Clinical Study

Spinal intraoperative three-dimensional navigation: correlation between clinical and absolute engineering accuracy

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Abstract

BACKGROUND CONTEXT: Spinal intraoperative computer-assisted navigation (CAN) may guide pedicle screw placement. Computer-assisted navigation techniques have been reported to reduce pedicle screw breach rates across all spinal levels. However, definitions of screw breach vary widely across studies, if reported at all. The absolute quantitative error of spinal navigation systems is theoretically a more precise and generalizable metric of navigation accuracy. It has also been computed variably and reported in less than a quarter of clinical studies of CAN-guided pedicle screw accuracy.

PURPOSE: This study aimed to characterize the correlation between clinical pedicle screw accuracy, based on postoperative imaging, and absolute quantitative navigation accuracy.

DESIGN/SETTING: This is a retrospective review of a prospectively collected cohort.

PATIENT SAMPLE: We recruited 30 patients undergoing first-time posterior cervical-thoracic-lumbar-sacral instrumented fusion decompression, guided by intraoperative three-dimensional CAN.

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OUTCOME MEASURES: Clinical or radiographic screw accuracy (Heary and 2 mm classifications) and absolute quantitative navigation accuracy (translational and angular error in axial and sagittal planes).

METHODS: We reviewed a prospectively collected series of 209 pedicle screws placed with CAN guidance. Each screw was graded clinically by multiple independent raters using the Heary and 2 mm classifications. Clinical grades were dichotomized per convention. The absolute accuracy of each screw was quantified by the translational and angular error in each of the axial and sagittal planes.

RESULTS: Acceptable screw accuracy was achieved for significantly fewer screws based on 2 mm grade versus Heary grade (92.6% vs. 95.1%, p=0.036), particularly in the lumbar spine. Inter-rater agreement was good for the Heary classification and moderate for the 2 mm grade, significantly greater among radiologists than surgeon raters. Mean absolute translational-angular accuracies were 1.75 mm-3.13° and 1.20 mm-3.64° in the axial and sagittal planes, respectively. There was no correlation between clinical and absolute navigation accuracy.

CONCLUSIONS: Radiographic classifications of pedicle screw accuracy vary in sensitivity across spinal levels, as well as in inter-rater reliability. Correlation between clinical screw grade and absolute navigation accuracy is poor, as surgeons appear to compensate for navigation registration error. Future studies of navigation accuracy should report absolute translational and angular errors. Clinical screw grades based on postoperative imaging may be more reliable if performed in multiple by radiologist raters. © 2016 Elsevier Inc. All rights reserved.

Introduction

Intraoperative three-dimensional (3D) computer-assisted navigation (CAN) is used routinely in cranial neurosurgery for the localization of subsurface structures. Although not employed as frequently, navigation for spinal procedures may guide implant placement and bony decompression, particularly in minimally invasive and complex deformity-correcting procedures where anatomical landmarks are less readily identifiable [1–3].

Modern spinal CAN techniques employ two-dimensional guidance using “virtual” fluoroscopy, or 3D guidance based on either preoperative or intraoperative computed tomography (CT) imaging [4]. The accuracy of spinal navigation systems is most easily studied for pedicle screw placement, as instrumentation is reliably localized on postoperative imaging. Computer-assisted navigation techniques have been widely reported to reduce pedicle screw breach rates, from 12% to 40% under freehand or fluoroscopic guidance to under 5% with 3D CAN [5–11]. Improved instrumentation accuracy is seen across all 3D CAN techniques, in each of the cervical, thoracic, lumbar, and sacral regions [12–16].

The clinical accuracy of spinal CAN for pedicle screw placement is variably reported. Up to half of studies assessing pedicle screw accuracy do not define methods of determining screw “breach,” and no consistent grading system is used by those that do [9,17]. The absolute accuracy of spinal navigation systems, quantified most commonly by the target registration error (TRE), has been reported to varying extent in fewer than 10 human clinical studies since 2000, whereas more than 40 studies on CAN-guided pedicle screw placement have been published in the same period [13,16,18–25]. Unsurprisingly, the absolute accuracy requirements of spinal CAN systems, and their relationship to radiographic screw position and clinical outcomes, remain poorly defined [26].

Here, we therefore review a prospectively collected series of 209 pedicle screws placed with 3D CAN guidance, with clinical accuracy grading using two established scoring systems, as well as quantitation of absolute translational and angular navigation accuracy, to identify any correlation between clinical and engineering accuracies.

Methods

Patient selection

Thirty patients enrolled in a prospective comparative trial of our research group’s optical topographic 3D CAN system (to be published separately) against two commercially available 3D CAN systems were retrospectively reviewed. All patients underwent posterior cervical-thoracic-lumbar-sacral instrumented fusion with pedicle screw constructs, with or without decompression, for predominantly traumatic, degenerative, or neoplastic pathologies. Procedures were performed at Sunnybrook Health Sciences Centre by a single surgeon (VXDY), with or without trainee assistance, from May 2014 to February 2015.

Intraoperative navigation

All screws were placed with 3D CAN guidance using either the Nav3/3i (Stryker; Portage, MI, USA), registered to preoperative imaging with point-matching followed by surface refinement, or the StealthStation S7 (Medtronic Sofamor Danek; Memphis, TN, USA), registered to intraoperative imaging using the O-Arm (Medtronic). Preoperative CT scans

Keywords: Intraoperative navigation; Frameless stereotaxy; Image guidance; Pedicle screw; Registration; Target registration error
were performed at a slice thickness of 0.625 mm on a GE LightSpeed VCT scanner (General Electric, Fairfield, Connecticut, USA). All patients underwent postoperative CT imaging of the instrumented region, using the same scanner at a slice thickness of 0.625 mm.

**Clinical grading**

Clinical grading of pedicle screw accuracy was performed on postoperative CT imaging using two established methods: the Heary and 2 mm classifications [25,27]. Summaries of each scoring system are shown in Tables 1 and 2, respectively.

Heary grading was performed for all screws independently by one neurosurgeon (DC), two orthopedic surgeons (RG, GT), and two radiologists (CH, PH). Two-millimeter grading was performed for all screws independently by two neurosurgeons (NMA, DG) and two radiologists (AK, JMK). Reviewers for each scoring system were blinded to the results of the other.

Clinical grades were dichotomized as acceptable (Heary grade ≤2, or 2 mm grade ≤2) or poor (Heary grade >2, or 2 mm grade >2), as has been previously reported [17,25,27].

**Absolute navigation accuracy**

Absolute navigation accuracy was measured by comparing the final screw position, on postoperative CT imaging, with a screenshot of the planned screw entry point and trajectory, as seen by the navigation system intraoperatively. Translational and angular deviations from the planned entry point and trajectory were then quantified, in both the axial and the sagittal planes, using multiplanar reformatting of both pre- and postoperative CT imaging. The method of absolute navigation error quantification is adapted from those described by Mathew et al. and Kotani et al. (Fig. 1) [19,21]. In the axial plane, positive translational deviations denote a lateral deflection of the entry point, and positive angular deviations denote a more lateral trajectory. In the sagittal plane, positive translational deviations denote a superior deflection of the entry point, and positive angular deviations denote a more cranial trajectory.

All image processing and measurements were performed using an OsiriX 64-bit workstation (version 10.9.5; PIXMEO SARL, Geneva, Switzerland).

**Statistical analysis**

Inter-rater reliabilities (IRR) of Heary and 2 mm grades were computed using two-way consistency average-measures intraclass correlation coefficients (ICC), appropriate for a fully crossed design [28]. As an approximation, ICC values between 0.60 and 0.74 were reflective of moderate agreement, 0.75–0.89 good agreement, and 0.90–1.00 excellent agreement [29]. Frequencies of categorical data were analyzed using Fisher exact tests. For paired categorical data, including the frequencies of poor-grade screws on both Heary and 2-mm grading scales, McNemar-Bowker tests of marginal homogeneity were used. Correlation of clinical grading with absolute navigation errors was performed by independent-samples t tests as well as generalized linear regression models. Regression models were first tested for nonlinearity with three cubic splines, with subsequent elimination of all nonsignificant nonlinear terms from the final model. Significance levels for all tests were set at α<0.05.

All statistical analyses were performed in SPSS Statistics 21 (IBM, Chicago, IL, USA).

**Literature review**

A search of the English-language literature from 2000 to present was performed, in June 2016, to identify articles reporting absolute navigation accuracy. MEDLINE, Web of Science, and Scopus databases were searched using the terms “spine” AND “navigation” AND (“error” OR “accuracy”). Abstracts were reviewed by a single author (DG) to identify human clinical in vivo studies; the full texts of eligible abstracts were reviewed to identify parameters and measurement methods of absolute navigation error.

**Results**

A total of 209 pedicle screws from 30 patients were included in our analysis. Three screws were placed in the cervical spine (all at C7), 138 in the thoracic spine, 64 in the lumbar spine, and 4 in the sacrum (all at S1).

**Clinical accuracy**

Of 209 screws, with 932 combined Heary grades from five independent reviewers, 95.1% were rated as acceptable. On the 2-mm grading scale, from four independent reviewers

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**Table 1**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Definition</th>
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<tbody>
<tr>
<td>1</td>
<td>Shaft+tip contained entirely within pedicle</td>
</tr>
<tr>
<td>2</td>
<td>Shaft violates lateral pedicle, but tip entirely contained within vertebral body</td>
</tr>
<tr>
<td>3</td>
<td>Tip penetrates anterior or lateral vertebral body</td>
</tr>
<tr>
<td>4</td>
<td>Shaft breaches medial or inferior pedicle wall</td>
</tr>
<tr>
<td>5</td>
<td>Tip or shaft violates pedicle or vertebral body, and endangers spinal cord, nerve root(s), or great vessels, requiring immediate revision</td>
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CT, computed tomography.

**Table 2**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shaft contained entirely within pedicle</td>
</tr>
<tr>
<td>2</td>
<td>Shaft violates pedicle cortical wall by ≤2 mm</td>
</tr>
<tr>
<td>3</td>
<td>Shaft violates pedicle cortical wall by 2–4 mm</td>
</tr>
<tr>
<td>4</td>
<td>Shaft violates pedicle cortical wall by &gt;4 mm</td>
</tr>
</tbody>
</table>

CT, computed tomography.
assessing the same dataset, significantly fewer screws were rated as acceptable, at 92.6%. These differences did not persist when thoracic screws were analyzed independently; however, the Heary grading system was significantly more generous in the lumbar spine. Cervical and sacral screws were not analyzed independently because of inadequate sample size. A summary of clinical grades is presented in Table 3.

The ICC, a measure of IRR, was 0.763 (95% confidence interval 0.665–0.809) for Heary grade, 0.428 among the three surgeon raters, and 0.781 among the two radiologist raters. For the 2 mm grade, overall ICC was 0.611 (95% confidence interval 0.517–0.690), 0.21 among the two surgeon raters, and 0.678 among the two radiologist raters.

**Absolute navigation accuracy**

The absolute translational and angular errors of all screws in our cohort, in both axial and sagittal planes, are shown in

![Fig. 1. Measurement of absolute navigation accuracy, in the axial (A+C) and sagittal (B+D) planes. Comparison is made between intraoperative navigation screenshots of planned entry points and trajectories (A+B), to final screw placement on postoperative CT (C+D). Reference lines (dashed) are drawn, in the axial plane, in the mid-sagittal line (bisecting the vertebral body, spinal canal, and spinous process), and in the sagittal plane, along the inferior endplate. Translational error is computed as ($d_1$–$d$); angular error is computed as ($\varnothing_1$–$\varnothing$).](image)

| Table 3 | Clinical grades of 209 pedicle screws, using the Heary and 2 mm grading systems |
|---------|------------------|------------------|------------------|------------------|
|         | Heary grade      | 2 mm grade       | Difference       | Significance     |
|         | (# of ratings)   | (# of ratings)   | (absolute value) |                  |
| All screws |                   |                  |                  |                  |
| Acceptable | 886 (95.1%)      | 774 (92.6%)      | 2.48%            | p=.036*          |
| Poor      | 46 (4.9%)        | 62 (7.4%)        |                  |                  |
| Thoracic screws |             |                  |                  |                  |
| Acceptable | 584 (93.4%)      | 509 (92.2%)      | 1.23%            | p=.43            |
| Poor      | 41 (6.6%)        | 43 (7.8%)        |                  |                  |
| Lumbar screws |               |                  |                  |                  |
| Acceptable | 272 (98.6%)      | 240 (93.8%)      | 4.80%            | p=.005*          |
| Poor      | 4 (1.4%)         | 16 (6.2%)        |                  |                  |

* Denotes significance at $\alpha<0.05$. 
For all screws, axial and sagittal translational errors were $1.75 \pm 3.57$ mm and $1.20 \pm 1.15$ mm, respectively, whereas axial and sagittal angular errors were $3.13 \pm 2.90^\circ$ and $3.64 \pm 3.48^\circ$, respectively (mean $\pm$ standard deviation). Axial angular errors were greater in the lumbar spine than in the thoracic spine (mean $3.74^\circ$ vs. $2.64^\circ$, respectively; $p=0.018$); all other errors were equivalent across spinal regions.

Clinical-engineering correlation

In a generalized linear regression model, there was no correlation between any absolute navigation error parameter and the mean Heary grade across all raters (Fig. 3). Comparison of absolute navigation errors between “poor” and “acceptable” dichotomized Heary grades also revealed no significant differences.

Similarly, no correlation was observed between absolute navigation errors and the mean 2 mm grade (Fig. 3). Comparison of absolute navigation errors between “poor” and “acceptable” dichotomized 2 mm grades revealed no significant differences.

Surgeon compensation for navigation error

We theorized that the lack of observed correlation between clinical screw grade and absolute navigation accuracy may be due, in part, to surgeon compensation for perceived misalignment of virtual and anatomical intended screw entry points, based on surgeon visualization and knowledge of anatomical landmarks. For instance, a “perfect” entry point as shown by the navigation system, which is felt by the surgeon to be excessively lateral based on anatomical knowledge, may lead the surgeon to compensate by medializing their screw trajectory (Fig. 4). In this situation, the signed axial translational error is expected to be positive, with a corresponding negative axial angular error.

Linear regression models were therefore generated between signed translational and angular errors, in the axial and sagittal planes, respectively. Negative linear correlations were observed for both axial ($p<0.001$) and sagittal ($p<0.001$) errors, suggestive of surgeon compensation occurring in both planes, greater in the axial plane than in the sagittal plane (Fig. 5).

Discussion

The primary purported benefit of CAN for spinal procedures is improved instrumentation accuracy and, in theory, minimization of complications from breached screws. Clinical sequelae of screw breach include, acutely, neurologic and vascular injury and, in the longer term, pseudoarthrosis due to poor osseous purchase and load-bearing [30]. As CAN techniques evolve, from two-dimensional fluoro to 3D fluoro to intraoperative CT-based registration, from surgeon-manipulated to robotically actuated instruments, the body of literature on navigation accuracy is rapidly expanding. In an era of fiscally responsible health care, the cost-effectiveness of various CAN techniques, in relation to their purported accuracy, is also being explored [31,32].

The grading systems used to quantify navigation accuracy for pedicle screw insertion remain highly heterogeneous [17]. Some, such as the 2-mm grading system, are based on screw shaft relation to the pedicle wall alone, whereas others, such as the Heary classification, include the relation of the screw tip to the vertebral body [27,33]. Similarly, whereas most scales quantify only the amount of pedicle wall breach, others have demonstrated the importance of directionality, with lateral breaches less likely to be clinically significant [34,35]. As assessments of in vivo screw accuracy are based on postoperative CT imaging, metallic artifact may also contribute to the reliability of accuracy ratings, although the type of screw material has been shown not to impact IRR [36].
Fig. 3. Scatter plots of mean Heary grade (top row) and mean 2 mm grade (bottom row), versus each of axial and sagittal translational and angular errors. No correlation is seen between Heary grade or 2 mm grade and any absolute navigation error parameter.
The commonest grading system in current use is the 2 mm classification, with variations in the grade cutoffs ranging from >4 mm breach to >6 mm breach for Grade IV screws [33,37]. The increasingly popular Heary classification accounts for tip position relative to the vertebral body, and emphasizes medial or inferior breaches over less clinically relevant lateral breaches, regardless of magnitude. In our series, the Heary classification was significantly more conservative than the 2 mm grade in identifying poorly placed screws, but only among lumbar pedicle screws. Although the Heary grade was developed for thoracic pedicle screws and has not formally been validated in the lumbar spine, it can reasonably be expected to perform similarly as its emphasis is to prioritize breaches more likely to be symptomatic [27]. Anterior, medial, and inferior perforations are given greater weight in the Heary classification because of risk of injury to the esophagus or trachea or lungs, spinal cord, and nerve roots, respectively, in the thoracic spine. In the lumbar spine, perforations in similar directions may injure the iliac vessels or bowel, conus medullaris or cauda equina, and nerve roots, respectively. Therefore, the relatively aggressive identification of poor-grade screws by the 2-mm grading system in the lumbar spine is likely reflective of the larger pedicles and screw diameters relative to the thoracic spine. A breach of 2 mm for a 7-mm diameter lumbar pedicle screw is far more likely to be tolerated by a surgeon than the same 2 mm breach for a 4.5-mm diameter thoracic screw. Whereas the 2 mm increment in this classification is appropriately justified, and the grade cutoffs in our study are those used most commonly in the literature, adjustment of grade cutoffs may be required across spinal levels [18,25,33,38–40]. For instance, “Grade IV: >4 mm breach” may be appropriate for the thoracic spine, whereas “Grade IV: >6 mm breach”
may be more appropriate in the lumbar spine, as described originally by Gertzbein and Robbins [33].

Good inter-rater agreement was demonstrated in our series for the Heary classification, and moderate agreement was demonstrated for the 2 mm scale. For both scales, IRR was significantly higher among radiologists than among surgeons. For the 2 mm system, using the same grade cutoffs as our study, ICC has been reported to vary from 0.45 to 0.69, in concordance with our results [41–44]. To our knowledge, this is the first study reporting on IRR of the Heary classification. It is also the first to compare IRR between radiologist and surgeon raters. Given the difficulty in distinguishing metallic screw artifact from pedicle cortex on CT imaging, it is unsurprising that radiology-trained raters are more consistent. It may therefore be prudent for future studies of navigation accuracy to employ multiple radiologists for rating clinical screw accuracy, rather than a single rater, as has been done in more than half of studies to date [17].

Absolute navigation accuracy, commonly quantified as the TRE, likely represents the most generalizable method of reporting navigation accuracy. The TRE of novel navigation techniques is commonly quantified ex vivo using specialized fiducial-implanted phantoms [45,46]. However, in vivo absolute navigation accuracy has been reported in only seven human clinical studies since 2000 (Table 4). Quantitation of absolute accuracy in these studies is highly variable, with the majority reporting only angular error. Given that surgeons employing CAN intraoperatively modulate both the position and the angulation of their instruments, in both the axial and the sagittal planes based on in-plane views on the navigation display, error tolerances in each of these parameters should be reported in future studies of navigation accuracy.

We have shown here furthermore that clinical grading, on two commonly used scales, does not correlate with absolute quantitative navigation accuracy. Using a novel technique of measuring both translational and angular error in axial and sagittal planes, we have also demonstrated quantitatively for the first time that surgeon compensation may lead to clinically acceptable screw placement despite navigation registration error. Although the absolute accuracy requirements for surgical navigation systems remain uncertain, in trained hands they are likely to be less stringent than the submillimeter tolerances suggested by rigid mathematical models [26]. Conversely, although CAN is a useful intraoperative adjunct, it cannot and should not replace dedicated subspecialty training, which affords the experience and anatomical knowledge required to identify and compensate for navigation registration errors.

Given the heterogeneity and inter-rater discordance in clinical grading scales, along with their lack of correlation with engineering accuracy, reporting of absolute navigation accuracy along with a summary of clinical sequelae may be a reasonable standard for future studies of navigation accuracy. Acute neurovascular injury from breached screws are rare events, however, and long-term pseudoarthrosis-related complications are difficult to attribute specifically to breached screws [16]. Clinical screw grading based on postoperative imaging will therefore continue to be of value in identifying breaches likely to cause significant sequelae.

Conclusions

Radiographic grading scales of pedicle screw accuracy are highly heterogeneous, with variability in performance across spinal levels, as well as in IRR. Correlation between clinical screw grade and absolute navigation accuracy is poor, in part owing to surgeon compensation for navigation error. Future studies of navigation accuracy should therefore report absolute translational and angular navigation accuracy, along with relevant clinical sequelae of any placed screws. If used, clinical screw grades based on postoperative imaging should ideally be generalizable, validated, and include the direc-

Table 4
Summary of the literature from 2000 to 2016, of human in vivo studies of CAN accuracy for pedicle screw placement, with reporting of absolute navigation accuracy

<table>
<thead>
<tr>
<th>Author, year</th>
<th>Spinal levels</th>
<th>CAN technique</th>
<th>Quantitative parameters</th>
</tr>
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<tbody>
<tr>
<td>Kleck et al., 2016 [18]</td>
<td>Thoracic, lumbar</td>
<td>Imaging: Intraoperative CT (Medtronic O-Arm) Navigation: Medtronic StealthStation S7</td>
<td>3D translation and angulation of screw tip from intended position</td>
</tr>
<tr>
<td>Mathew et al., 2013 [19]</td>
<td>Lumbar</td>
<td>Imaging: Intraoperative CT (Medtronic O-Arm) Navigation: Medtronic StealthStation S7</td>
<td>Axial and sagittal angular error</td>
</tr>
<tr>
<td>Scheufler et al., 2011 [21]</td>
<td>Cervical, thoracic</td>
<td>Imaging: Intraoperative CT (Siemens SOMATOM) Navigation: BrainLab iCT</td>
<td>Axial and sagittal angular error</td>
</tr>
<tr>
<td>Kotani et al., 2007 [21]</td>
<td>Thoracic, lumbar</td>
<td>Imaging: preoperative CT Navigation: Medtronic StealthStation</td>
<td>Axial angular error, with comparison with “ideal” pedicle axis from preoperative CT</td>
</tr>
</tbody>
</table>

CAN, computer-assisted navigation; CT, computed tomography; 3D, three-dimensional.
tionality of breach, and may be more reliable if performed in multiple by radiologist raters. Navigation systems are not intended to replace quality surgical training, which affords the experience and anatomical knowledge required to identify and compensate for navigation errors.

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