Deviation Analysis of Atlantoaxial Pedicle Screws Assisted by a Drill Template

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abstract

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Although C1-C2 pedicle screw fixation provides an excellent fusion rate and rigid fixation, this technique has a potential risk. It is essential to develop an accurate screwing method to avoid this neurovascular injury. To develop and validate the accuracy of a novel navigational template for C1-C2 pedicle screw placement in cadaveric specimens, computed tomography scans with 1-mm-wide cuts were obtained of 32 cadaveric cervical specimens. The authors developed 64 three-dimensional full-scale templates that were created by computer modeling with a rapid prototyping technique from the computed tomography data. Drill templates were constructed with a custom trajectory for each level and side. The drill templates were used to guide the establishment of a pilot hole for screw placement. The average distances between ideal and actual entry points of the C1 pedicle screws in the x, y, and z axes were 0.16±0.46 mm, 0.11±0.52 mm, and -0.01±0.54 mm, respectively, on the left side and 0.11±0.49 mm, 0.01±0.56 mm, and -0.09±0.59 mm, respectively, on the right side. The average distances between ideal and actual entry points of the C2 pedicle screws in the x, y, and z axes were 0.05±0.54 mm, 0.20±0.59 mm, and -0.06±0.58 mm, respectively, on the left side and 0.17±0.55 mm, 0.1±0.58 mm, and -0.01±0.49 mm, respectively, on the right side. Factors related to human error and imprecision are responsible for most malpositioning of instrumentation. The rapid prototyping drill template for C1-C2 screw placement is described to minimize human error, although it introduces error related to computer software and variation in manufacturing.

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Much controversy surrounds the use of posterior screw fixation of the atlantoaxial junction.\textsuperscript{5-8} C1 pedicle screw fixation, first introduced by Resnick and Benzel,\textsuperscript{3} is often used when fixation is needed to treat C1-C2 instability. Because of its unique anatomy, however, instrumentation of the C1-C2 joint presents challenges that are different from those in other parts of the cervical spine.\textsuperscript{5,7} The unique architecture of the atlantoaxial complex, with its horizontal articular surfaces, ligamentous connections, and distinctive vertebral anatomy, allows not only flexion, extension, and lateral bending but also significant axial rotation.\textsuperscript{8} C1-C2 pedicle screw fixation has become popular because it achieves superior biomechanical stability against forces in all planes of motion.\textsuperscript{9}

The potential risks associated with the technique may limit the use of the C1 and C2 pedicle screw technique, particularly in the hands of less experienced surgeons. Yeom et al\textsuperscript{10} discussed the possibility of injury to the C2 nerve root during C1 pedicle screw placement. More seriously, cranial cortical violation of the pedicle risks injuring the vertebral artery;\textsuperscript{6,11; pedicle screw placement requires a very precise screw trajectory to minimize the risk of associated complications. The use of computer-assisted technology for this type of surgery may be an efficient way to improve the accuracy of pedicle screw insertion, in particular by removing some components of imprecision from surgeon-dependent error and variation in the surface anatomy. Computer-assisted surgery, however, introduces new variables related to heavy dependence on accurate image registration and transmission.\textsuperscript{12}

Another technique that may prove useful for improving the accuracy of screw placement is the design and use of a rapid prototyping drill template that has been used for other purposes and has been shown to be a relatively simple and effective way to place spinal instrumentation accurately.\textsuperscript{13-18} Previous application of this technology to stabilize the C1-C2 articulation was performed, but the report did not carefully describe the screw trajectory or deviations from the intended screw location.\textsuperscript{19} The current study focuses on the accuracy of screw placement and examines the reason for deviation from ideal screw placement in cadavers after a rapid prototyping drill template C1 and C2 pedicle screw procedure. The goal of the study was to validate the accuracy of drill templates for placement of C1 and C2 pedicle screws and quantitatively analyze deviation of the screw trajectory.

**MATERIALS AND METHODS**

**Specimens**

Thirty-two formalin-fixed cervical cadaver spines (C1-C7), including 20 male and 12 female specimens, were obtained with permission from the department of anatomy at the University of Ningbo. The average age was 47.2 years, ranging from 29 to 57 years. Specimens were imaged with volumetric computed tomography (CT) scanning (Philips Brilliance 64 CT; Philips Medical Systems, Amsterdam, The Netherlands) with 0.625-mm slice thickness to exclude specimens with deformity or traumatic injury. The images were stored in digital imaging and communications in medicine format. Specimens were refrigerated at -20° to preserve soft tissues. On the day before the experiment, the specimens were exposed to room temperature for thawing.

**Construction of Drill Templates**

The volumetric data stored in digital imaging and communications in medicine format were transferred into Mimics Innovation Suite 10.01 software (Materialise, Leuven, Belgium) to build a 3-dimensional model of the cervical spine. There are 4 workable representations of the original specimen using Mimics software, including the axial plane, sagittal plane, coronal plane, and 3-dimensional plane reconstructions. Because of the complicated process required to implement a representation of a threaded screw in the virtual environment of the software, the authors instead used a 3.5-mm-diameter cylinder, which was much easier to fabricate and adjust with the program and still allowed direct observation of the relationship between the cylinder and the pedicle cortical bone in 2-dimensional and 3-dimensional representations.

Both the 3-dimensional cervical model and the cylindrical screw representations were transferred in stereo lithography format into UG (Unigraphics NX) + Imageware 12.0 (Siemens PLM Software, Nuremberg, Germany), a software program that was used to determine the optimal entry point and orientation of pedicle screws. An important feature of this software is that it allows designation of a “danger zone” where screw placement could have dire consequences that can then be viewed in relation to the location of the pedicle in multiple planes to observe and analyze the safety of customized screw trajectories. Using this software, safe screw channels were designed and further analysis of the pedicle anatomy allowed calculation of the maximal safe screw diameter and length.

A rapid prototyping drill template was made of a component designed to complement the vertebral anatomy and a drill orienting tube to be used when drilling screw pilot holes. The inner and outer diameters of the 15-mm-high orienting tube were designed to be 2.7 mm and 5.7 mm, respectively. To design a lock-and-key fit for the complement component to match the vertebral surface, data describing the bony contours were extracted and a complementary surface that was 2.5 mm thick was designed. The cannulated drill orienting tubes and the vertebral complement component were combined into a single surgical instrument using the Boolean operation (Figure 1).

The virtual 3-dimensional models of the drill template were then converted into a physical template produced in acrylate resin (Somos 14120; DSM Desotech, Inc,
Buckinghamshire, United Kingdom) using stereolithography, a rapid prototyping technique (Hen Tong Co, Suzhou, China).

**Insertion Technique**

All simulated operations were performed in the anatomy laboratory. Specimens were maintained in a prone position on the table. The soft tissue overlying the posterior arch of C1 and the spinous process, lamina, and lateral masses of C2 was removed to facilitate a good fit between the template and the posterior vertebral surfaces. A high-speed 2.7-mm drill bit was then used to drill the pedicle screw pilot hole through the cannulated orienting tube to the desired depth based on preoperative planning on both sides. Drill bits were switched after the first side to ensure that bone fragments in the bit did not affect the trajectory. The drill bit from the first side was left in place to fix the template while the second side was drilled. After removal of the drill bits and the template, 3.5-mm-diameter screws of appropriate length were advanced into the bony channel (Figure 2).

**Assessment of Drill Template Accuracy**

After the pedicle was placed into the pilot hole that was made with the customized drill template, postoperative CT scans were obtained to assess the accuracy of placement (Figure 3). The volumetric imaging data stored in digital imaging and communications in medicine format were imported to Mimics 10.01 to create a 3-dimensional reconstruction of the preoperative cervical vertebrae and screw. Both the pre- and postoperative images were transferred in stereo lithography format to Geomagic Studio 9 (Geomagic, Morrisville, North Carolina). Four points on the preoperative specimen were selected and used as calibration points to superimpose the preoperative and postoperative images and facilitate comparison of the intended and actual screw trajectories (Figure 4). Superimposition of the preoperative and postoperative images allowed visualization and comparison of the screw and templating cylinder to measure angles related to ideal vs actual angle and location of screw insertion.

To coordinate the C1 vertebral anatomy between image sets, the origin of the 3 axes in space was assumed to coincide with the anterior tubercle of the atlas. From this starting point, the x axis occupies the coronal plane and is parallel...
to a line connecting the lowest point of the outer edge of the inferior articulating process on each side, whereas the y and z axes pass through the anterior tubercle and lie perpendicular to the x axis (Figures 5a-5c). This axis system was used to measure the discrepancy between the entry point that was designed and the actual C1 screw entry point in the x, y, and z axes (Δx, Δy, Δz) (Figures 5d-5f). To coordinate C2 vertebral anatomy between image sets, the x axis was set as the line connecting the 2 sides of the lowest point of the outer edge of the superior articulating process. The y axis is perpendicular to the x axis and perfectly bisects the vertebrae, whereas the z axis is simply perpendicular to the x and y axes. The positive direction of the axes was selected arbitrarily (Figures 6a-6c). This axis system was used to measure the discrepancy between the entry point that was designed and the actual C1 screw entry point in the x, y, and z axes (Δx, Δy, Δz) (Figures 6d-6f).

**Data Analysis**

Statistical analysis was performed with SPSS version 13.0 software (SPSS, Inc, Chicago, Illinois). A paired t test was used to determine statistical significance, assuming that \( P < .05 \) represented statistical significance.

**RESULTS**

The findings showed that 64 C1 pedicle screws and 64 C2 pedicle screws were safely placed without a single violation of the pedicle cortex. Average transverse angle for ideal and actual screw trajectories for C1 pedicle screws measured 6.66°±0.83° and 6.7°±0.84° on the left and 6.32°±0.97° and 6.24°±1.01° on the right. Average sagittal angle of the ideal and actual C1 pedicle screws measured 7.91°±0.59° and 7.9°±0.59° on the left and 8.14°±0.71° and 8.17°±0.7° on the right (Table 1). Average transverse angle for ideal and actual screw trajectories for C2 pedicle screws measured 11.6°±1.59° and 11.57°±1.51° on the right. Average sagittal angle of the ideal and actual C2 pedicle screws measured 24.52°±1.19° and 24.4°±1.17° on the left and 25.7°±1.74° and 25.61°±1.92° on the right (Table 2) (Figure 7). The average difference between the entry point of the left C1 pedicle screws when ideal and actual trajectories were compared in the x, y, and z axes was 0.11±0.49 mm, 0.01±0.56 mm, and -0.09±0.59 mm, respectively (Table 3). The average difference between the entry point of left C2 pedicle screws when ideal and actual trajectories were compared in the x, y, and z axes was 0.05±0.54 mm, 0.2±0.59 mm, and -0.06±0.58 mm, respectively. The average difference between the entry point of right C2 pedicle screws when ideal and actual trajectories were compared in the x, y, and z axes was 0.17±0.55 mm, 0.1±0.58 mm, 0.11±0.57 mm, respectively.

**Figure 4:** Use of Geomagic Studio 9 software (Geomagic, Morrisville, North Carolina) to compare the spatial position between pre- and postoperative images. Preoperative image for C1 (a), postoperative image for C1 (b), and images based on any 4 points not in the same plane and coincided to compare a and b (c). Preoperative image for C2 (d), postoperative image for C2 (e), and images based on any 4 points not in the same plane and coincided to compare d and e (f).

**Figure 5:** Schematic diagram of the C1 space coordinates in the coronal plane (a), the axial plane (b), and the oblique plane (c). Schematic diagram of the C2 space coordinates in the coronal plane (d), the axial plane (e), and the oblique plane (f).
mm, and -0.01±0.49 mm, respectively (Table 4) (Figure 8). There was no statistically significant difference (P>.05) in the deviation of either entry point location or screw orientation between the ideal and actual trajectories.

**Discussion**

The traditional method for insertion of cervical pedicle screws relies on careful analysis of preoperative imaging and knowledge of anatomic landmarks to avoid errant placement.\(^{20-23}\) Such techniques, however, are challenging during C1 and C2 pedicle screw placement because of variations in individual anatomy and the small margin for error when placing screws into a small bony channel.\(^{24}\) Although many methods have been described that purportedly increase the precision of pedicle screw placement, cortical pedicle perforation still occurs.\(^{25-28}\) To overcome difficulties related to variations in individual anatomy and reduce the rate of complications related to cortical perforations, the authors used rapid prototyping of a customized drill template to ensure the accuracy of atlantoaxial pedicle screw placement.

This study was conducted to quantify the accuracy of a drill template in the placement of C1 and C2 pedicle screws and analyze screw trajectory deviation compared with ideal screw trajectory based on preinstrumentation image analysis. Because safe placement of pedicle screws involves several factors, the authors considered the screw entry point, the screw channel trajectory, the screw diameter, the depth of insertion, and the relationship between the screw outer threads and the cortical confines of the pedicle. The initial selection of C1 pedicle screw entry points was based on the width of the junction of the C1 posterior arch,\(^2\) and the entry points for the C2 pedicle screw were aligned with the vertical line of intersection of the C2 lateral mass.\(^4\) These entry points were eventually modified by adjusting the screw channel direction based on anatomic constraints of the pedicle to ensure a safe screw trajectory, and the screw diameter and length were maximized using the software described earlier.

The template meant to rest against the C1 lamina is limited by the relatively simple bony architecture of the posterior arch of C1, which allows minimal contour against which to build a complementary fit. Although the authors were concerned that this might cause the C1 screws to deviate from the predetermined trajectory, no evidence was found of significant deviation between the position of the screw after placement using the template and the planned trajectory. This is evidence of the accuracy of rapid prototyping drill template technology and its ability to create individualized drill templates that are accurate even in the face of relatively undistinguished bony surfaces. Other associated surgical techniques, such as keeping the drill bit on the 1st side to stabilize the template while drilling the 2nd pilot hole, likely contributed to success at C1.
Because of the relatively high complexity of the posterior element surface anatomy of C2, the C2 drill template was correspondingly multifaceted to optimize contact with the C2 lamina and spinous process. Although the C2 bony surfaces available for inclusion in the drill template allowed stabilization against translation of the drill in 4 different directions (left, right, posterior, and superior), the authors were initially concerned that there was nothing preventing anterior-inferior translation of the vertebrae during drilling on the angled entry point surface. Although no specimen showed perforation of the pedicle cortex, there was still deviation in each direction for C1 and C2 screws. This discrepancy may indicate that slight deformation or movement of the drill template was caused by the force used to drill the pilot hole. In this study, this discrepancy was not enough to compromise the accuracy of screw placement in a clinically meaningful way.

In addition, several other factors may affect the accuracy of rapid prototyping drill template technology, including human error in using the instruments or software described earlier and technical errors during surgery.\textsuperscript{18,19,29,30} Use of CT scans without sufficient thin cuts may lead to an incomplete or inaccurate 3-dimensional representation of the bony surface and a poorly fitting drill template. Alternatively, if the deficiencies of the vertebral representation are realized, there is a risk of operator error in attempting to manually account for missing image data, again leading to an inaccurate and poorly fitting drill template. Furthermore, data loss may occur when images are converted between digital imaging and communication in medicine and stereo lithography formats because stereo lithography configures 3-dimensional reconstructions using polyhedrons formed from many triangular surfaces. This technique for creating a customized drill guide is heavily reliant on production specifications so that all surfaces, including the posterior

<table>
<thead>
<tr>
<th>Measurement</th>
<th>C2LPSTA, Mean±SD (Range)</th>
<th>C2RPSTA, Mean±SD (Range)</th>
<th>C2LPSSA, Mean±SD (Range)</th>
<th>C2RPSSA, Mean±SD (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>11.8°±1.52° (9.11°-15.00°)</td>
<td>11.6°±1.59° (8.14°-11.55°)</td>
<td>24.52°±1.19° (22.65°-24.66°)</td>
<td>25.7°±1.74° (22.11°-26.88°)</td>
</tr>
<tr>
<td>Screw</td>
<td>11.79°±1.30° (10.99°-14.65°)</td>
<td>11.57°±1.51° (8.54°-12.43°)</td>
<td>24.4°±1.17° (21.78°-24.81°)</td>
<td>25.61°±1.92° (20.31°-27.85°)</td>
</tr>
<tr>
<td>( P )</td>
<td>.904</td>
<td>.521</td>
<td>.079</td>
<td>.574</td>
</tr>
</tbody>
</table>

Abbreviations: C2LPSSA, C2 left pedicle screw sagittal angle; C2LPSTA, C2 left pedicle screw transverse angle; C1RPSSA, C2 right pedicle screw sagittal angle; C2RPSTA, C2 right pedicle screw transverse angle.

Figure 7: Graph showing angulation of the ideal trajectory vs actual trajectory of the C1 and C2 pedicle screw. Abbreviations: ps, pedicle screw; SA, sagittal angle; TA, transverse angle.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( \Delta x ) Mean±SD (Range)</th>
<th>( \Delta y ) Mean±SD (Range)</th>
<th>( \Delta z ) Mean±SD (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1LPS, mm</td>
<td>0.16±0.46 (-0.89-0.98)</td>
<td>0.11±0.52 (-0.90-0.88)</td>
<td>-0.01±0.54 (-0.87-0.92)</td>
</tr>
<tr>
<td>C1RPS, mm</td>
<td>0.11±0.49 (-0.75-0.96)</td>
<td>0.01±0.56 (-0.93-0.79)</td>
<td>-0.09±0.59 (-0.91-0.89)</td>
</tr>
<tr>
<td>( P ), left</td>
<td>.055</td>
<td>.243</td>
<td>.953</td>
</tr>
<tr>
<td>( P ), right</td>
<td>.220</td>
<td>.920</td>
<td>.389</td>
</tr>
</tbody>
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Abbreviations: C1LPS, C1 left pedicle screw; C1RPS, C1 right pedicle screw.
element complement and the drill guide itself, are precisely manufactured. Finally, soft tissue on the surface of the posterior elements must be completely removed without damaging the underlying cortical surface to optimize drill guide fit. Many of these factors are under the control of the surgeon and must be carefully attended to throughout all stages of drill design and use.

The theoretical availability of this technique centers on overcoming 3 obstacles. First, the critical technical consideration is that soft tissue on the surface of the posterior elements must be completely removed without damaging the underlying cortical surface to optimize drill guide fit, and the template must be held in place very carefully by the surgical assistant to achieve an ideal screw channel. Second, the time and cost of production must be considered as well as whether the template can withstand high-temperature sterilization protocols. Fortunately, fabrication of these drill guides is timely because the process from image transfer to final template production requires only 2 or 3 days. In addition to being quick, the process is inexpensive because each template costs $30 to design and produce. Finally, acrylate resin, the material used in fabrication of the template, has been shown experimentally to maintain its high strength and refractory and water-repellent properties after high-temperature sterilization. Maintenance of these properties suggests that this material can be used clinically to create drill guide templates without concerns about poststerilization deformation or degradation.

**CONCLUSION**

Both human factors and inherent errors in software and machined instrumentation may contribute to deviation of C1 and C2 pedicle screw placement assisted by a rapid prototyping drill template. Despite the multiple potential sources of error, little difference was found between intended and actual screw position and trajectory. The ease of use and the potential for individualized instrumentation are the principal advantages of this technique; improvements in the precision of screw placement and reduction of clinically significant pedicle breeches are possible if this technology becomes widely used in clinical practice, particularly by surgeons with less experience placing freehand C1 and C2 pedicle screws.

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