Pedicle Screw Placement Using Augmented Reality Surgical Navigation With Intraoperative 3D Imaging

A First In-Human Prospective Cohort Study

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Study Design. Prospective observational study.

Objective. The aim of this study was to evaluate the accuracy of pedicle screw placement using augmented reality surgical navigation (ARSN) in a clinical trial.

Summary of Background Data. Recent cadaveric studies have shown improved accuracy for pedicle screw placement in the thoracic spine using ARSN with intraoperative 3D imaging, without the need for periprocedural x-ray. In this clinical study, we used the same system to place pedicle screws in the thoracic and lumbosacral spine of 20 patients.

Methods. The study was performed in a hybrid operating room with an integrated ARSN system encompassing a surgical table, a motorized flat detector C-arm with intraoperative 2D/3D capabilities, integrated optical cameras for augmented reality navigation, and noninvasive patient motion tracking. Three independent reviewers assessed screw placement accuracy using the Gertzbein grading on 3D scans obtained before wound closure. In addition, the navigation time per screw placement was measured.

Results. One orthopedic surgical surgeon placed 253 lumbosacral and thoracic pedicle screws on 20 consenting patients scheduled for spinal fixation surgery. An overall accuracy of 94.1% of primarily thoracic pedicle screws was achieved. No screws were deemed severely misplaced (Gertzbein grade 3). Fifteen (5.9%) screws had 2 to 4 mm breach (Gertzbein grade 2), occurring in scoliosis patients only. Thirteen of those 15 screws were larger than the pedicle in which they were placed. Two medial breaches were observed and 13 were lateral. Thirteen of the grade 2 breaches were in the thoracic spine. The average screw placement time was 5.2 ± 4.1 minutes. During the study, no device-related adverse event occurred.

Conclusion. ARSN can be clinically used to place thoracic and lumbosacral pedicle screws with high accuracy and with acceptable navigation time. Consequently, the risk for revision surgery and complications could be minimized.

Key words: augmented reality, image-guided surgery, intraoperative 3D cone beam computed tomography imaging, pedicle screw accuracy, scoliosis.

Level of Evidence: 3

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Misplaced pedicle screws can result in neurological or vascular injuries or insufficient bone purchase and need for revision surgery. The literature shows that pedicle screw placement accuracy ranges from 60% to 97.5% in the lumbar spine, and from 27.6% to 96.5% in the thoracic spine, when the surgery is performed with the free-hand method.4

Traditionally, intraoperative 2D radiographic imaging is performed to guide and assess screw placement. However, it only detects 52% of misplaced screws compared to 3D computed tomography (CT) imaging.5 Thus, 3D imaging
becomes a necessity in the operating room (OR) to allow for the immediate evaluation and correction of misplaced screws. It has been documented that intraoperative 3D imaging enables immediate intraoperative revision in 9% of screws corresponding to 35% of the treated patients.

Another technological advancement brought into the OR to reduce screw malposition rate is the use of intraoperative 3D imaging in combination with a navigation system. Several meta-analyses have demonstrated that pedicle screw placement accuracy using intraoperative 3D navigation (i3Dn) is significantly higher than when using the free-hand method, 2D navigation, or preoperative CT navigation.

This is especially important in scoliosis treatment where most of the screws are placed in the thoracic spine where the pedicles are narrow. Consequently, i3Dn decreases the risk of revision surgery to almost half of that associated with the free-hand method.

State-of-the-art i3Dn systems use passive optical infrared cameras with a dynamic reference frame attached to the spine for patient tracking. Intraoperative 3D augmented reality surgical navigation (ARSN) is a novel concept of navigation using optical video cameras to augment the surgical field with 3D intraoperative imaging with a navigation path for screw placement. Patient tracking is ensured by video tracking of noninvasive markers placed on the skin. The intraoperative 3D imaging is performed with a robotic ceiling-mounted C-arm in a hybrid OR. A preclinical study on cadavers demonstrated a significant improvement in pedicle screw placement accuracy in the thoracic spine with ARSN compared to free-hand. In this study, we present the first clinical results using ARSN in a hybrid OR.

**MATERIALS AND METHODS**

**Patient Data**

The study was a prospective observational study approved by the ethics committee including patients of 16 years and older. All enrolled patients signed informed consent.

**The Hybrid Operating Room with Intraoperative 3D Augmented Reality Navigation System**

The study was conducted in a hybrid OR equipped with a radiolucent, motorized, carbon fiber surgical table connected to a robotic ceiling-mounted C-arm system (AlluraClarity Flexmove, Philips, Best, The Netherlands). The ARSN system is based on video input from four optical cameras mounted into the frame of the C-arm detector (Figure 1). Patient tracking is ensured by continuous video detection of flat, adhesive circular markers placed on the surface around the surgical field. The C-arm enables 3D cone-beam CT (XperCT, Philips, Best, The Netherlands) scans for planning screw placement as well as confirming proper screw position. The vertebrae and corresponding pedicles are automatically segmented on the planning XperCT scan. The optimal screw path through the vertebra as well as screw dimensions, that is, width and length, are specified by the operator (Figure 2). The intraoperative XperCT and the planned paths for screw placement are augmented to the video images showing the surgical field. The screws are navigated to the desired location by following the planned path displayed on a medical grade monitor (Figure 1).

**Surgical Procedure and Workflow**

The subjects were placed under general anesthesia in prone position on the surgical table. The optical markers were placed on the skin around the incision after completed dissection and prior to XperCT acquisition of the region of interest. Subsequently, an automatic 3D segmentation of the region of interest to identify the vertebrae and their pedicles was performed. The surgeon selected the appropriate pedicles one at a time, and virtual screw positions were defined. If desired, the surgeon adjusted the planning for each screw. The screws to be placed were then, one by one, activated in the system; for each screw, the C-arm rotated to the proper position to display the path to follow for instrument navigation.

In deformity cases, the surgeon performed hybrid constructs where hooks were placed or levels were skipped when deemed necessary.
The entry-point on the bone was identified with augmented reality and an awl was used to create an initial hole. Subsequently, a gearshift or power drill was used to navigate along the planned path and probe for cortical breach before screw placement with a screw driver with the help of the ARSN system (Figure 1).

When all screws were placed, an intraoperative XperCT was performed to verify the screw positions. A screw was revised if the surgeon judged its position unsatisfactory. Neurophysiological monitoring was performed at the end of the procedure to assess the likelihood of pedicle breach. Postoperative CT were not performed as XperCT was deemed adequate for clinical evaluation.

Navigation time per screw from preparing the entry point on the bone to final screw placement was documented. Screw diameters and intraoperative neurophysiological monitoring to assess motor and sensory responses were documented as part of standard care.

Analysis of Screw Placement Accuracy
Two neuroradiologists and an orthopedic spine surgeon independently assessed screw positions using the Gertzbein grading for clinical accuracy evaluation: grade 0 (screw within the pedicle without cortical breach), grade 1 (0–2 mm breach, minor perforation including cortical encroachment), grade 2 (>2–4 mm breach, moderate breach), and grade 3 (>4 mm breach, severe displacement). Breach direction (lateral vs. medial) in case of grade 2 or 3 was documented. The pedicle widths were measured to correlate with the assigned grades.

Statistical Analysis
Descriptive summary statistics are expressed as mean (±standard deviation), median (min-max range), or frequency (percentage), as appropriate. Jonckheere-Terpstra test was applied to demonstrate trends. Normality test was applied to the data, with skewness and kurtosis calculations to identify outliers from the data distribution. Statistical significance was set at $P < 0.05$.

RESULTS
A total of 20/21 consecutive patients underwent spine surgery with 253 pedicle screws placed using ARSN between January and October 2017. One obese patient (body mass index of 37) did not undergo surgery under ARSN because proper isocentering of the spine could not be achieved causing cropped 3D visualization of the spine and limited space between the detector and the patient for navigation. Most screws (64.4%) were placed in the thoracic spine. Most patients (65.0%) had scoliotic deformity with a total of 207 implanted screws (81.8%). One of the surgeries was a complex revision surgery of an imbalanced scoliotic spine previously treated with fusion and Harrington rods. The scoliosis patients had a preoperative major curve Cobb angle of $55\degree \pm 14\degree$. All surgeries were performed by the same orthopedic surgeon with 18 years of experience in deformity surgery and without prior experience with any type of navigation systems. Table 1 summarizes patients’ demographics and surgical characteristics.

Out of all 253 screws placed with ARSN, three (1.2%) were revised intraoperatively after being judged unsatisfactory
by the surgeon. Because all pedicles visible on XperCT were
planned for screw placement, attempts to place screws were
made in eight pedicles where our institutional clinical
practice is to place hooks or avoid instrumenting the pedi-
cle. Seven pedicles were instrumented by the free-hand
method because the navigation system could not achieve
line of sight to the bone entry-point: in two cases spine
exposure was not wide enough obstructing proper align-
ment of the instruments, in two cases we had limited
visibility and accessibility to the entry point on the bone,
in one case tissue was still present on top of the bone at the
entry point, and in two cases the pedicle was reported as too
small with uncompleted documentation on the reason of
not using navigation or placing a hook instead. These cases
corresponded to one case with scoliosis and four
with scoliosis. These four scoliosis cases had a more severe
visibility and accessibility to the entry point on the bone,
revision surgery case. Figure 3 depicts the
distribution of grades for all screws per spinal level along
with the corresponding pedicle widths. The average pedicle
width-to-screw size ratio was 1.3 ± 0.7; and were 1.4 ± 0.8,
1.0 ± 0.3, and 0.8 ± 0.2 for screws rated as grade 0, 1, and 2,
respectively. The decreasing trend of this ratio with increas-
ing level of breaches was statistically significant, P < 0.05
(Figure 4). The pedicle width-to-screw size ratio was supe-
rior to 1 in only 2/15 grade 2 screws.

Figure 5 shows an example of a 4.35-mm screw which
was placed in a 2.5-mm wide pedicle and was judged as a
grade 2 breach.

**Screw Navigation Time**

The navigation time for screw placement did not follow a
normal distribution (P < 0.05). Half of the total amount of
screws was navigated in less than 4.0 minutes. The average
time for screw navigation was 3.2 ± 1.1 minutes. The screw
placement time was skewed to lower values (skewness of
3.1) and the kurtosis was 14.7 suggesting outliers from the
screr
time navigation distribution (Figure 6). The average
screw placement time for each surgical procedure is depicted
in Figure 7.

**DISCUSSION**

This clinical study is the first to assess ARSN for pedicle
screw placement using a hybrid OR. The achieved accuracy
with this navigation technology was 94.1% out of a total of
253 screw placements in 20/21 consecutive patients. Most
grade 2 screws (13/15) in this study were lateral, in agree-
ment with previously published data. The intraoperative
screw revision rate of 1.2% was within the reported range of
0 to 3% from existing i3Dn studies, yielding a significant
reduction in revision surgery thanks to the intraoperative 3D
imaging in the OR.

The main risk factor for pedicle screw breach is narrow
pedicles. The narrowest pedicles are in the mid-
thoracic (T5-T8) levels with an average width of 4 mm
(Figure 3). Consequently, the mid-thoracic region is
the spinal region with the highest reported amount of grade
2 screws. The smallest pedicle screw diameter used in

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**Table 1. Patient Demographics and Surgical Characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Number of patients</td>
<td>20 (100%)</td>
</tr>
<tr>
<td>Male-female</td>
<td>9–11 (45%–55%)</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>30.5 ± 19.4</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>58.8 ± 7.0</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>19.8 ± 2.1</td>
</tr>
<tr>
<td>Total number of navigated screws</td>
<td>253 (100%)</td>
</tr>
<tr>
<td>Thoracic spine</td>
<td>163 (64.4%)</td>
</tr>
<tr>
<td>Lumbosacral spine</td>
<td>90 (35.6%)</td>
</tr>
<tr>
<td>Screw diameter (mm)</td>
<td>5.8 ± 1.1</td>
</tr>
</tbody>
</table>

BMI indicates body mass index.

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**Table 2. Accuracy of Navigated Screws**

<table>
<thead>
<tr>
<th>Screw assessment</th>
<th>Frequency (%)</th>
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<tbody>
<tr>
<td>Grade 0 + 1</td>
<td>238 (94.1%)</td>
</tr>
<tr>
<td>Grade 0</td>
<td>161 (63.6%)</td>
</tr>
<tr>
<td>Grade 1</td>
<td>77 (30.4%)</td>
</tr>
<tr>
<td>Grade 2 + 3</td>
<td>15 (5.9%)</td>
</tr>
<tr>
<td>Grade 2</td>
<td>15 (5.9%)</td>
</tr>
<tr>
<td>Grade 3</td>
<td>0 (0.0%)</td>
</tr>
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</table>
this study was 4.35 mm, which consequently implies that
breaches as determined by the Gertzbein scale were
expected. However, neurophysiological monitoring showed
no signs of neurological injuries. In idiopathic and congeni-
tal scoliosis, pedicles are dysplastic and tend to be smaller on
the convex side of the deformity, especially in the upper
vertebra.28 The accuracy of pedicle screw placement highly
depends on the size of the pedicles. Misplacement screw rate
increases from 2.9% to 31.5% for pedicles between 2 and
4 mm to pedicles below 1 mm when placed by free hand.25
When the screws were placed with i3Dn, the accuracy was
93.8% and 91.7% in pedicles of widths above and below
3 mm, respectively.29

The pedicle-to-screw size ratio is an important factor for
preventing screw pullout. It was demonstrated that the
ability of i3Dn to plan and optimize screw size reduced
the pedicle-to-screw size ratio from 1.6 to 1.4 for non-
avigated techniques.30 In this study, the pedicle-to-screw
size ratio was 1.3 ± 0.7 which is comparable to reported
values of 1.3 ± 0.3 by Hecht et al. However, our standard
deviation was higher due to the high proportion of scoliosis
cases in our cohort with very small pedicles.16 In some cases,
we deliberately opted for screws larger than the pedicle for
better bone purchase instead of placing hooks or not instru-
menting the pedicles. Rajasekaran et al31 reported that 10/
27 misplaced screws were intentional as the “in-out-in”
technique was used. Strictly following the Gertzbein scale,
although clinically safe, these screws are considered as
inaccurate placements.

To compare our results with the existing literature, it is
thus important to know the proportion of screws placed in
the thoracic versus the lumbosacral spine as the smallest
pedicle widths in the thoracic spine yield lower accuracy.
For the sake of proper comparison with our study, we
searched available studies in the literature which (1) used
i3Dn with automatic registration between the navigation
and the intraoperative imaging, (2) placed screws in T1 to
S1, (3) provided the numbers of screws placed in the thoracic
and lumbar spine, (4) and assessed accuracy based on the
Gertzbein scale. Eight studies were identified with accuracy
ranging from 90.2% to 98.6%.15,16,27,31–35 This variation
in accuracy highly correlates with the percentage of thoracic
screws ranging from 8.2% to 73.9% (correlation of −0.90,
P < 0.05). Our accuracy falls within the range reported in
literature with 64.4% of thoracic screws.

Another risk factor of pedicle screw misplacement
described in the literature is the distance between the posi-
tion of the dynamic reference frame for patient tracking and
the operated spinal level.16,27,36 In scoliosis patients, screw
malposition rate with i3Dn increases from 4.8% to 20.6% when instrumenting a vertebrate adjacent to the one with
the reference frame versus three or more levels away.27 With
the noninvasive tracking of the markers on the patient skin,
there is no such dependency. However, because the tracked
markers are on the skin surface around the incision, it is
important that the tissue above the surgical field is retracted
widely enough to have free access to pedicles with large
transverse angles. In the beginning of the study, two screws
were placed using the free-hand technique at L5 because the
tissue above that vertebra was obscuring the navigation
systems’ line of sight since the skin incision was not wide
enough. L5 is known to have the largest transverse pedicle angle; with an angle of 30° almost twice as wide as L4.37 Throughout this study and increased

Figure 3. Distribution of amount per screws (histogram) and mean ±
standard deviation of pedicle widths (continuous line with bars) per
spinal level.
experience-building with the technology, adequate skin incision in the lumbosacral junction was performed to be able to properly navigate instruments with ARSN.

The average navigation time for screw placement was 5.2 ± 4.1 minutes and is comparable to values reported in other i3Dn studies, for example, Zhang et al.\textsuperscript{4} and Kotani et al.\textsuperscript{38} which reported 5.1 ± 1.1 and 5.4 ± 1.1 minutes, respectively. However, our standard deviation for screw placement is larger as probably a learning curve effect is associated to it. Hence the skewness and outliers of the distribution of screw placement time is shown in Figure 6. In fact, the first case was a four-screw placement surgery in which each screw was placed in more than 17 minutes as the surgeon took extra care for his first clinical experience with the technology. Although our average navigation time per screw placement is comparable to existing values in literature, shorter average navigation time per screw placement of 1.8 ± 0.9 minutes was reported. However, the authors nuanced this short time compared to existing literature explaining that the operating surgeon had a long experience with navigation technology and its associated learning curve.\textsuperscript{31}

There are some differences between the augmented reality system and traditional i3Dn systems. The augmented reality system has cameras integrated cameras within the C-arm, reducing the amount of equipment in the OR. In
addition, there are no line-of-sight issues as four cameras with four different viewing directions are used for navigation instead of only one camera with a single viewing direction such as in traditional navigation systems. The noninvasive skin markers are quick to place and their tracking is robust; a new registration is not needed in case some markers are touched or accidentally removed. The dynamic reference frame from traditional navigation can be inadvertently touched and therefore a new registration is needed requiring an additional intraoperative 3D scans.

Figure 5. Planning 3D-Cone Beam CT showing pedicle isthmus measurement of 2.5 mm at T7 left in the concave side and at the apical region of a scoliotic patient (left sub-figure). Corresponding verification 3D-CBCT scan with a 4.35 mm 80% larger than the pedicle (pedicle-to-screw size) which was rated as a grade 2 screw.

Figure 6. Distribution of screw placement time with mean (solid vertical line) and standard deviation (dashed vertical lines) as well as box plot depicting median, quantile, and outliers (red crosses) from distribution.
yielding extra radiation exposure to the patient and staff. Furthermore, traditional navigation accuracy decreases when the distance between the instrumented spinal levels and the vertebrate with the attached dynamic reference frame increases. This issue is not applicable to the augmented reality navigation system as the markers are placed on a wide area of the skin surface around the surgical incision (Figure 1).

The main limitation of our study is that it is not a randomized controlled study to assess the difference in performance and clinical outcomes with a conventional method. A larger cohort study would potentially help in assessing the learning curve effect of ARSN. Rivkin et al demonstrated in 270 patients that accuracy increased from 86.8% to 98.9% when analyzing every 30 consecutive patients. Ryang et al analyzed data every quarter of a year and demonstrated that accuracy increased from 83.1% to 92.4% over four quarters, whereas the average pedicle screw time decreased from a comparable time to our study of 5.3 ± 2.5 down to 3.2 ± 2.3 minutes. Finally, one enrolled subject was not treated with ARSN due to the limited gantry of the robotic C-arm which does not enable imaging of very obese patients with an x-ray source-to-detector distance of 120 cm; a 3D imaging limitation which also applies to other intraoperative imaging such as the O-arm with equal x-ray source-to-detector distance.

CONCLUSION

ARSN in a hybrid OR achieves high accuracy in pedicle screw placement (94.1%) with acceptable navigation time. Further studies are needed to confirm our results and reassess the performance over a longer period with a larger cohort.

Key Points
- Intraoperative 3D augmented reality navigation in a hybrid OR is feasible with a high accuracy of 94.1% in this series of primarily thoracic pedicle screws.
- There was no case of severely misplaced screws in this study, using the intraoperative 3D augmented reality navigation system.
- The risk of breach increases with the screw to pedicle diameter ratio.
- The use of ARSN with intraoperative 3D was associated with an acceptable navigation time for screw placement comparable to other navigation systems.

References