 13:412–418
55. Assaker R, Reyns N, Vinchon M, Demondion X, Louis E (2001) Transpedicular screw placement: image-guided versus lateral-view fluoroscopy: in vitro simulation. *Spine* 26:2160–2164
56. Amiot LP, Bellefleur C, Labelle H (1997) In vitro evaluation of computer-assisted pedicle screw system. *Ann Chir* 51:854–860
57. Foley KT, Sahjpaul RL, Rodts GR (2000) Virtual fluoroscopy improves lumbar pedicle screw placement accuracy. *Neurosurgery* 47:530
58. Carl AL, Khanuja, Sachs HS, Gatto BL, John CA, Kirby V, John V, William S (1997) In vitro simulation: early results of stereotaxy for pedicle screw placement. *Spine* 22:1160–1164
59. Foley KT, Smith MM, Abitbol JJ (1996) Thoracic pedicle screw placement accuracy: image-interactive guidance versus conventional techniques paper. *Neurosurgery* 39:653
60. Reinhold M, Bach C, Audigé L, Bale R, Attal R, Blauth M, Magerl F (2008) Comparison of two novel fluoroscopy-based stereotactic methods for cervical pedicle screw placement and review of the literature. *Eur Spine J* 17:564–575
61. Kosmopoulos V, Schizas C (2007) Pedicle screw placement accuracy: a meta-analysis. *Spine* 32:E111–E120