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Research Article

Intraoperative accuracy of O-arm navigated pedicle screw placement in the thoracic and lumbo-sacral regions of the spine – does localization matter?

Ivo Kehayov[1,3], Atanas Davarski[1,3], Polina Angelova[1,3], Rumyana Stoyanova[2], Borislav Kitov[3]

1 *Department of Neurosurgery, Faculty of Medicine, Medical University of Plovdiv, Plovdiv, Bulgaria*
2 *Department of Health Management and Health Economics, Faculty of Public Health, Medical University of Plovdiv, Plovdiv, Bulgaria*
3 *Clinic of Neurosurgery, St George University Hospital, Plovdiv, Bulgaria*

Corresponding author: Polina Angelova, Department of Neurosurgery, Faculty of Medicine, Medical University of Plovdiv, 15A Vassil Aprilov Blvd., 4002 Plovdiv, Bulgaria; Email: dr.polina.angelova@gmail.com

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Abstract

Aim: The aim of the current study was to determine the intraoperative accuracy of pedicle screw placement using a 3D CT-assisted navigation system with an O-arm in the thoracic, lumbar, and sacral regions of the spine, as well as to investigate the effect of localization on pedicle screw positioning accuracy.

Materials and methods: This single-center retrospective study was carried out on 180 patients who had open navigated pedicle screw implantation in the sacral, lumbar, and thoracic regions of the spine at our facility between January 2017 and December 2024. All patients underwent intraoperative scanning with the O-arm before and after screw placement and after screw trajectory correction in case of malpositioning. Additionally, early postoperative CT imaging was uniformly performed. The accuracy of screw placement was assessed by an experienced radiologist and a neurosurgeon using the Gertzbein-Robbins Grading Scale.

Results: Intraoperative post-implantation O-arm CT scans revealed 44 (3.5%) malpositioned screws out of 1257 implanted pedicle screws, resulting in 96.5% Grade A screw placement accuracy. Clinically, 98.2% (1234) of the pedicle screws were properly positioned (Grade A + B). Screw placement in the thoracic region correlated with significantly higher grades of malpositioning: Grade C (ρ=0.315, p<0.001) and Grade D (ρ=0.191, p=0.010), especially in the upper thoracic spine.

Conclusion: Image-guided 3D O-arm spinal navigation assistance during pedicle screw implantation can lower the risk of screw malpositioning, thus reducing the need for subsequent revision surgery, especially in the upper thoracic segment of the spine.

Keywords

accuracy, navigation, O-arm, pedicle screw, spine, surgery

Introduction

Over the past decades, the shift from 2D to 3D CT-assisted navigation systems has been reported to improve the safety and accuracy of spinal instrumentation in the treatment of degenerative, traumatic, neoplastic, inflammatory, and deformity spinal conditions.[1] However, minor placement errors still occur.

Aim

Therefore, the aim of this study was to evaluate the intraoperative accuracy (i.e., correct positioning vs. malpositioning) for pedicle screw placement using the 3D CT-based O-arm navigation system in the thoracic, lumbar, and sacral spine and to analyze the influence of localization on the accuracy of screw placement.

Materials and methods

Patient selection and demographics

This retrospective single-center study evaluated the accuracy of open posterior thoracic, lumbar, and sacral pedicle screw placement in 180 consecutive patients operated on for different spinal diseases between January 2017 and December 2024 at our institution. Two experienced surgeons performed all surgeries. Ninety-two of the patients were males, and their mean age was 57.9 years (15–83 years). Posterior pedicle instrumentation was performed in 33 patients (18.3%) with primary or secondary neoplasms, 41 (22.8%) with traumatic fractures, 69 patients (38.3%) with degenerative spinal disease (stenosis and/or scoliosis), 21 patients (11.7%) with spondylolisthesis, 14 patients (7.8%) with inflammatory conditions, and 2 patients (1.1%) with parasitic diseases. These data are summarized in **Table 1**.

Table 1. Demographic data, type of pathology, number of implanted pedicle screws, and their localization by spinal region

Demographic characteristics	Value (%)
Number of patients	180 (100)
Number of implanted screws	1257 (100)
Males / Females	92/88
Mean age (range), yrs	57.9 (5–83)
Etiology	Number of patients (%)
Tumors	33 (18.3)
Primary	17 (9.4)
Metastases	16 (8.8)
Traumatic fractures	41 (22.8)
Degenerative diseases	90 (50)
Spinal stenosis	68 (38.3)
Spondylolisthesis	22 (12.2)
Inflammatory and parasitic diseases	16 (8.8)
Infections	14 (7.8)
Parasitic (echinococcosis)	2 (1.1)
Distribution of pedicle screws by spinal region	Number (%): 1257 (100)
Thoracic	336 (26.1)
Lumbar	748 (58.2)
Sacral (S1)	173 (13.5)

The inclusion criterion was the placement of navigated pedicle screws in the thoracic, lumbar, and sacral regions of the spine with the assistance of O-arm for different spinal pathologies. The exclusion criteria were a) placement of pedicle screws outside the mentioned spine regions; b) placement of pedicle screws without the O-arm navigation system; and c) patients who refused to sign the informed consent form. Data collected encompassed demographic information; preoperative and postoperative neurological status; the level and type of spinal pathology; the number of screws placed; clinical outcomes and complications; scores on the Modified McCormick Scale; and imaging data from the preoperative, intraoperative, and postoperative phases. The study was approved by the local Ethics Committee. Informed consent was obtained from all patients.

Workflow for assessment of accuracy of navigated pedicle screw placement

All patients underwent intraoperative O-arm imaging to assess screw placement accuracy. This included scans performed before and after screw placement and, if necessary, after intraoperative correction of malpositioned screws. The intraoperative assessment of accuracy was performed by a leading neurosurgeon and experienced radiologist using the Gertzbein-Robbins Grading Scale, the results of which are presented in **Table 2**.[2] In addition, an early postoperative CT scan with a slice thickness of 1 mm was performed in all cases. The final accuracy of screw placement after the conventional CT scanning was also evaluated by an experienced radiologist and the leading neurosurgeon using the same scale. None of the patients needed a revision surgery due to screw misplacement.

For the purposes of this study, Grade A was considered a perfect position, and Grade B was considered a clinically acceptable position. For grades C, D, or E, immediate intraoperative repositioning was performed to achieve a clinically acceptable screw placement, which was confirmed by repeat intraoperative O-arm scanning.

Table 2. Gertzbein-Robbins scale

Grade	Description
A	Completely within the pedicle
B	Breach of pedicle wall ≤2 mm
C	Breach >2 mm and ≤4 mm
D	Breach >4 mm and ≤6 mm
E	Breach >6 mm

Statistical analysis

All data were analyzed using IBM SPSS, version 23. Descriptive statistical methods were applied in order to assess the distribution of both qualitative and quantitative variables. For the purpose of making comparisons between two independent groups, the non-parametric Mann-Whitney U test was utilized; in the case of comparisons involving more than two groups, the Kruskal-Wallis test was employed. The associations between variables were evaluated using Spearman's rank correlation coefficient (Spearman's rho). The Wilson method was used to calculate the 95% confidence intervals (CI) for relative proportions. A *p*-value of <0.05 was considered to be statistically significant.

Results

Accuracy of navigated screw placement by spine segments

A total of 1286 navigated screws were implanted. Of these, only the 1257 pedicle screws placed in the thoracic, lumbar, and sacral regions of the spine were included in the analysis.

Intraoperative O-arm scans revealed 44 (3.5%) malpositioned screws out of a total of 1257. Of the 336 screws placed in the thoracic spine, 35 (10.4%) had pedicle breaches, with 16 screws (4.8%) graded as Grade B, 10 screws (3.0%) as Grade C, 5 screws (1.5%) as Grade D, and 4 screws (1.2%) as Grade E. Lateral pedicle breaches were observed in 30 cases (8.9%), while medial breaches were seen in 5 cases (1.5%).

There was a significant difference in the number of malpositioned pedicle screws between the upper and lower thoracic spine. Ninety screws were placed in the upper thoracic region (T1-T6), with 10 (11.1%) of them requiring intraoperative revision (grades C-E). At levels T7–T12, 246 screws were implanted, of which 9 (3.6%) were malpositioned.

A total of 748 screws were placed in the lumbar spine, and only 5 (0.7%) were found to be misplaced: 2 screws (0.3%) were Grade B, 1 screw (0.1%) was Grade C, and 2 screws (0.3%) were Grade E. All misplaced screws were found to be lateral in position.

In the sacral region (S1-S2), 173 screws were implanted, and 4 (2.3%) were found to be malpositioned: 3 screws (1.7%) were Grade B, and 1 screw (0.6%) was Grade D. The misplaced screws in this region were with ventral penetration.

As evident from **Tables 3** and **4**, 1213 pedicle screws (96.5%) had a perfect position (Grade A). On the other

Table 3. Distribution of implanted and malpositioned screws by spinal region according to the Gertzbein-Robbins grading system

Level	Number	Grade A n/%	Grade B n/%	Grade C n/%	Grade D n/%	Grade E n/%	n / malpositioned	95% CI Wilson
T1	6	6/100	0/0	0/0	0/0	0/0	0/0	0.00–39
T2	12	10/83.3	0/0	1/8.3	0/0	1/8.3	2/16.7	4.70–44.8
T3	14	13/92.9	0/0	1/7.1	0/0	0/0	1/7.1	1.27–31.5
T4	24	20/83.3	0/0	2/8.3	1/4.2	1/4.2	4/16.7	6.68–35.9
T5	24	19/79.2	3/12.5	1/4.2	0/0	1/4.2	5/20.8	9.24–40.5
T6	10	6/60	3/12.5	1/10	0/0	0/0	4/40	16.82–68.7
T7	32	29/90.6	2/6.3	0/0	0/0	1/3.1	3/9.4	3.24–24.2
T8	24	17/70.8	4.16.7	1/4.2	2/8.3	0/0	7/29.2	14.91–49.2
T9	28	24/85.7	1/3.6	2/7.1	1/3.6	0/0	4/14.3	5.70–31.5
T10	38	37/97.4	1/2.6	0/0	0/0	0/0	1/2.6	0.47–13.5
T11	56	54/96.4	2/3.6	0/0	0/0	0/0	2/3.6	0.98–12.1
T12	68	66/97.1	0/0	1/4.2	1/4.2	0/0	2/2.9	0.81–10.1
Total thoracic	336	301/89.6	16/4.8	10/3	5/1.5	4/1.2	35/10.4	**7.60–14**
L1	74	72/97.3	1/1.4	1/1.4	0/0	0/0	2/2.7	0.74-9.3
L2	124	0/0	0/0	0/0	0/0	0/0	0/0	0.00–3
L3	182	180/99	1/0.6	0/0	0/0	1/0.6	3/1.1	0.30-3.9
L4	202	202/100	0/0	0/0	0/0	0/0	0/0	0.00-2.1
L5	166	16/99.4	0/0	0/0	0/0	1/0.6	1/0.6	0.11-3.3
Total lumbar	748	743/99.3	2/0.3	1/0.1	0/0	2/0.3	5/0.7	**0.29-1.6**
S1	173	169/97.7	3/1.7	0/0	0/0	1/0.6	4/2.3	0.90-5.8
Total sacral	173	169/97.7	3/1.7	0/0	0/0	1/0.6	4/2.1	**0.90-5.8**

Table 4. Type and grade of malpositioned screws in the thoracic, lumbar, and sacral regions

Type of malposition Grade	Thoracic area (number/%)	Lumbar area (number/%)	Sacral area (number/%)
Lateral malposition	30/68.2	5/11.4	0/0.0
Grade B	16/53.3	4/80.0	0/0.0
Grade C	5/16.7	0/0.0	0/0.0
Grade D	5/16.7	0/0.0	0/0.0
Grade E	4/13.3	1/20.0	0/0.0
Medial malposition	5/11.4	0/0.0	0/0.0
Grade B	2/40	0/0.0	0/0.0
Grade C	3/60	0/0.0	0/0.0
Ventral penetration	0/0.0	0/0.0	4/9.0
Grade B	0/0.0	0/0.0	3/75
Grade D	0/0.0	0/0.0	1/25

hand, 1234 screws (98.2%) in total had clinically acceptable positions (Grade A + Grade B) with no need for intraoperative revision. A total of 19 screws (1.8%) had an unacceptable position (Grade C, D, or E) and underwent intraoperative repositioning in the thoracic, lumbar, and sacral regions of the spine.

Correlations between the pedicle screw misplacement and the localization

We used the Spearman's rank correlation coefficient to investigate the uneven distribution of malpositioned pedicle screws across different spinal segments **(Table 5)**.

The analysis using Spearman's rank correlation coefficient revealed statistically significant associations between the number of pedicle screws placed in different spinal regions and the severity of their malposition according to the Gertzbein-Robbins Grading Scale.[2] The strongest positive correlation was observed between the number of screws placed in the lumbar region and Grade A (ρ=0.643, p<0.001), indicating that screw implantation in the lumbar spine achieves significantly more accurate positioning. Negative correlation was found between the number of lumbar screws and Grade C (ρ=−0.256, p<0.05) and Grade D (ρ=−0.175, p<0.05), further emphasizing that lumbar localization is associated with easier and more precise screw placement.

For screws localized in the sacral region (S1/S2), a moderate positive correlation was found between their number and Grade A (ρ=0.356, p<0.001), along with a weaker negative correlation for Grade C (ρ=−0.169, p=0.023).

The thoracic region was associated with a significant increase in cases of pedicle screw malposition: Grade C (ρ=0.315, p<0.001) and Grade D (ρ=0.191, p=0.010).

All screws with breach grades (Grade C to Grade E) were intraoperatively revised following analysis of the intraoperative imaging obtained by the O-arm **(Figs 1, 2)**.

Comparison of preoperative vs. postoperative neurological deficits

The preoperative neurological status was assessed using the Modified McCormick Scale. It was 2.97 (2–5) for all patients, varying from 2.67 to 3.72. The average postoperative score for all patients was 2 (range 1–5), with variation from 1.6 to 2.96 depending on the specific spinal disease. None of the patients developed additional neurological deficits related to the surgery itself.

Table 5. Correlations between the localization of implanted pedicle screws and malpositioning

Correlations between localization (by number of screws) and screw malposition		Grade A	Grade B	Grade C	Grade D	Grade E
Lumbar	Spearman's rho	0.643**	−0.243**	−0.256**	−0.175*	0.009
	Sig. (2-tailed)	**0.000**	**0.001**	**0.001**	**0.019**	0.908
	N	180	180	180	180	180
Sacral	Spearman's rho	0.356**	−0.131	−0.169*	−0.095	−0.070
	Sig. (2-tailed)	**0.000**	0.079	**0.023**	0.207	0.352
	N	180	180	180	180	180
Thoracic	Spearman's rho	−0.121	−0.275**	−0.315**	−0.191*	−0.025
	Sig. (2-tailed)	−0.104	**−0.000**	**−0.000**	**−0.010**	−0.736
	N	180	180	180	180	180

Statistically significant p-values are displayed in bold.

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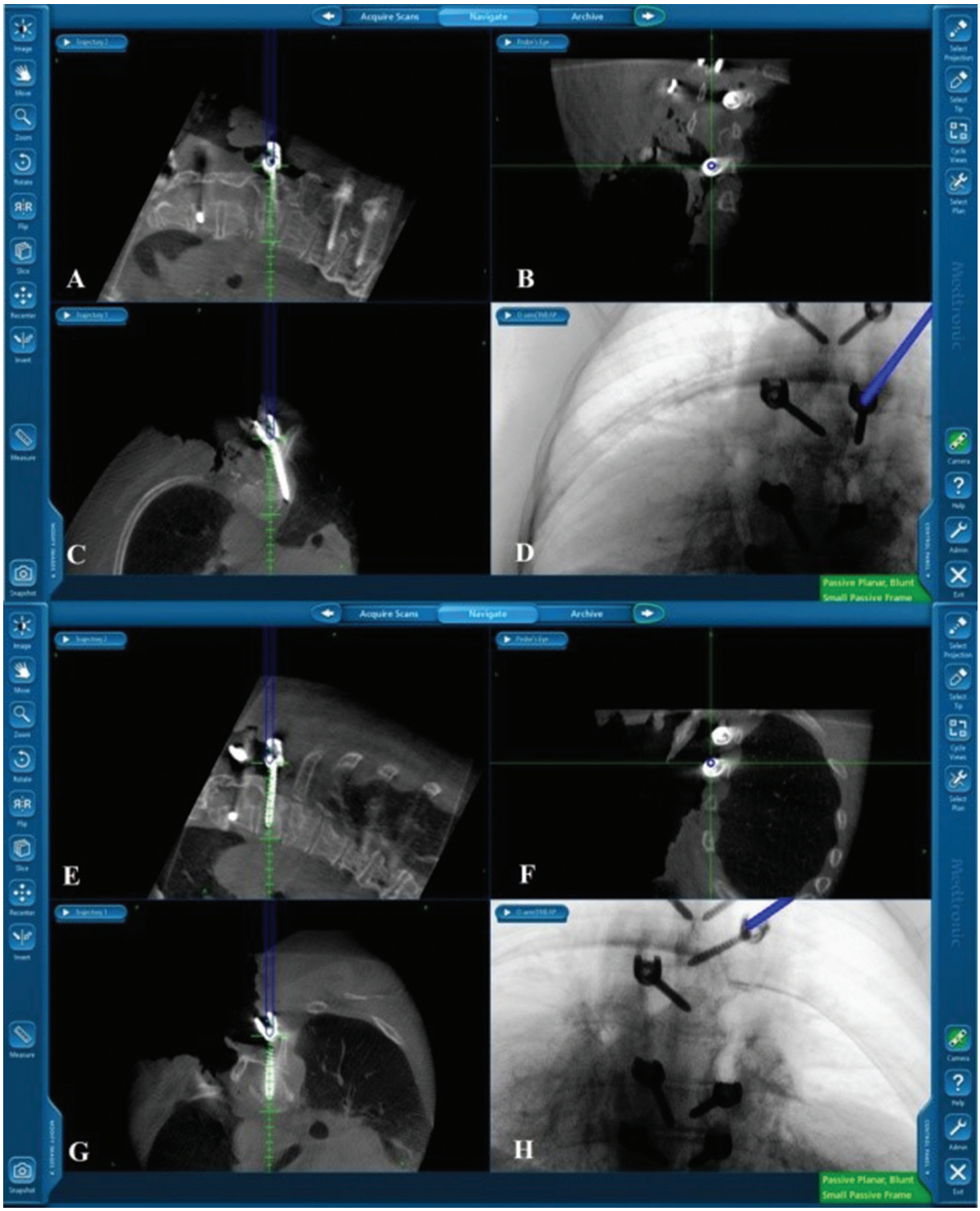

Figure 1. Intraoperative images from the neuronavigation screen demonstrates the correction of a laterally malpositioned pedicle screw Grade D (4–6 mm) at the right T8 level. Intraoperative repositioning: **A–D**) before and **E–H**) after the repositioning.

Discussion

Pedicle screw fixation has become a routine surgical procedure for stabilizing spinal segments affected by various pathologies, including degenerative diseases, scoliosis, trauma, tumors, and infections, over the past few decades. The focus has now shifted to achieving the highest possible accuracy in screw placement. Improper screw positioning can result in severe complications, such as neurological, vascular, and visceral injuries, as well as hardware failure, which can lead to increased medical costs and patient risks.[3]

According to literature data, the rate of pedicle screw misplacement varies widely—5% to 41% in the lumbar spine and 3% to 55% in the thoracic spine—highlighting

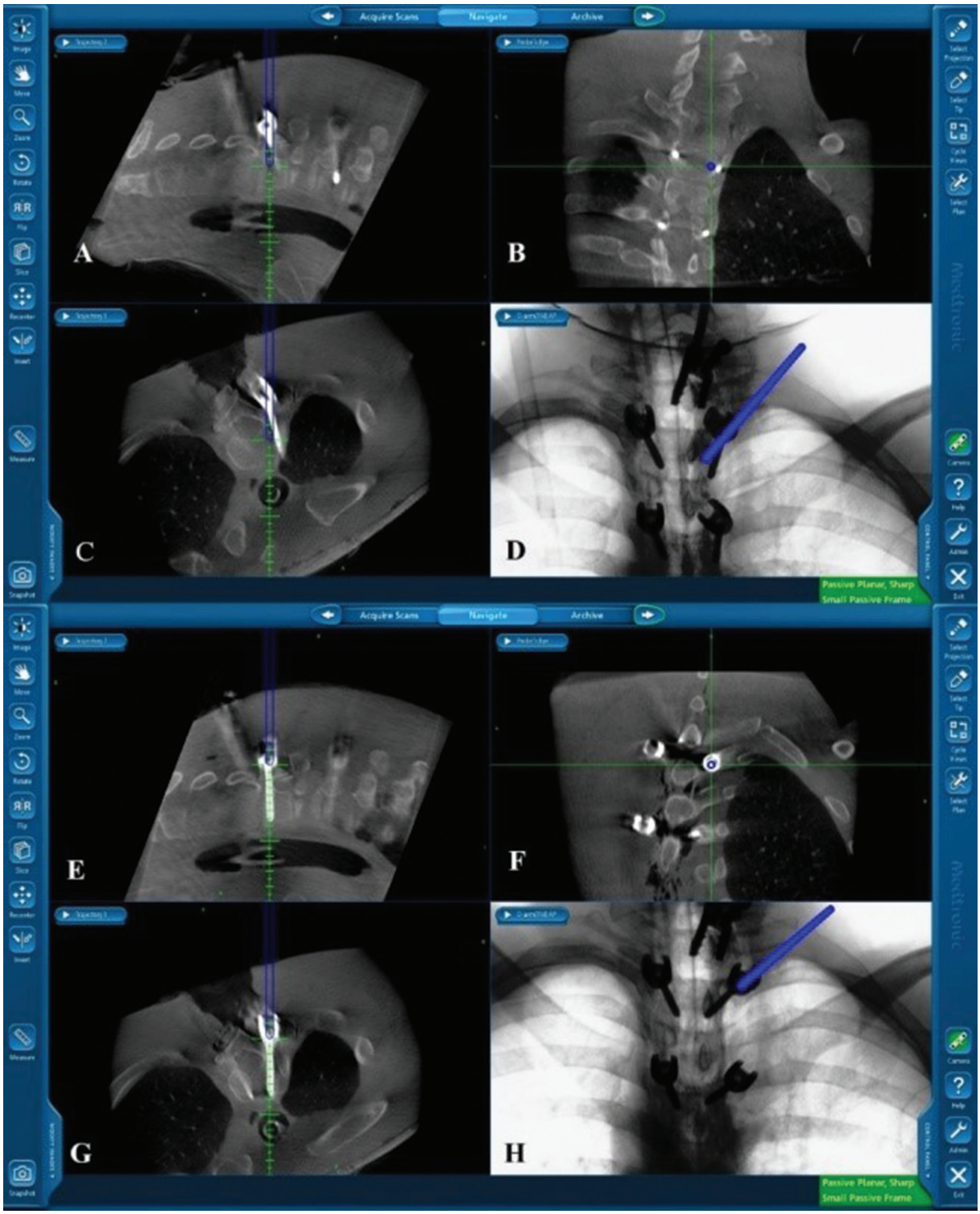

Figure 2. Intraoperative images from the neuronavigation screen present the correction of laterally malpositioned pedicle screw Grade E (>6 mm) at the right T2 level. Intraoperative repositioning: **A–D**) before and **E–H**) after the screw trajectory correction..

the need to improve placement techniques and enhance accuracy.[4]

In their meta-analysis, Tian and Xu report an average accuracy rate of 90.8% from 6063 thoracolumbar pedicle screws placed using 3D CT-assisted spinal navigation (3DCTSN).[5] A systematic review and meta-analysis by Perdomo-Pantoja et al. found an accuracy of 95.5% based on 51161 pedicle screws placed with 3DCTSN.[6] Another meta-analysis, including 30 publications with a total of 24600 navigated pedicle screws, reports a clinically acceptable accuracy rate of 96.2% (Grade A and Grade B) according to the Gertzbein-Robbins grading system using

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3DCTSN.[3] In our series of 1257 navigated pedicle screws placed in the thoracic and lumbosacral spine, the perfect position rate (Grade A) of 96.6% and clinically acceptable positioning (Grade A + Grade B) of 98.2%, rank high in the list reported in the literature in terms of accuracy.

Our results confirm the fact that in contrast to the lumbar region, the placement of thoracic pedicle screws remains a challenge even with modern technologies and computer assistance, especially in the upper thoracic spine, where screw misplacement rates of up to 40% have been reported.[7] Charles et al. reported perforation rates of 16.7% in the lower thoracic spine (T7–T12) and 6.9% in the lumbosacral spine (L1–S1) during percutaneous pedicle screw placement using fluoroscopic navigation.[8] According to these studies, pedicle cortex perforation ≥2 mm almost always occurs when the pedicle width is less than 4.8 mm.[8] When 3DCTSN is used, the reported accuracy for thoracic screw placement is significantly higher.[9,10]

We achieved acceptable accuracy (Grade A + Grade B) in the thoracic region as a whole (94.4%), and 99.6% in the lumbosacral region. The acceptable accuracy for the 90 pedicle screws placed in the T1-T6 segment was lower (88.9%) than in the T7-Th12 segment, which was 96.3%.

The percentage of the intraoperatively revised malpositioned screws in the thoracic region was 5.7%, compared to 0.4% in the lumbosacral region. To the best of our knowledge, this is the first study to establish a statistically significant association between thoracic screw placement and malposition (Grade C–Grade E), which correlates with literature data and emphasizes that special attention must be paid when placing pedicle screws in the thoracic region, especially from the T1 to T6 spinal level.

These findings correlate with studies on the bony morphology of thoracic pedicles, which highlight variability in pedicle size and orientation, particularly in the upper and middle thoracic spine, where pedicles are smaller.[11] In fact, pedicles between T4 and T8 may be too narrow to accommodate perfect pedicle screw placement.[12]

To ensure accurate pedicle screw placement, the screws must be inserted immediately after image acquisition, without any additional operative manipulations such as decompression, fracture repositioning, or discectomy. This is because even minor movement of the spinal segments can result in loss of navigational accuracy, leading to cortical breach, particularly in the upper and mid-thoracic spines, where pedicle width is typically less than 4 mm.[1]

The 3DCTSN systems are known to have an average registration error of 2–3 mm, and any additional changes to the anatomy after the registration scan may compromise screw placement accuracy.[12] According to Oertel et al., there is a minimal difference in the angle of 2.8°±1.9° between virtual and intraoperative images, likely due to improper instrument attachment to the implants.[13] Another potential source for error is the inadequate fixation of the reference frame to the skeleton.[13] We do agree with Aguilar-Chavez et al. that intraoperative 3D system images can be used to assess screw placement without the need for postoperative studies such as CT scans, which may reduce unnecessary costs and patient exposure to radiation.[14]

Limitations

This study has several limitations that must be considered when interpreting the results. First, it is a retrospective single-center analysis, which may introduce selection bias and limit the generalizability of the findings.

Second, the study did not compare O-arm navigation with other guidance methods such as freehand, fluoroscopy-assisted, or robotic techniques. As such, while the observed malposition rates are comparable or superior to those reported in other studies, the lack of a control group limits our ability to draw direct conclusions about the superiority of this approach.

Finally, the sample size, particularly for certain spinal levels (e.g., upper thoracic spine), though sufficient for detecting statistical differences, may still be underpowered for subgroup analyses, and larger multicenter studies would be beneficial to validate these findings.

Conclusion

In experienced hands, the 3D CT-based O-arm navigation system can provide high accuracy and precision when placing pedicle screws in the thoracic, lumbar, and sacral regions of the spine. This was especially true for the upper thoracic spine, which had a higher risk of pedicle screw misplacement.

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Competing interests

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