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ORIGINAL ARTICLE

The accuracy of 3D fluoroscopy-navigated screw insertion in the upper and subaxial cervical spine

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Abstract
Purpose Due to better primary stability and repositioning options, pedicle screws are increasingly used during posterior stabilization of the cervical spine. However, the serious risks generally associated with the insertion of screws in the cervical spine remain. The purpose of this study is to examine the accuracy of pedicle screw insertion with the use of 3D fluoroscopy navigation systems, also accounting for various spine levels.
Methods Data of 64 patients were collected during and after screw implantation (axial and subaxial) in the cervical spine. 207 screws were implanted from C1 to C7 and analyzed for placement accuracy according to postoperative CT scans and following the modified Gertzbein and Robbins classification.
Results The accuracy of most of the inserted screws was assessed as grade 2 according to the modified Gertzbein and Robbins classification. 93.9 % of the screws implanted at C1 or C2, and 78.51 % of the screws implanted at levels C3–C7 showed placement accuracy grade 2 or better, indicating pedicle wall perforation of <2 mm. Overall, seven complications were observed. In three cases, the vertebral artery was affected, leading to one fatality. Surgical revision was necessary once because of Magerl screw misplacement and three times due to impaired wound healing. No radicular symptoms resulted from screw malposition.
Conclusion Axial and subaxial screws can be inserted with a high grade of accuracy using 3D fluoroscopy-based navigation systems. Nevertheless, while this useful innovation helps to minimize the risks of misplacement, the surgery is still a challenge, as arising complications remain severe.

Keywords Navigated screw insertion · Cervical spine · Accuracy of screw insertion · Spine surgery · Complications in cervical spine surgery

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Introduction

Posterior stabilization of the cervical spine (CS) is increasingly carried out by placing pedicle screws in the respective segment [4, 6, 31, 34].

Better primary stability and repositioning accuracy can be achieved in comparison to lateral mass screws, thereby reducing the number of fused segments [5, 12, 27]. Therefore, pedicle screws are particularly applied in cases of long-distance fusion. Recent studies suggest superior precision of navigated pedicle screws over screws placed under fluoroscopic control in the cervical spine [15, 21, 31]. It is assumed that, especially in less experienced hands, screw placement precision can be significantly increased using navigation [23, 25, 26, 31, 36].

For this reason, navigated posterior instrumentation of the cervical spine has become the gold standard in most clinics. Benefits of this technique include lower radiation exposure for the surgical team as well as for the patient and, above all, a lower risk of screw displacement. This is particularly important due to the potentially serious consequences that can result from the anatomical proximity to the vertebral artery as well as the cervical spinal cord [3, 25, 31, 32].

Therefore, in contrast to lateral mass screws in the upper and subaxial CS, or transarticular Magerl screw fixation, which can both be safely done without navigation, transpedicular instrumentation of the subaxial CS is currently completely covered by the navigated surgical technique [21, 25, 26, 30].

There are several navigation procedures. Most frequently, CT-based or 3D fluoroscopy navigation are used. Both methods have advantages and disadvantages [9, 13, 14, 19, 21, 22, 36]. One advantage of CT-based navigation is better image quality. However, data sets recorded pre-surgically with supine positioning of the patient can differ from images performed during surgery with the patient lying prone, and this can make vertebral height localization difficult. This is why each vertebral body must be verified before instrumentation in a rather time-consuming way by palpation of reference points on the bone surface. 3D fluoroscopy navigation methods combine the advantages of the ability to produce a reference data set after patient positioning on the operating table, and again, if necessary, after reduction of a deformity, very good height localization, and relatively low radiation exposure. A clear drawback is the worse image quality compared to CT, especially at the cervico-thoracic junction.

The purpose of the present study is to investigate the positional accuracy of pedicle screws placed in the cervical spine using 3D fluoroscopy navigation.

Materials and methods

Patient population and data collection

This is a single-center analysis performed in the orthopedic and trauma surgery department of a university hospital. Data were obtained from 64 patients who underwent axial and subaxial screw insertion surgery to the cervical spine between 2007 and 2012. A total of 207 screws were implanted from levels C1 to C7. Prior to the planned posterior stabilization of the cervical spine, CT angiography was routinely performed to demonstrate the exact course of the vertebral artery. With only one exception, the operation was carried out by a team containing two surgeons.

After general anesthesia with muscle relaxation, the patient was placed in a prone position; the head was fixed with a carbon Mayfield clamp, arms pulled inferiorly with strips of adhesive bandage (Fig. 4).

In order to extend the upper body as far as possible beyond the operating table to avoid the interference of metal braces with X-ray imaging, a radiolucent board with a gel cushion was used for positioning the chest. When necessary, closed reduction of displacement was performed under fluoroscopic control in two planes. The posterior cervical spine was approached through a median incision above the spinous process line. After exposure of the operative field, reference reflectors were attached to a spinous process. For vertebral bodies C1–C4, the spinous process of C2 was used, and for C5–C7, the spinous process of C7. The reference terminal with three infrared light-reflecting diodes was attached either via intraosseous pin or via terminal to the spinous process, depending on bone quality. C-arm-based 3D imaging (3D ArcadisOrbic, Siemens, Germany) was used for navigation. During a 180° orbital rotation, a total of 100 radiographs were made and upsampled to a 3D data set. Once the instruments, also equipped with infrared light-reflecting diodes, were detected, this data could be used for navigated spine surgery using VectorVisionfluoro 3D Trauma Software (BrainLAB Inc., Heimstetten, Germany). To this point, the X-ray image intensifier was used only for height control in the lateral beam projection. Once navigational accuracy was verified, the pedicle entry point was approached with a 1.8-mm drill sleeve (Fig. 7). Because the courses of the C3–C6 pedicles converge, separate auxiliary incisions were made for each before advancement of a blunt trocar until bone contact. After transpedicular placement of 1.8 mm K-wires, a 180° scan was performed without navigation to visualize the intraosseous course of the K-wires. The thread for the definitive pedicle screw was then cut over these K-wires with a cannulated screw tap. Two different fixation systems were applied, the Neon system (Ulrich Medical Inc., Ulm, Germany) and the VertexMax system (Medtronic Inc., Basel, Switzerland). The latter offers the advantage of being compatible with thoracic systems implanted with a minimally invasive technique, allowing for long segment cervico-thoracic stabilization. The disadvantage is that an additional screw–rod connection for extensors between longitudinal rod and pedicle screw is often necessary because of the far lateral entry point, reducing the stability of the construct. In addition, the cervical longitudinal bars in this system are comparatively thin.

Postoperatively, multiplanar CT scans were performed and then assessed by both a spine surgeon and an experienced radiologist. Position accuracy of screw placement was evaluated according to the modified classification by Gertzbein and Robbins [10] consisting of 5 grades. Grade 1 describes ideal screw position with pedicle wall perforation

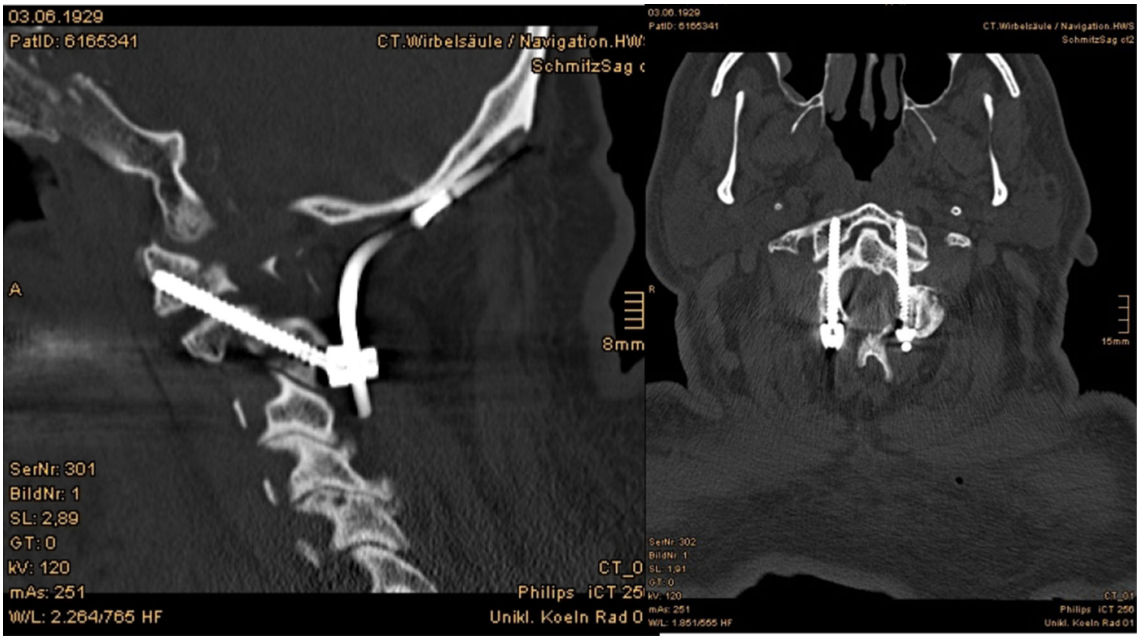

Fig. 1 Postoperative CT scan in sagittal and axial planes, grade 1 in modified Gertzbein and Robbins classification

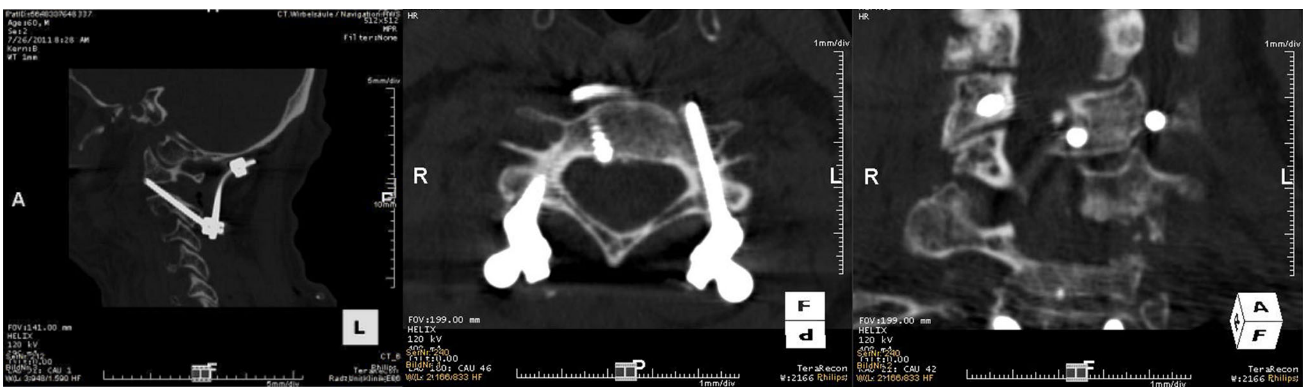

Fig. 2 Postoperative CT scan in sagittal, coronal, and axial planes, grade 5 in modified Gertzbein and Robbins classification

of <1 mm (Fig. 1), grade 2 with pedicle wall perforation of <2 mm, grade 3 of <3 mm, and grade 4 of <4 mm. Grade 5 (Fig. 2) represents a cortical breach of >4 mm and/or obstruction of the transverse foramen by more than half a screw diameter. Secure anchoring of the Magerl screws within the C1 lateral mass was additionally evaluated. Analysis of intra- and postoperative surgical complications was based on separate documentation. In the study, The Magerl screw had to be changed because of uncorrect placement (Table 3), so revision was performed via open reduction of the disposition by dismantling the longitudinal rods, removing the inserted Magerl screws, renewing the inclining reposition in the Mayfield clamp (for enhanced screw positioning), and navigated repositioning of the Magerl screws.

Statistical analysis

Patient characteristics were described using summary statistics (continuous data with mean, standard deviation, median, minimum and maximum; binary and categorical data with number and percentage).

Multivariate logistic regression was used to assess the risk for lower accuracy (grades 3–5) according to cervical spine level (upper cervical spine vs. subaxial cervical spine), taking into account relevant possible confounders such as diagnosis (trauma vs. other diagnosis) or surgeon (2 surgeons) as factors, and age as a continuous covariate. The possible within-patient correlation was accounted for using generalized estimating equations. The $n = 203$ includes all observed cases except those operated by a single surgeon,

Table 1 Characteristics of the complete patient collective and classified by the level of screw placement [upper cervical spine (CS), subaxial cervical spine, or both; number of patients and percent with reference to group or statistical parameters, respectively; SD standard deviation]

	All patients ($n = 64$)	Group 1 Upper CS C1–C2 ($n = 28$)	Group 2 Subaxial CS C3–C7 ($n = 26$)	Group 3 Both C1–2 + C3–7 ($n = 10$)
Age				
Mean	61.3	63.8	56.5	66.8
SD	7.4	16.8	18.8	12.6
Median	64.5	6625	57.5	67.5
Minimum	19	89	19	42
Maximum	89		85	82
Gender				
Female	24 (37.5 %)	12 (42.9 %)	8 (30.8 %)	4 (40.0 %)
Male	40 (62.5 %)	16 (57.1 %)	18 (69.2 %)	6 (60.0 %)
Diagnosis				
Trauma	36 (56.2 %)	16 (57.1 %)	18 (69.3 %)	2 (20.0 %)
Degeneration	5 (7.8 %)	0 (0.0 %)	2 (7.7 %)	3 (30.0 %)
Tumor	9 (14.1 %)	2 (7.1 %)	4 (15.4 %)	3 (30.0 %)
Rheumatism	13 (20.3 %)	10 (35.7 %)	1 (3.8 %)	2 (20.0 %)
Discitis	1 (1.6 %)	0 (0.0 %)	1 (3.8 %)	0 (0.0 %)
No. of screws per patient				
2	30 (46.9 %)	21 (75.0 %)	9 (34.6 %)	0 (0 %)
3	4 (6.3 %)	3 (10.7 %)	0 (0 %)	1 (10.0 %)
4	21 (32.8 %)	4 (14.3 %)	12 (46.2 %)	5 (50.0 %)
>4	9 (14.0 %)	–	5 (19.2 %)	4 (40.0 %)
Surgery time (min)				
Mean	214.7	177.8	236.1	262.4
SD	84.2	71.7	93.0	45.8
Median	193	155	218	264.5
Minimum	85	85	107	182
Maximum	518	379	518	320
Surgeon				
A	43	16	18	9
B	2	2	0	0
C	19	10	8	1

who operated on only 2 patients (4 screws). Statistical analyses were carried out using SAS V9.3.

Results

Between 2007 and 2012, a total of 64 patients with an average age of 61.3 years (SD 17.4; range 19–89 years) were included (Table 1). Altogether, 21 lateral mass screws in the atlas, 33 Magerl screws, 27 pedicle screws in the axis, 120 pedicle screws in the subaxial cervical spine, and 6 laminar screws were placed.

Mean operative time was 262.4 (SD 45.8) min when the entire cervical spine was involved ($n = 10$), 177.8 (SD 71.7) min for operations solely at the upper cervical spine ($n = 28$), and 236.1 (SD 84.2) min for the lower cervical spine ($n = 26$) (Table 1).

With regard to etiology, 36 patients were included in the study due to trauma, 5 due to degenerative changes of the cervical spine, 9 because of tumors, and 13 because of rheumatoid changes; there was also 1 patient with spondylodiscitis (Fig. 3).

Positioning accuracy of all screws is shown in Table 2. Screw position of grade 3 or worse was found in 19.01 % ($n = 23/121$) of screws implanted in surgeries for trauma. In surgeries for degenerative changes, 18.0 % of screw positions ($n = 4/22$) showed low accuracy (rated grade 3 or worse), in the field of tumor and rheumatic disease surgeries, low accuracy was found in 6.7 % each ($n = 2/30$). No low accuracy in screw position ($n = 0/4$) was observed in the spondylodiscitis case (Fig. 4).

85.7 % ($n = 18/21$) of the lateral mass screws inserted in the atlas were assessed as grade 1 on the modified Gertzbein and Robbins scale, 4.8 % ($n = 1/21$) were classified as grade

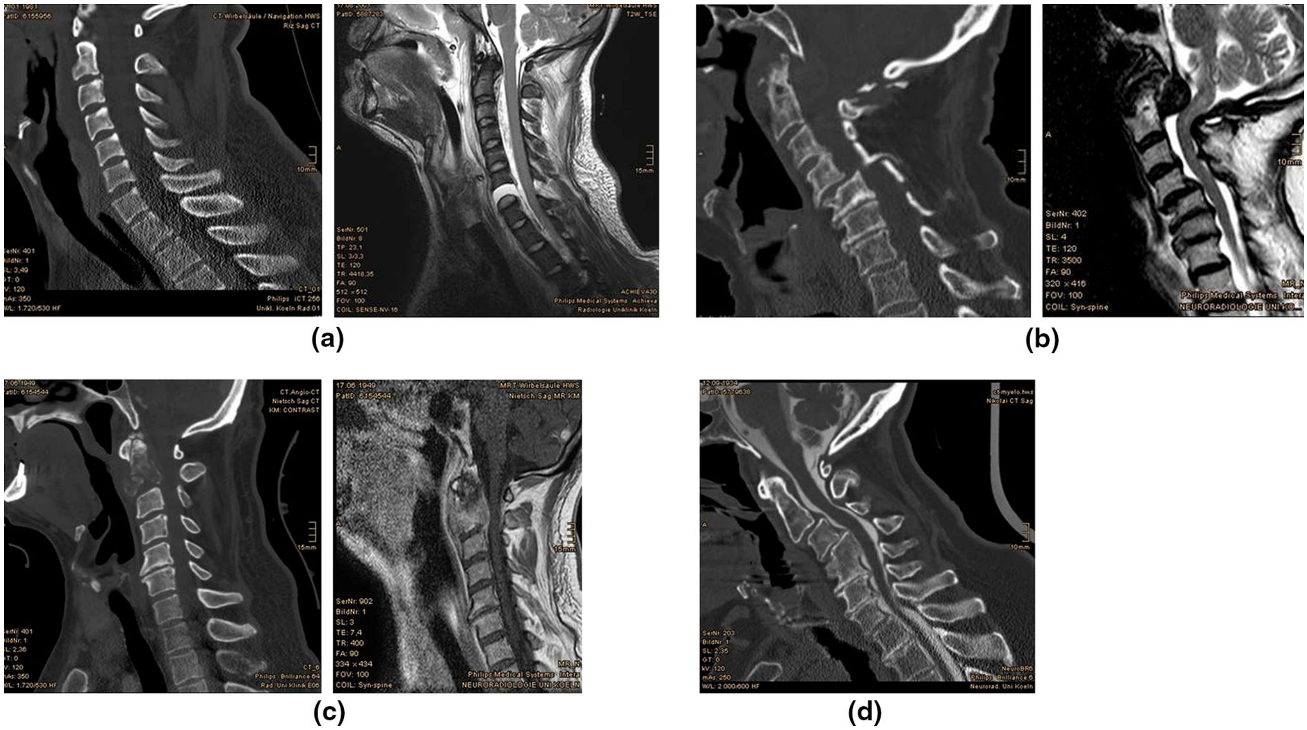

Fig. 3 Overview of the different diagnoses (**a** trauma, **b** rheumatoid instability, **c** tumor-related instability and **d** degenerative instability) with sample images

Table 2 Number of screws inserted and accuracy of screw placement according to the modified Robbins and Gertzbein classification, by cervical spine level (a) and screw type (b)

	Total	Accuracy of screw placement				
		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
(a) Level of screw insertion						
C-1 (Atlas)	21 (10.1 %)	18 (85.7 %)	1 (4.8 %)	1 (4.8 %)	0 (0.0 %)	1 (4.8 %)
C-2 (Axis)	65 (31.4 %)	48 (73.9 %)	14 (21.5 %)	2 (3.1 %)	0 (0.0 %)	1 (1.5 %)
C-3	10 (4.8 %)	4 (40.0 %)	6 (60.0 %)	0 (0.0 %)	0 (0.0 %)	0 (0.0 %)
C-4	16 (7.7 %)	4 (25.0 %)	8 (50.0 %)	2 (12.5 %)	2 (12.5 %)	0 (0.0 %)
C-5	32 (15.5 %)	12 (37.5 %)	10 (31.3 %)	6 (18.8 %)	2 (6.3 %)	2 (6.3 %)
C-6	30 (14.5 %)	12 (40.0 %)	11 (36.7 %)	6 (20.0 %)	1 (3.3 %)	0 (0.0 %)
C-7	33 (16.0 %)	19 (57.6 %)	9 (27.3 %)	4 (12.1 %)	0 (0.0 %)	1 (3.0 %)
(b) Screw type						
Lateral mass atlas	21 (10.1 %)	18 (85.7 %)	1 (4.8 %)	1 (4.8 %)	0 (0.0 %)	1 (4.8 %)
Magerl screw	33 (16.0 %)	27 (81.8 %)	5 (15.2 %)	0 (0.0 %)	0 (0.0 %)	1 (3.0 %)
Pedicle screw	147 (71.0 %)	67 (45.6 %)	53 (36.1 %)	19 (12.9 %)	5 (3.4 %)	3 (2.0 %)
Axial	27 (18.4 %)	17 (63.0 %)	9 (33.3 %)	1 (3.7 %)	0 (0.0 %)	0 (0.0 %)
Subaxial	120 (81.6 %)	50 (41.7 %)	44 (36.7 %)	18 (15.0 %)	5 (4.2 %)	3 (2.5 %)
Laminar screw	6 (2.9 %)	5 (83.3 %)	0 (0.0 %)	1 (16.7 %)	0 (0.0 %)	0 (0.0 %)
Total (*n*)	207	117	59	21	5	5

2, 4.8 % ($n = 1/21$) as grade 3, 4.8 % ($n = 1/21$) as grade 4 or less (Table 2). Regarding the Magerl screws, 81.8 % ($n = 27/33$) were rated as Gertzbein and Robbins grade 1 and 15.2 % ($n = 5/33$) as grade 2; however, 3.0 % ($n = 1/33$) were classified as grade 5. The placement of 147 pedicle screws (axial and subaxial together, see Table 2) was classified as follows: 45.6 % ($n = 67/147$) grade 1, 36.1 % ($n = 53/147$) grade 2, 12.9 % ($n = 19/147$) grade 3, 3.4 % ($n = 5/147$) grade 4, and 2 % ($n = 3/147$) grade 5. 83.3 % of the laminar screws ($n = 5/6$) were classified as grade 1 and 16.7 % ($n = 1/6$) as grade 3. Regarding subgroups, 27 axial pedicle screws were classified as follows: 63.0 % ($n = 17$) as grade 1,

Fig. 4 Intraoperative overview of the positioning of the patient, drill guide with reference spheres and navigation unit

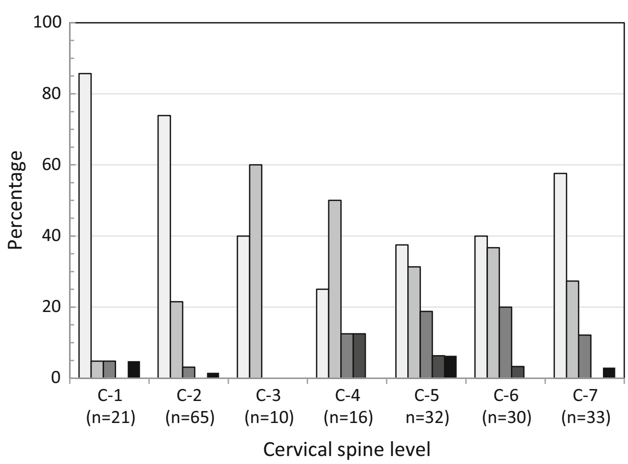

Fig. 5 Accuracy of screw placement according to cervical spine level

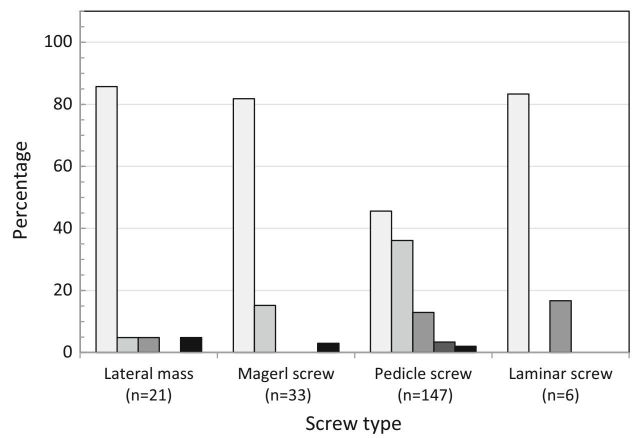

Fig. 6 Accuracy of screw placement according to screw type

33.3 % ($n = 9$) as grade 2, 3.7 % ($n = 1$) as grade 3, and 0 % as grade 4 or 5 (Table 2b). Of the 120 subaxial pedicle screws inserted, 41.7 % ($n = 50$) were classified as grade 1, 36.7 % ($n = 44$) as grade 2, 15.0 % ($n = 18$) as grade 3, 4.2 % ($n = 5$) as grade 4, and 2.5 % ($n = 3$) as grade 5 (Figs. 5, 6).

Comparing the different types of screws according to the percentage assessed as grades 1 and 2, Magerl screws yielded 96.97 %. 90.48 % of the lateral mass screws to the atlas were rated grade 2 or better, 83.3 % of the laminar screws, and 81.63 % of the pedicle screws (Fig. 7).

In terms of spinal levels, the following differences were identified. Grade 1 precision of screws inserted to C1 or C2 was 85.7 and 73.9 %, respectively (Table 2). Regarding precision of screws inserted into C3 and C4, only 4 of 16 screws (C4) were rated less than grade 2. In contrast, the precision of screws inserted into C5, C6, and C7 was lower. 12–31 % of these screws were rated as grade 3 or higher.

Applying a multiple logistic regression model including level of screw placement, diagnosis, and surgeon as factors (with age as a continuous covariate), and accounting for the possible within-patient correlation, the precision of subaxial cervical pedicle screws was significantly lower than that of screws inserted in the upper cervical spine ($P = 0.005$) (Table 4). Regardless of screw type, 93.9 % of screws placed in the upper CS (at C1 and C2) were rated grades 1 and 2, compared to only 78.5 % located in the subaxial cervical spine (C3–C7).

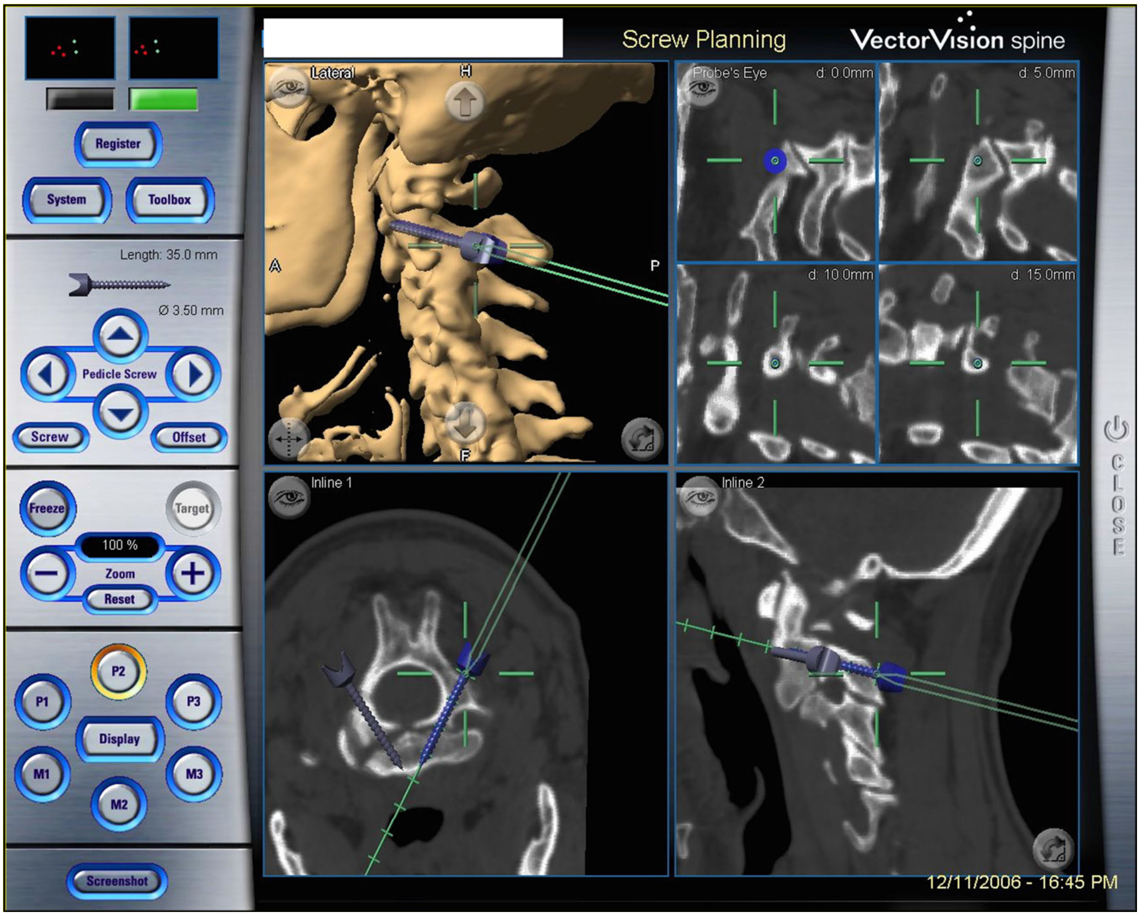

Fig. 7 Intraoperative screenshot of the navigation unit while positioning

Analysis of surgical complications (Table 3) revealed that 178 of the 207 screws (86 %) were implanted without causing clinical symptoms. In three cases the vertebral artery was affected, one case with fatal outcome. Screw revision was only necessary in one case (a malpositioned Magerl screw requiring surgical correction), and there was only a single case of CSF fistula. Spondylodiscitis in the adjacent segment, after anterior–posterior spinal canal decompression requiring anterior–posterior revision (6 affected screws), was diagnosed once, and impaired wound healing requiring surgical revision occurred three times (18 affected screws). Radicular symptoms due to poor screw position did not occur (Table complications according to location) (Table 3).

Discussion

Based on the present data, we conclude that axial and subaxial screws can be inserted with a high grade of accuracy using 3D-fluoroscopy-based navigation systems. There is no statistical significance for any of the cervical spine levels regarding screw insertion.

Cervical pedicle screw fixation is considered to be the most stable fixation [1, 2, 14, 23]. Due to a high perioperative perforation rate during the insertion [16], and the risks of injury to the vertebral arteries and neural structures associated with screw malposition, several methods supporting the surgeon or improving cervical screw placement have been previously investigated [36]. Roy-Camille et al. [28] stated that screw placement in the C3–C6 pedicles are accompanied by unacceptable risks. Over the years, technology and experience have continuously improved, so that a best rate of 7 % of misplaced cervical pedicle screws has been reported in the literature [3], even with the use of conventional insertion techniques without navigation. These are excellent results, and not reproducible by less experienced spine surgeons, even today. Currently, rates of screw misplacement of 5–40 % are reported using conventional techniques [10, 11, 17, 25, 33].

Anatomically, the diameter of the cervical pedicle is narrower than that of the thoracolumbar pedicle [16, 20, 24, 29, 35], the pedicle axis is more strongly convergent, and there are few anatomic landmarks to

Table 3 Complications from screw insertion stratified by screw type (number of screws inserted inserted and percentage of all screw insertions)

Complication	Total ($n = 207$)	Lateral mass atlas ($n = 21$)	Magerl screw ($n = 33$)	Pedicle screw ($n = 147$)	Laminar screw ($n = 6$)
Wound healing deficit	18 (8.7 %)	2 (9.5 %)	0 (0.0 %)	15 (10.2 %)	1 (16.7%)
Spondylodiscitis	6 (2.9 %)	0 (0.0 %)	0 (0.0 %)	6 (4.1 %)	0 (0.0 %)
Vertebral artery affection	3 (1.4 %)	3 (14.3 %)	0 (0.0 %)	0 (0.0 %)	0 (0.0 %)
CSF fistula	1 (0.5 %)	0 (0.0 %)	0 (0.0 %)	1 (0.7 %)	0 (0.0 %)
Screw malposition with need for revision surgery	1 (0.5 %)	0 (0.0 %)	1 (3.0 %)	0 (0.0 %)	0 (0.0 %)

Table 4 Risk of low accuracy (grade 3–5) according to cervical spine level and additional influencing factors based on a multivariate logistic regression model (cervical spine level, diagnosis, surgeon as factors and age as a continuous covariate). The possible within-patient correlation was taken into account by generalized estimating equations (GEEs; all observed cases excluding patients operated by one surgeon (3), who operated only 2 patients (4 screws). The level of significance was set at 5 %

Factor	High accuracy (grade 1–2) ($n = 172$)	Lower accuracy (grade 3–5) ($n = 31$)	OR [95 % CI]*	Probability value
Cervical spine level				
Upper CS (C1–C2)	77 (93.9 %)	5 (6.1 %)		
Subaxial CS (C3–C7)	95 (78.5 %)	26 (21.5 %)	3.88 [1.50–10.06]	0.005
Diagnosis				
Other	74 (90.2 %)	8 (9.8 %)		
Trauma	98 (81.0 %)	23 (19.0 %)	2.17 [0.77–6.11]	0.143
Surgeon				
A	51 (91.1 %)	5 (8.9 %)		
C	121 (82.3 %)	26 (17.7 %)	1.85 [0.52–6.52]	0.339

identify the exact entry point [8, 16, 18]. And although it is possible to identify the entry points on the basis of landmarks, targeting the exact drill angle remains very difficult [24]. C3 pedicle width averages 4.9 mm in males and 4.5 mm in females, with a minimum width reported as 3.0 mm. C4 pedicle width averages 4.7 mm in males and 4.6 mm in females with a minimum of 3.1 mm [7, 26]. This underscores the need for preoperative CT imaging.

The superiority of 3D navigation over free-handed techniques to improve the accuracy of cervical screw insertion and thus reduce the complication rate has been evaluated and documented in several studies [14, 21, 23, 25, 26, 36]. As a result, navigated posterior instrumentation of the cervical spine has become the standard in most hospitals. Advantages and disadvantages of the method have been well documented [21, 23]. In a multivariate analysis, precision was determined according to operated level and etiology. The risk of lower precision for screw placement in the subaxial cervical spine is increased by a factor of 3.88 compared to the upper cervical spine (Table 4). Diagnosis (Trauma vs. other) and surgeon showed no significant influence on precision.

The results of the current study provide evidence for a high level of precision (defined as pedicle perforation of <2 mm, corresponding to grades 1 and 2 according to the modified Gertzbein and Robbins [10] classification).

In addition and regardless of type, 93.9 % of the screws inserted into the upper cervical spine (C1 and C2) showed an accuracy of grade 2 or better; the same applies to 78.51 % of the subaxially inserted screws (C3–C7). This difference can be explained by the fact that the anatomical conditions are more difficult in the lower versus upper cervical spine (smaller pedicle, more convergence requiring a more lateral entry point, inferior image quality due to shadow cast by the shoulder). Based on the current data, screw placement accuracy is better in the upper cervical spine (C1–C2) than in the lower cervical spine (C3–C7). Responsible for this was the partly lacking navigation accuracy in the lower cervical spine, especially the moderate visual quality caused by X-ray based navigation! Subsequently, a K-wire was inserted and a control scan performed. The moderate quality of this scan (metal-related artifacts caused by multi-exposure, so that the wire sometimes appeared fan-shaped, poor radiolucency of the lower cervical spine due to shoulder superimposition and bad image resolution) made it possible for the malposition to remain undetected. A second control scan performed after screw positioning brought similar problems.

Screw displacement is less frequent in the upper cervical spine, but when it occurs, it is fraught with more serious complications. One of three patients with vertebral artery involvement died of this complication.

All of the 3 vertebral artery affections were caused by lateral mass screws in the atlas and not in C2. This is the area of closest anatomical proximity to the vertebral artery—at least when the posterior arc of the atlas is chosen as entry point, as it was performed in 2 of the cases. On the other hand, the C2-nerve root is prevented from damage when this technique is used.

In the third case, the screw was inserted by using the Harms technique, which entails approaching the mass by surgical preparation below the posterior arc. This technique may result in more blood loss and increased danger for the C2 root, but the vertebral artery is kept at a safer distance. In this case an osteoporotic vertebra led to the dislocation of the screw.

Taking into account the modified Gertzbein and Robbins classification, we consider it justifiable to conclude that the accuracy is higher in the upper area of the cervical spine in statistical regards. This statement remains correct irrespective of anatomical conditions.

The level allowing for the most accurate screw insertion in our study was C3; here, 10 screws were implanted, and all met our definition of high precision (4 screws graded 1, 6 graded 2). At C2, 48 of 65 screws were placed with grade 1 accuracy, 14 with grade 2.

This study has some limitations. Although the learning curves of the surgeons were eliminated by previous experience, there were 3 experienced surgeons. Because of this number of surgeons, minor inaccuracies are possible. A single surgeon would have made standardization simpler. Because of the small case number and low complication rates, factors influencing the occurrence of complications could not be further analyzed in our patient collective.

Our results are supported by a meta-analysis conducted by Nakashima et al. [23], who did not identify statistical significance for screw insertion to any of the cervical spine levels in his multivariate analysis based on 390 implanted cervical screws. Nevertheless, his study reached the same conclusion as ours, that spine level should be regarded as an important factor in screw placement accuracy [23].

Conclusion

Axial and subaxial screws can be inserted with a high grade of accuracy using 3D fluoroscopy-based navigation systems. Nevertheless, while this useful technical innovation helps minimize the risks of misplacement, the surgery remains a challenge, as complications, when they arise, remain severe.

Conflict of interest The authors declare that they have no competing interests. We have no personal or financial conflicts of interest related to the preparation and publication of this manuscript.

References

1. Abumi K, Itoh H, Taneichi H, Kaneda K (1994) Transpedicular screw fixation for traumatic lesions of the middle and lower cervical spine: description of the techniques and preliminary report. J Spinal Disord 7(1):19–28
2. Abumi K, Kaneda K (1997) Pedicle screw fixation for nontraumatic lesions of the cervical spine. Spine 22(16):1853–1863
3. Abumi K, Shono Y, Ito M, Taneichi H, Kotani Y, Kaneda K (2000) Complications of pedicle screw fixation in reconstructive surgery of the cervical spine. Spine 25(8):962–969
4. Barnes AH, Eguizabal JA, Acosta FL Jr, Lotz JC, Buckley JM, Ames CP (2009) Biomechanical pullout strength and stability of the cervical artificial pedicle screw. Spine 34(1):E16–E20. doi:10.1097/BRS.0b013e3181891772
5. Blauth M, Richter M, Lange U (1999) Trans-articular screw fixation of C1/C2 in atlanto-axial instability. Comparison between percutaneous and open procedures. Der Orthopade 28(8):651–661
6. Dunlap BJ, Karaikovic EE, Park HS, Sokolowski MJ, Zhang LQ (2010) Load sharing properties of cervical pedicle screw-rod constructs versus lateral mass screw-rod constructs. Eur Spine J 19(5):803–808. doi:10.1007/s00586-010-1278-0
7. Ebraheim NA, Xu R, Knight T, Yeasting RA (1997) Morphometric evaluation of lower cervical pedicle and its projection. Spine 22(1):1–6
8. Gebauer M, Barvencik F, Briem D, Kolb JP, Seitz S, Rueger JM, Puschel K, Amling M (2010) Evaluation of anatomic landmarks and safe zones for screw placement in the atlas via the posterior arch. Eur Spine J 19(1):85–90. doi:10.1007/s00586-009-1181-8
9. Gelalis ID, Paschos NK, Pakos EE, Politis AN, Arnaoutoglou CM, Karageorgos AC, Ploumis A, Xenakis TA (2012) Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. Eur Spine J 21(2):247–255. doi:10.1007/s00586-011-2011-3
10. Gertzbein SD, Robbins SE (1990) Accuracy of pedicular screw placement in vivo. Spine 15(1):11–14
11. Glossop ND, Hu RW, Randle JA (1996) Computer-aided pedicle screw placement using frameless stereotaxis. Spine 21(17):2026–2034
12. Haid RW Jr (2001) C1–C2 transarticular screw fixation: technical aspects. Neurosurgery 49(1):71–74
13. Ishikawa Y, Kanemura T, Yoshida G, Ito Z, Muramoto A, Ohno S (2010) Clinical accuracy of three-dimensional fluoroscopy-based computer-assisted cervical pedicle screw placement: a retrospective comparative study of conventional versus computer-assisted cervical pedicle screw placement. J Neurosurg Spine 13(5):606–611. doi:10.3171/2010.5.SPINE09993
14. Ishikawa Y, Kanemura T, Yoshida G, Matsumoto A, Ito Z, Tauchi R, Muramoto A, Ohno S, Nishimura Y (2011) Intraoperative, full-rotation, three-dimensional image (O-arm)-based navigation system for cervical pedicle screw insertion. J Neurosurg Spine 15(5):472–478. doi:10.3171/2011.6.SPINE10809
15. Kantelhardt SR, Keric N, Giese A (2012) Management of C2 fractures using Iso-C(3D) guidance: a single institution's

experience. Acta Neurochir (Wien) 154(10):1781–1787. doi:10.1007/s00701-012-1443-9
16. Karaikovic EE, Kunakornsawat S, Daubs MD, Madsen TW, Gaines RW Jr (2000) Surgical anatomy of the cervical pedicles: landmarks for posterior cervical pedicle entrance localization. J Spinal Disord 13(1):63–72
17. Kosmopoulos V, Schizas C (2007) Pedicle screw placement accuracy: a meta-analysis. Spine 32(3):E111–E120. doi:10.1097/01.brs.0000254048.79024.8b
18. Lee DH, Lee SW, Kang SJ, Hwang CJ, Kim NH, Bae JY, Kim YT, Lee CS, Daniel Riew K (2011) Optimal entry points and trajectories for cervical pedicle screw placement into subaxial cervical vertebrae. Eur Spine J 20(6):905–911. doi:10.1007/s00586-010-1655-8
19. Liu YJ, Tian W, Liu B, Li Q, Hu L, Li ZY, Yuan Q, Lu YW, Sun YZ (2010) Comparison of the clinical accuracy of cervical (C2–C7) pedicle screw insertion assisted by fluoroscopy, computed tomography-based navigation, and intraoperative three-dimensional C-arm navigation. Chin Med J 123(21):2995–2998
20. Ludwig SC, Kramer DL, Vaccaro AR, Albert TJ (1999) Transpedicle screw fixation of the cervical spine. Clin Orthop Relat Res 359:77–88
21. Luther N, Iorgulescu JB, Geannette C, Gebhard H, Saleh T, Tsiouris AJ, Hartl R (2013) Comparison of navigated versus non-navigated pedicle screw placement in 260 patients and 1434 screws: screw accuracy, screw size, and the complexity of surgery. J Spinal Disord Tech. doi:10.1097/BSD.0b013e31828af33e
22. Mueller CA, Roesseler L, Podlogar M, Kovacs A, Kristof RA (2010) Accuracy and complications of transpedicular C2 screw placement without the use of spinal navigation. Eur Spine J 19(5):809–814. doi:10.1007/s00586-010-1291-3
23. Nakashima H, Yukawa Y, Imagama S, Kanemura T, Kamiya M, Yanase M, Ito K, Machino M, Yoshida G, Ishikawa Y, Matsuyama Y, Ishiguro N, Kato F (2012) Complications of cervical pedicle screw fixation for nontraumatic lesions: a multicenter study of 84 patients. J Neurosurg Spine 16(3):238–247. doi:10.3171/2011.11.SPINE11102
24. Panjabi MM, Shin EK, Chen NC, Wang JL (2000) Internal morphology of human cervical pedicles. Spine 25(10):1197–1205
25. Richter M, Cakir B, Schmidt R (2005) Cervical pedicle screws: conventional versus computer-assisted placement of cannulated screws. Spine 30(20):2280–2287
26. Richter M, Mattes T, Cakir B (2004) Computer-assisted posterior instrumentation of the cervical and cervico-thoracic spine. Eur Spine J 13(1):50–59. doi:10.1007/s00586-003-0604-1
27. Richter M, Schmidt R, Claes L, Puhl W, Wilke HJ (2002) Posterior atlantoaxial fixation: biomechanical in vitro comparison of six different techniques. Spine 27(16):1724–1732
28. Roy-Camille R, Saillant G, Laville C, Benazet JP (1992) Treatment of lower cervical spinal injuries—C3 to C7. Spine 17(10 Suppl):S442–S446
29. Sakamoto T, Neo M, Nakamura T (2004) Transpedicular screw placement evaluated by axial computed tomography of the cervical pedicle. Spine 29(22):2510–2514 **discussion 2515**
30. Schmidt R, Wilke HJ, Claes L, Puhl W, Richter M (2003) Pedicle screws enhance primary stability in multilevel cervical corpectomies: biomechanical in vitro comparison of different implants including constrained and nonconstrained posterior instrumentations. Spine 28(16):1821–1828. doi:10.1097/01.BRS.0000083287.23521.48
31. Tian W, Liu Y, Zheng S, Lv Y (2013) Accuracy of lower cervical pedicle screw placement with assistance of distinct navigation systems: a human cadaveric study. Eur Spine J 22(1):148–155. doi:10.1007/s00586-012-2494-6
32. Wang Y, Xie J, Yang Z, Zhao Z, Zhang Y, Li T, Liu L (2013) Computed tomography assessment of lateral pedicle wall perforation by free-hand subaxial cervical pedicle screw placement. Arch Orthop Trauma Surg 133(7):901–909. doi:10.1007/s00402-013-1752-3
33. Weinstein JN, Spratt KF, Spengler D, Brick C, Reid S (1988) Spinal pedicle fixation: reliability and validity of roentgenogram-based assessment and surgical factors on successful screw placement. Spine 13(9):1012–1018
34. Xu R, Ebraheim NA, Skie M (2008) Pedicle screw fixation in the cervical spine. Am J Orthop 37(8):403–408 **discussion 408**
35. Yukawa Y, Kato F, Ito K, Nakashima H, Machino M (2009) Anterior cervical pedicle screw and plate fixation using fluoroscope-assisted pedicle axis view imaging: a preliminary report of a new cervical reconstruction technique. Eur Spine J 18(6):911–916. doi:10.1007/s00586-009-0949-1
36. Zhang HL, Zhou DS, Jiang ZS (2011) Analysis of accuracy of computer-assisted navigation in cervical pedicle screw installation. Orthop Surg 3(1):52–56. doi:10.1111/j.1757-7861.2010.00110.x