Brain and Spine 5 (2025) 104199

Contents lists available at ScienceDirect

Brain and Spine

journal homepage: www.journals.elsevier.com/brain-and-spine

Navigated percutaneous placement of cervical pedicle screws: An anatomical feasibility study

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ARTICLE INFO

Handling Editor: Prof F Kandziora

Keywords:
Percutaneous
Pedicle screw
Subaxial cervical spine
Navigation

ABSTRACT

Introduction: Percutaneous cervical pedicle screw placement is challenging due to complex anatomy, and requires navigation support. It is unclear how to ensure navigation accuracy in minimally invasive procedures.
Research question: How accurate is image-guided percutaneous pedicle screw positioning after referencing with only one clamp for the complete subaxial cervical spine?
Materials and methods: In six cadavers, all subaxial cervical pedicles were fitted with screws using a standardized procedure. Briefly, a reference clamp was placed via a small skin incision on spinous process C7. The procedure started from C3 and progressed towards C7, without additional imaging, using one registration for all vertebrae. Screws were placed using a navigated screwdriver. Cone-beam CT was performed at three time-points. Screw position was directly intraoperatively evaluated by the surgeons using a modified classification—from Grade 1 (perfect placement) to Grade 5 (highly inaccurate)—and these data were re-evaluated by two independent radiologists.
Results: In six human specimens, 10 guidewires each were placed bilaterally in C3–C7. One screw (1.7%) was intraoperatively classified as Grade 3, but as Grade 4 in the second assessment. All other screws were classified as Grades 1–2 (89.8%) or 3 (8.5%). Screw placement accuracy was not significantly impacted by distance to the clamp or side selection.
Discussion: In percutaneously navigated screw placement with intraoperative imaging, safe screw placement was possible with a reference clamp on C7. Clinical application of this technique has been limited to individual cases. We also propose a new classification for improving screw accuracy and clinical consequences.

1. Introduction

Since pedicle screws became standard for fixation in the thoracolumbar spine, there has been ongoing discussion about the best method of placing pedicle screws in the cervical spine. Such procedures are technically challenging, because the cervical pedicle is narrow; exhibits wide variability of the angle; and is near critical structures, such as the vertebral arteries, nerve roots, and spinal cord. The reported incidence of complications directly attributed to misplaced cervical pedicle screws varies from 0.0 to 5.7%, and the reported rates of screw-related revision surgeries range from 1.0 to 2.4% (Yoshihara et al., 2013; Soliman et al., 2023). Importantly, complications caused by misplaced cervical screws can be severe and irreversible, and devastating for the patient (Bindels et al., 2024).

Assessment of correct screw placement was first introduced by Gertzbein et al. for thoracolumbar pedicel screws (Gertzbein and Robbins, 1990). Among the suggested classification scores for the accuracy of cervical pedicle screws, two systems stand out as the most practical. Neo et al. (2008) described a “2-mm increment grading system”. Additionally, Bredow et al. (Bredow et al., 2016; Aoude et al., 2015) proposed a 1-mm classification, which includes the 2-mm grading system. In the present study, we worked with both classifications simultaneously.

Over recent years, increasing numbers of studies have described

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https://doi.org/10.1016/j.bas.2025.104199
Received 13 December 2024; Received in revised form 11 January 2025; Accepted 30 January 2025
Available online 1 February 2025

Fig. 1. Lateral X-ray image obtained to check the reference clamp placement on the C7 vertebrae, for the navigation-guided surgical technique.

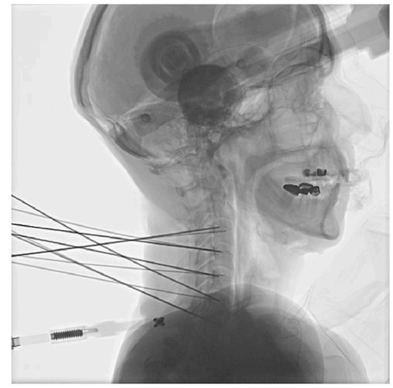

Fig. 2. Lateral X-ray image obtained to check the inserted K-wires.

techniques for either the freehand setting or image-guided placement of cervical pedicle screws. Navigation techniques show slightly superior accuracy (Mahmoud et al., 2021), which has also been shown for navigated paraspinal image-guided instrumentation in the thoraco-lumbar spine (Tkatschenko et al., 2020). However, the available evidence does not conclusively show that navigation-supported techniques are the safest open procedures (Bindels et al., 2024).

The introduction of percutaneous techniques for cervical pedicle screw placement changes the nature of this discussion, because percutaneous placement of cervical pedicle screws is not conceivable without navigation support. In this context, navigation must be safe and accurate, and requires a reference clamp that should be placed as near as possible to the referenced vertebra. This necessitates the preparation of each instrumented spinal process, which counteracts the idea of minimal invasiveness. Open posterior approaches to the subaxial cervical spine are associated with significant approach-related morbidity, primarily due to infection risk, and secondarily due to denervation with atrophy of the paraspinal musculature. Additionally, lateral mass instrumentation generally involves limited screw fixation in comparison to the placement of pedicle screws (Kothe et al., 2004; Ito et al., 2014).

With the aim of avoiding the need for an invasive approach, here we performed a cadaver study to verify the accuracy of image-guided percutaneous pedicle screw instrumentation at the cervical spine. Our procedure applied state-of-the-art intraoperative cone-beam CT imaging, and spinal navigation with a single reference clamp on the most caudal instrumented vertebra (C7).

2. Material and methods

A total of six cadavers were instrumented bilaterally from C3 to C7 by three experienced spine surgeons. To avoid bias, surgeons were changed between the different specimens, and at the beginning of instrumented sides. A total of 60 screws were placed.

Each specimen was placed in a prone position, and a small incision (app. 2 cm) was made at the C7 level to fixate the navigation clamp to the spinous process of this vertebrae, prior to 3D cone-beam CT imaging (Loop-X; Brainlab, Germany) (Fig. 1). The approx. 6 cm longitudinal skin incision was then made laterally on both sides. The entry points of the pedicle screws were located with the pointer and then prepared in this area by making a small fascial opening and bluntly pushing the muscles apart as far as the bone.

The procedure started from C3 and progressed towards C7, without additional imaging, using one registration for all vertebrae. A navigated drill guide and canulated drill were used to place K-wires in all pedicles, utilizing the navigation system. All K-wires were placed before initiating screw insertion, to avoid putting pressure on the vertebrae and to prevent tilting of the vertebrae, which would compromise the navigation accuracy. In four specimens, K-wires (and later screws) were introduced on the left side first, before instrumenting the right side. The fascia and muscles were dilated to allow screw placement. It was ensured that the K-wire remained in place as the drill was removed, with dilators serving as working ports for the subsequent steps. Next, a cone-beam CT scan was performed with all K-wires in place (Fig. 2). Finally, screws of the appropriate diameter and length and with percutaneous shafts (Ennovate® Cervical by Aesculap/B. Braun, Germany) were inserted under image guidance, with control by a third cone-beam CT Scan (Fig. 3) (see Fig. 4).

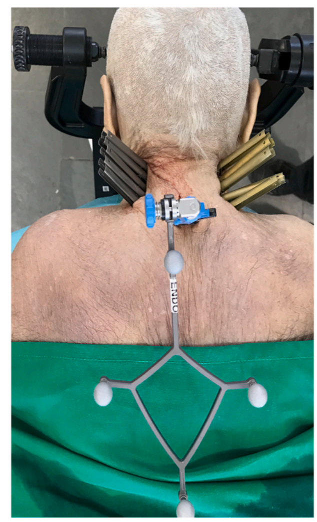

Fig. 3. Navigated screws in place.

Postprocedural 3D scans were obtained after K-wire and screw placement, and were graded by two independent radiologists. To maximize clinical accuracy, we followed the method described by Bredow et al. (2016). Screw placement accuracy was rated as five grades: Grade 1: perfect screw position with pedicle wall perforation <1 mm, Grade 2: pedicle wall perforation <2 mm, Grade 3: pedicle wall perforation <3 mm, Grade 4: pedicle wall perforation <4 mm, and Grade 5: pedicle wall perforation >4 mm and/or obstruction of transverse foramen by over half a screw diameter. In the event that grading differed by 2 or more grades between the two radiologists, a third radiologist was consulted for assessment. Weighted Kappa was calculated to assess the interobserver variation.

3. Results

Overall, 89.8% of the inserted screws was assessed as Grade 2 or better, indicating pedicle wall perforation of less than 2 mm. In detail, 66.1% ($n = 39$) of the inserted screws were assessed as Grade 1 (perfect

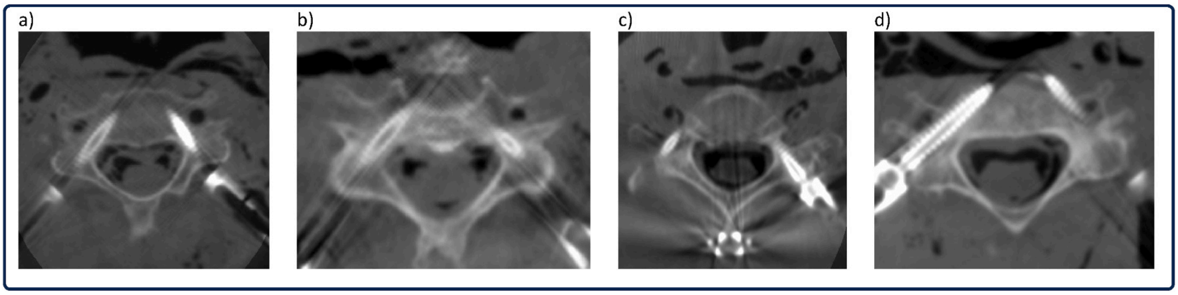

Fig. 4. The accuracy of screw placement using the minimally invasive surgical approach was evaluated using the method described by Bredow et al. (Yoshihara et al., 2013). Images show examples of the grading of the screws, from left to right: Grade 1: pedicle wall perforation <1 mm, Grade 2: pedicle wall perforation <2 mm, Grade 3: pedicle wall perforation <3 mm, and Grade 4: pedicle wall perforation <4 mm.

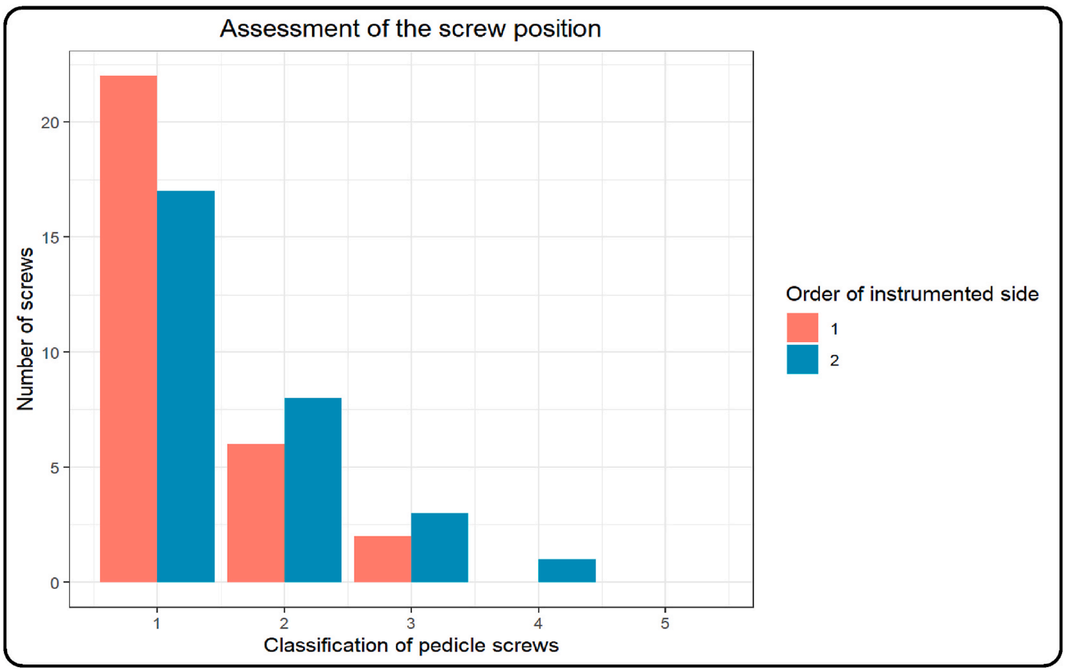

Fig. 5. Distribution of screws in the evaluation classes according to Bredow et al. (Yoshihara et al., 2013), differentiated into first instrumented side (red) and second instrumented side of the specimen (blue).

screw position); 23.7% ($n = 14$) as Grade 2; 8.5% ($n = 3$) as Grade 3; 1.7% ($n = 1$) as Grade 4, 1.7% ($n = 1$) as "not assessable", and no screws were rated as Grade 5. The estimated weighted kappa was 0.78, indicating good agreement between the two evaluating radiologists.

It was assumed that worse results would be obtained on the side that was instrumented second, and for the screws that were further away from the reference clamp, due to movements of the vertebral bodies in relation to each other, resulting from the forces applied during surgery. We used a multivariate linear regression model to calculate the influences of the side instrumented at the first or second position, and the distance of the measured vertebral body to the navigation clamp. The results indicated that neither of these parameters had a significant influence ($p = 0.16$; $p = 0.3$) (Figs. 5 and 6).

The calculation of a further linear regression model revealed that a K-wire being rated good or very good was very likely to lead to a screw placement rated good or very good (Fig. 7).

4. Discussion

There are two established procedures available for posterior stabilization of the cervical subaxial spine: lateral mass screw fixation, and pedicle screw fixation. The technique for cervical pedicle screw installation requires advanced skills, while the surgical technique for lateral mass screws does not. Notably, compared to lateral mass screws, cervical pedicle screws have a significant higher stability and pull-out strength (Kothe et al., 2004; Ito et al., 2014). In particular, pedicle screw constructs seem to be preferable for restoring the lordosis (Hey et al., 2020). Due to these advantages, setting pedicle screws, even in the subaxial cervical spine, has become more common and safer over time, as described by Soliman et al. in a meta study from 2013 (Soliman et al., 2023).

Although it seems that navigation makes it easier to set pedicle screws in the atlantoaxial and subaxial regions, various studies have not demonstrated that navigation significantly improves the accuracy of screw placement. Bindels et al. (2024) performed a comparison of two large studies including several hundred non-navigated screws (Abumi, 2015; Wang et al., 2013) versus many smaller studies of navigated screw placement (Richter et al., 2005; Hecht et al., 2018; Kisinde et al., 2022; Gelinne et al., 2021; Coric and Rossi, 2022; Holly and Foley, 2006), and reported that navigation is not significantly better but also not worse (Tkatschenko et al., 2020). Overall, it seems that navigation is a useful aid, especially for those who do not regularly insert cervical pedicle screws.

It is preferable to use a percutaneous minimally invasive approach to

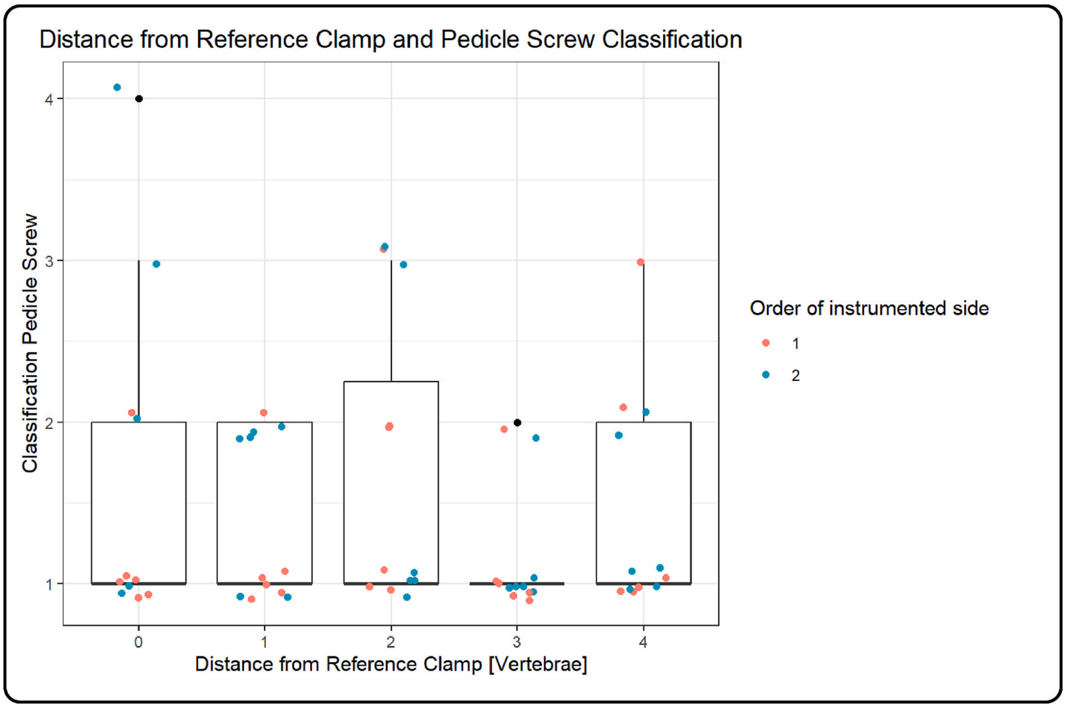

Fig. 6. Box-Plot diagram shows no significant difference of accuracy based on the distance from the reference clamp.

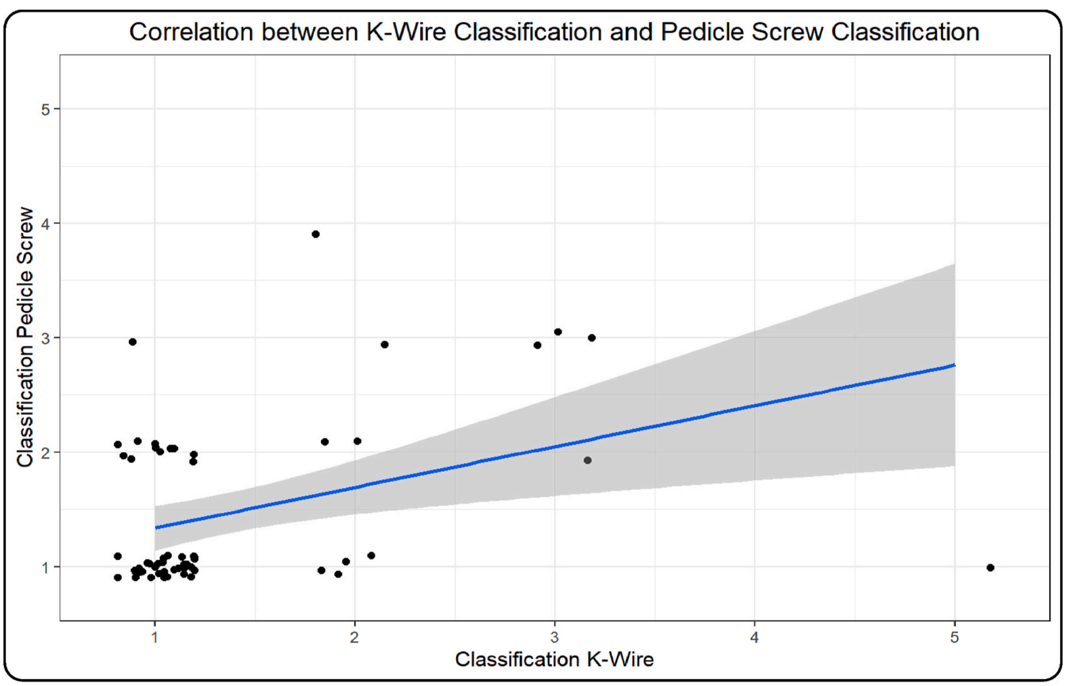

Fig. 7. Plot diagram showing a good correlation in the accuracy of K-wire placement and the accuracy of screw placement.

prevent iatrogenic damage of the posterior cervical muscles and tension band system, which can lead to significant postoperative neck pain and muscle dysfunction with atrophy (Takeshita et al., 2004). The first studies in this field examined minimally invasive techniques with a lateral approach (Richter et al., 2005; Schaefer et al., 2011), and were followed by percutaneous techniques, which all demonstrated high accuracy, but no previous study includes only subaxial screws (Gelinne et al., 2021; Coric and Rossi, 2022).

The guidewire-assisted pedicle screw insertion technique used in the present study is standard for percutaneous screw placement in the spine. It has been shown that good wire placement results in good screw placement. On the other hand, the repeated cone-beam CT monitoring performed in our study is not feasible in everyday clinical practice, as it subjects the patient to excessive radiation. Moreover, it is extremely technically challenging to carry out cone-beam CT with the horizontal wires in place, as they can easily become unsterile due to their length, and dislocation is possible. Therefore, in clinical application, we prefer to perform an X-ray check after placement of the wires in two planes, and an intraoperative CT check after placement of the screws to evaluate the final screw position.

Table 1
Grading of screw placement.

	Classification	Consequence
Grade 0	Screw in the pedicle, perforation of one cortex <2 mm	None
Grade 1	Screw in the pedicle, perforation of 2 cortices <2 mm	None
Grade 2	Screw in the pedicle, perforation >2 mm lateral (foramen transversum) or craniocaudal (nerve root)	Consider correction of screw
Grade 3	Screw not in the pedicle (all directions)	Severe malposition of screw, has to be corrected

Although we initially assumed that the screw position accuracy would decrease with increasing distance from the reference clamp, this was not verified by our data. In fact, the accuracy of pedicle screw placement was not significantly influenced by the side instrumented first, or the distance to the reference clamp. However, it must be mentioned that all specimens showed degenerative changes in the cervical spine, which may also cause reduced mobility of the cervical spine.

It is difficult to compare the screw positioning accuracy found in this study with previous reports in the literature, due to the various classifications used. Notably, Azimi (Azimi et al., 2020) lists 12 different grading systems, which each have specific advantages and disadvantages. One particular concern is that the available systems do not consider the altered relationship between screw diameter and pedicle diameter compared to the thoracolumbar spine. As correctly pointed out by Gierse (Gierse et al., 2024), there is also no classification system that describes a perforation cranially or caudally. In our opinion, a classification for evaluating the correct or acceptable position of cervical pedicle screws must account for anatomical position—and must consider the risk to neural or vascular structures (spinal cord, nerve root, and vertebral artery) on one hand, and not overestimate clinically irrelevant perforations on the other hand. Table 1 shows a proposal for such a classification system. However, until there is a standardized and easily applicable classification of the correct position of cervical pedicle screws, we must use the existing ones—especially the systems of Neo (Neo et al., 2008) or Bredow (Bredow et al., 2016)—and be aware of their weaknesses.

One limitation to the validity of this study is the use of cadavers, which do not always reflect the normal mobility of the bony cervical spine. Secondly, cone-beam CT was performed intraoperatively, rather than intraoperative CT. However, recent evidence in the cervical spine suggests that image quality does not substantially differ between cone-beam CT and true CT technology of the latest state-of-the-art generation (Kendlbacher et al., 2022).

Furthermore, robot-assisted screw placement may be an alternative for percutaneous pedicle screw placement in the subaxial cervical spine. Initial studies are promising but also reveal technical difficulties due to the current set up of robotic systems (Mao et al., 2023).

In summary, evaluation of the study data suggest that the presently described technique is a reliable, accurate, and technically feasible method for percutaneous navigated pedicle screw placement in the subaxial cervical spine. Notably, in everyday clinical practice, we initially recommend that it only be used in patients with reduced mobility—for example, in cases of ankylosing spondylitis—or as an additional stabilization following anterior surgery with plate fixation and high rigidity (e.g., after tumor resection, infection, type-C fractures, or kyphotic deformity correction).

5. Conclusion

The results of the present feasibility study indicate that percutaneously placed cervical pedicle screws can be inserted with a high grade of accuracy, using the described technique. The risk of screw misplacement seems to be higher in patients with sclerotic bone or a flexible cervical spine. In such cases, the described surgical technique may be unsuitable, and each instrumented vertebral body should be registered independently, or pedicle screws should not be used.

Declaration of competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Gregor Schmeiser reports financial support was provided by Aesculap B. Braun. Gregor Schmeiser reports a relationship with B Braun Aesculap Germany that includes: board membership. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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