A radiographic computed tomography–based study to determine the ideal entry point, trajectory, and length for safe fixation using C-2 pars interarticularis screws

Clinical article

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Object. Effective methods for fixation of the axis include C1–2 transarticular and C-2 pedicle screw placement. Both techniques pose a risk of vertebral artery (VA) injury in patients with narrow pedicles or an enlarged, high-riding VA. Pars screws at C-2 avoid the pedicle, but can cause VA injury with excessively long screws. Therefore, the authors evaluated various entry points and trajectories to determine ideal pars screw lengths that avoid breaching the transverse foramen.

Methods. Both pars were studied on 50 CT scans (100 total). Various pars lengths were assessed using 2 entry points and 3 trajectories (6 measurements). Entry point A was the superior one-fourth of the lateral mass. Entry point B was 3-mm rostral to the inferior aspect of the lateral mass. Using entry points A and B, Trajectory 1 was the minimum distance to the transverse foramen; Trajectory 2 was the maximum distance to the transverse foramen; and Trajectory 3 was the steepest angle to the pars/C-2 superior facet junction without transverse foramen breach.

Results. The mean patient age was 46 ± 17 years, and 84% of the CT scans reviewed were obtained in men. There was no significant difference in right or left measurements. Entry point B demonstrated greater pars lengths for each trajectory compared with entry point A (p < 0.0001). For both entry points, Trajectory 3 provided the greatest pars length. Using Trajectory 3 with entry point B, 84, 95, and 99% had a pars length that measured ≥18, 16, and 14 mm, respectively. Using Trajectory 3 with Entry point A, only 41, 64, and 87% had a pars length that measured ≥18, 16, and 14 mm, respectively.

Conclusions. Using an entry point 3-mm rostral to the inferior edge of the lateral mass and a trajectory directed toward the superior facet/pars junction, 99% of partes interarticularis in this study would tolerate a 14-mm screw without breach of the transverse foramen. (DOI: 10.3171/2009.12.SPINE09543)

Key Words • axis • C-2 • pars interarticularis • instrumentation • vertebral artery • transverse foramen

Recently, various techniques for screw fixation of C-1 and C-2 have developed to stabilize the atlantoaxial complex. Previous methods included posterior wiring to immobilize C1–2, but suboptimal arthrodesis rates, the need for postoperative halo immobilization, and incompatibility with cases requiring decompressive laminectomy led to the subsequent introduction of C1–2 transarticular screw fixation by Magerl and Seeman. Transarticular screws gained widespread popularity for their superior biomechanical immobilization of C1–2, especially when used in combination with posterior wiring. As a result, improved fusion rates were observed even without the use of adjunctive halo immobilization.

However, transarticular screw fixation is technically demanding with a potential risk for VA injury, particularly as the artery courses through the transverse foramen of C-2. The risk of VA injury is reported to range from 0 to 8.2%, with a higher susceptibility in patients with a large tortuous high-riding VA, enlarged transverse foramen, or hypoplastic C-2 pars interarticularis. It is estimated that as many as 23% of patients are unable to undergo C1–2 transarticular screw placement due to these aforementioned anatomical variations.

Abbreviation used in this paper: VA = vertebral artery.
Anatomical study of the C-2 pars interarticularis

As a result, Goel et al. developed a technique for direct C-1 screw fixation, a method popularized by a report from Harms and Melcher, who used a cantilever beam construct consisting of C-1 lateral mass screws and C-2 pedicle screws with connecting rods. With this technique, the C-2 pedicle screw enters the C-2 lateral mass posteriorly, traverses the pars interarticularis into the pedicle, and exits the ventral cortex of the C-2 vertebral body. One of the reported advantages of this method compared with transarticular screws is a potential decreased risk of VA injury.

Anatomical studies, however, suggest that the risk of VA injury from C-2 pedicle screw placement is equivalent to that with transarticular screws. Both techniques rely on screw cannulation of the pars interarticularis into the C-2 pedicle, thereby passing medial to the transverse foramen and VA. Therefore, reasonably, patients with a hypoplastic pedicle will equally not tolerate a C-2 pedicle screw or C1–2 transarticular screw. Alternatively, C-2 pars interarticularis screw placement has been described in which the screw similarly enters the C-2 lateral mass into the pars interarticularis. Unlike the pedicle screw, however, the pars screw stops short of the pedicle and the transverse foramen, thereby minimizing the risk of VA injury (Fig. 1 left).

Vertebral artery injury from a C-2 pars interarticularis screw is theoretically possible with an excessively long screw (Fig. 1 right), but assessment of this risk has not been well established. More specifically, there are no definite reports identifying appropriate pars screw lengths that maximize bone fixation while minimizing risk of overpenetration and breach of the transverse foramen. This likely stems from frequent imprecise terminology in C-2 anatomical studies and common grouping of C-2 pedicle and pars screws in clinical studies. Often, the literature is inconsistent in reporting C-2 pedicle versus pars screws and occasionally uses these terms interchangeably, although the risk of VA injury with these techniques is seemingly distinctly different.

Therefore, in this study, we attempted to better define the clinically relevant anatomy of the C-2 pars interarticularis as it relates to the transverse foramen, and to characterize the risk of VA injury from C-2 pars screw placement. Specifically, we evaluated the dimensions of the pars with respect to various potential screw entry points and trajectories. In doing so, our objective was to determine the length of the pars for safe screw fixation without violating the transverse foramen.

Methods

Study Population

We retrospectively reviewed CT scans of the cervical spine performed in March 2009 at a Level 1 trauma center (Los Angeles County General Hospital, Los Angeles, California). Multislice 3D helical CT acquisition was obtained at near-isotropic parameters (0.5-mm detector size). Multiplanar reformats were constructed from this dataset at 2-mm thickness with a spatial resolution of 0.5 mm in all planes. A random selection of 50 consecutive CT scans was reviewed, eliminating any imaging in patients < 18 years of age, or that demonstrated pathology or anatomical abnormalities involving the axis or atlas. All 50 CT scans with axial, sagittal, and coronal reconstructions were evaluated by a single observer (D.J.H.) at a computer workstation using digital radiology imaging software (Synapse PACS/RIS, Fujifilm Medical Systems). All measurements were performed on both the right and left sides. Demographic information was collected, including patient age and sex.

Pars Interarticularis Measurements

The length of the pars for screw placement was assessed on sagittal CT imaging. The sagittal slice that bisected the pars interarticularis longitudinally was selected for measurements. The length of the pars was measured from a defined entry point in the C-2 lateral mass to the dorsal-most aspect of the transverse foramen, which was delineated by correlating axial, sagittal, and coronal images through the area. Two entry points were

![Fig. 1. Axial CT scans demonstrating screws placed in the C-2 pars interarticularis stopping short of the transverse foramen and pedicle (left), and the path of an overpenetrated C-2 pars screw (arrow) that breaches the transverse foramen (right).]
used based on previously described techniques for C-2 screw fixation.\textsuperscript{7,12,17,26,28} Entry point A was an entry point at the superior one-fourth of the C-2 lateral mass (Fig. 2A and B).\textsuperscript{17} Alternatively, Entry point B was an entry point 3-mm rostral from the inferior edge of the C-2 lateral mass (Fig. 3A and B).\textsuperscript{12} The length of the pars was then measured from either entry point to the dorsal-most aspect of the transverse foramen along 1 of 3 different trajectories. Trajectory 1 was the shortest distance from the entry point to the dorsal-most aspect of the transverse foramen (Figs. 2C and 3C). Trajectory 2 was the longest distance from the entry point to the dorsal-most aspect of the transverse foramen. Trajectory 3 was the steepest trajectory from the entry point to the junction of the pars interarticularis and the C-2 superior facet. The angle created by the trajectory and a vertical line tangential to the anterior border of the C-1 lateral mass was also measured in degrees (Fig. 4).

Additional measurements included evaluating the width of the pars interarticularis and the diameter and height of the transverse foramen. The width of the pars was defined as the largest width assessed on the axial slice that bisected the pars longitudinally (Fig. 5A). The diameter of the transverse foramen was defined as the largest width of the transverse foramen on axial imaging (Fig. 5B). The transverse foramen height was characterized as the largest cranial-caudal measurement of the transverse foramen on the coronal slice that bisected the transverse foramen (Fig. 5C).

Statistical Analysis

Data were reported as average length in millimeters or angle in degrees ± SD. Comparisons between different measurements were conducted using the Student t-test.
Anatomical study of the C-2 pars interarticularis

Results

Both the right and left pars interarticularis and transverse foramina were evaluated on 50 CT scans (for a total of 100 partes interarticularis and transverse foramina measured). The mean age of the patients was 46 ± 17 years (range 19–88 years), and 84% of the CT scans were obtained in men. Average measurements for right, left, and bilateral transverse foramina and partes interarticularis are shown in Table 1. Measurements are also reported for male and female patients separately (Table 1). There was no statistical difference in any measurement between the right and left sides. There was no statistical difference in any measurements between male and female sex, except for the pars length using Entry point B and Trajectory 3 (Fig. 6).

Significantly longer pars lengths for screw placement were observed with Entry point B compared with Entry point A for all 3 trajectories (p < 0.0001; Fig. 7). Significantly longer pars lengths for screw placement were also observed for Trajectory 3 compared with Trajectories 1 and 2, except when comparing Trajectory 2 and 3 for Entry point A (Fig. 8).

Using Trajectory 3 with Entry point B, 99% of partes interarticularis that were evaluated were at least 14 mm in length (Fig. 9). Using the same trajectory and entry point, the pars length was ≥ 16 mm and ≥ 18 mm in 95% and 84%, respectively. Alternatively, using Trajectory 3 with Entry point A, only 87% of pars that were evaluated were at least 14 mm in length. Likewise, using the same trajectory and entry point, the pars length was ≥ 16 mm and ≥ 18 mm in only 64% and 41%, respectively.

Discussion

Magerl and Seeman introduced C1–2 transarticular screws in the 1970s and these screws have since gained wide popularity for stabilization of the atlantoaxial complex. Transarticular screws are inserted just above the caudal edge of the C-2 lateral mass, traverse the pars interarticularis and the C-2 pedicle, cross the C1–2 joint, and enter the C-1 lateral mass. Vertebral artery injury from transarticular screws is possible with either misdirected screws or placement in patients with a hypoplastic pedicle, enlarged transverse foramen, or a large tortuous or high-riding VA. The reported risk of VA injury in clinical series is between 0 and 8%. A survey of the members of the AANS/CNS Joint Section on Disorders of the Spine and Peripheral Nerves documented the risk of VA injury for transarticular screws to be 2.2% per screw placed. Harms and Melcher subsequently introduced an alternative method for posterior C1–2 fixation using C-1 lateral mass and C-2 pedicle screws with connecting rods. In this technique, the C-2 pedicle screw is inserted in the upper quadrant of the C-2 lateral mass, as opposed to the inferior aspect of the lateral mass with transarticular screws. The C-2 pedicle screw, however, similarly traverses the pars interarticularis, but then enters the C-2 pedicle and exits the ventral cortex of the C-2 vertebral body, without crossing the C1–2 joint or entering C-1.

The technique of placing C-1 lateral mass and C-2 pedicle screws was designed to overcome certain technical and anatomical limitations associated with transarticular screws. Among these limitations are nonreducible atlantoaxial dislocations and an exaggerated thoracic kyphosis. Some argue that C-2 pedicle screw placement also presents a lower risk of VA injury than transarticular screws. However, C-2 pedicle screws, similar to transarticular screws, must still cross the C-2 pars interarticularis and be navigated medial to the transverse foramen to enter the C-2 pedicle. In patients with a hypoplastic pedicle (< 4 mm), neither a C-2 pedicle screw nor a transarticular screw is possible, as both would violate the transverse foramen. Consequently, anatomical studies have demonstrated that the risk of VA injury from C-2 pedicle screws is equivalent to that of transarticular screws.

Alternatively, C-2 pars screws are also placed in the C-2 lateral mass and cannulate the pars interarticularis, but stop short of the pedicle and the transverse foramen. Therefore, the risk of VA injury with C-2 pars screws appears to be less than with either transarticular or C-2 pedicle screws. The potential for VA injury would only occur with an excessively long C-2 pars screw that overpenetrates the transverse foramen.

Yet prior studies do not clearly characterize the normal length of the pars interarticularis or the risk of VA injury from an overpenetrated C-2 pars screw. Pars widths
have been previously well documented with respect to placement of transarticular and C-2 pedicle screws, with average pars widths ranging from 7.2 to 8.2 mm.\textsuperscript{4,27} For pars screw placement, however, the length of the pars interarticularis from a clinically defined entry point to the transverse foramen is the critical dimension, as an excessively long screw is at risk for violating the VA. Unfortunately, 2D intraoperative lateral fluoroscopy poorly images the transverse foramen at C-2, and therefore does not facilitate determining appropriate screw lengths.\textsuperscript{9,24,25,40}

The absence of literature specifically characterizing C-2 pars lengths for screw placement likely comes from a persistent ambiguity in terminology for the C-2 pars interarticularis and pedicle. Many studies measure lengths of the C-2 pedicle and pars as 1 structure, often referring to the combined pedicle and pars as the C-2 pedicle, without isolating the pars for measurement. Abou Madawi et al.\textsuperscript{1} evaluated 50 cadaveric specimens and performed measurements of multiple parameters involving C-2. It is unclear from the report what structure was identified as the pedicle or pars interarticularis. However, these authors reported an average pedicle length of 28.7 mm, which likely encompasses both the pedicle and the pars. Xu et al.\textsuperscript{40} refer to a poorly defined pedicle axis, which is a line projecting through the pedicle and pars interarticularis, and subsequently measured the length of the bony limits of this axis as the pedicle length. Xu et al. observed a pedicle length of 25.6 mm in males and 25.5 mm in females, similar to the results of Abou Madawi et al. Naderi et al.\textsuperscript{31} identified the pedicle and pars as separate structures, but continue to measure the lengths as a single pedicle-isthmic complex at 28.8 mm.

This previous imprecise use of anatomical terminology regarding C-2 has been more recently acknowledged,\textsuperscript{3,8} with most studies now distinguishing the pedicle and pars interarticularis as distinct bony structures. The pedicle is defined as the portion of C-2 that connects the vertebral body to the superior facet and dorsal elements, and as a result is generally a relatively short structure that is grooved anterolaterally by the transverse foramen.\textsuperscript{8} The pars interarticularis is the bony structure that interconnects the superior and inferior articulating process of C-2 (Fig. 10). The inexact reporting of C-2 pedicle and pars dimensions in anatomical studies, however, makes it difficult to draw any reasonable conclusions as to the relevant C-2 pars length for pars screw instrumentation.

Paralleling the anatomical literature, many clinical, biomechanical, and review articles tend to group togeth-
Anatomical study of the C-2 pars interarticularis

<table>
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* All data given as means ± SDs.

Fig. 6. Bar graph presenting the average pars length (mm) by sex for Entry points A and B with Trajectories 1, 2, and 3. *p < 0.05.
placement of a pars screw, we selected 2 different entry points and 3 trajectories for each of these entry points. The two entry points were based on previously described techniques for either transarticular screw or C-2 pedicle screw placement, because both involve screw placement through the C-2 lateral mass to cannulate the pars interarticularis. However, unlike with transarticular or C-2 pedicle screws, we measured the length of the pars stopping short of the transverse foramen, and did not continue the trajectory into the pedicle or across the C1–2 joint. Also, we assessed 3 different trajectories to identify potential pars lengths that were the shortest and longest distances to the transverse foramen, and a third trajectory that was the steepest allowable angle that avoided the transverse foramen. In doing so, our objective was to better define the clinically relevant length of the pars for screw fixation, as well as to determine the ideal entry point and trajectory to provide the greatest screw length without violating the transverse foramen. For clarification, it should be noted that the measurement of the “pars length” in this study includes a small portion of the lateral mass where the screw entry point involves the lateral mass. Therefore, this represents a clinically relevant measurement because it pertains to lengths for C-2 pars screw placement, rather than a true anatomical characterization of the pars interarticularis.

In our study, we observed that Entry point B, which starts 3-mm rostral to the inferior edge of the C-2 lateral mass, results in significantly greater pars lengths for all trajectories compared with Entry point A. Entry point B represents an entry point that has been previously described for transarticular screw insertion and generally results in a much steeper angle across the pars than Entry point A, which is a standard C-2 pedicle starting point. Therefore, it appears that using an entry point near the caudal edge of the C-2 lateral mass, similar to placing a transarticular screw, allows for a greater screw length without violating the transverse foramen.

We then studied specifically the distribution of pars lengths when using both entry points with the steepest trajectory (Trajectory 3). Interestingly, when evaluating Entry point B with Trajectory 3, in only 84% of cases would the pars tolerate an 18-mm screw, whereas in 16% the measured pars length was < 18 mm. Ninety-nine percent of pars that were measured in this study, however, had a length that was at least 14 mm when using Entry point B and Trajectory 3. Therefore, these findings suggest that 99% of pars can tolerate a screw of 14 mm or less when using this entry point and trajectory. By comparison, using Entry point A with the same trajectory, only 87% of pars measured at least 14 mm, whereas 13% of pars were < 14 mm. Of note, 14-mm screws are a commonly used length for subaxial lateral mass screws. Therefore, presumably a 14-mm screw in the pars interarticularis would provide similar fixation compared with the subaxial lateral mass, although biomechanical comparison of pullout strength for pars and lateral mass screws is necessary to verify this conclusion. Alternatively, a longer screw of 16 mm would be tolerated by 95% of pars that were measured when using Entry point B and Trajectory 3, compared with only 64% with Entry point A.

Interestingly, while we frequently found asymmetry among several measurements, the combined measurements were not statistically significant when comparing right and left sides. This observation appears to contradict several prior anatomical studies that have noted differences in right- and left-side morphology; however, this disparity is likely attributable to different aspects of the C-2 pars and pedicle undergoing evaluation, compared with the present study (Fig. 10B and C). Vertebral artery asymmetry is common, with a dominant left VA in 35.8%, compared with a dominant right VA in 23.4%. Of particular relevance to C-2 bone anatomy, the VA takes a serpentine course through the axis, and in ectatic cases, loops more medially within C-2, effectively “eroding” or “thinning” out the portion of C-2 medial to the transverse foramen (Fig. 11). Because transarticular and C-2 pedicle screws must traverse this area, many anatomical studies have examined this aspect of the C-2 pedicle, and have noted apparent right- and left-side dif-
References.\textsuperscript{1,9,27,32} Mandel et al.\textsuperscript{27} specifically evaluated this bony structure in 205 cadaveric specimens, and found that the right-side height and width were smaller by 0.3 and 0.6 mm, respectively, compared with the left. However, C-2 pars screws do not extend into the pedicle, which is the basis by which pars screws have a decreased risk of VA violation than transarticular or pedicle screws (Fig. 1). As such, in our study we did not evaluate this portion of C-2 because it is not relevant to C-2 pars screw placement, and therefore likely reflects the relative symmetry observed in this investigation.

This study has several limitations. Male patients were disproportionately represented in the CT scans that were reviewed. This sex difference is likely due to our random selection of consecutive scans performed at a Level 1 trauma center, and therefore demonstrates the common
male predominance noted among trauma patients at this institution and elsewhere.\textsuperscript{10,22,23,33,35,38} When measurements were compared by sex, however, there was no statistically significant difference observed for nearly all of the measurements (Fig. 6). Also, the statistical analysis compiled right and left sides for all measurements (50 CT scans, 100 total sides measured), which may have artificially inflated the statistical significance by doubling the number of measurements. However, a separate statistical analysis of only right-sided measurements (50 CT scans) achieved statistical significance for all of the same measurements ($p < 0.05$) as the compiled right and left data.

Using the digital radiology workstation, longitudinal measurements were made on single sagittal images. This technique assumes that screws are inserted with 0° of medial angulation in the axial plane. Clinically, however, pars screws are often inserted with 10 to 15° of medial angulation.\textsuperscript{30} Using trigonometric calculations, a 15° medialized trajectory through the pars increases the measured pars length by approximately 3.5%, compared with a screw with 0° of medialization. Therefore, while 10 to 15° of medialization may provide a longer screw length, for these measurements, the increase in pars length was <1 mm for all CT scans evaluated.

A potential criticism of this study is that measurements were performed using CT data rather than directly on cadaveric specimens. The main benefit of CT imaging is the capability for multiple measurements per patient (6 different screw lengths and trajectories per side), whereas creating the same number of screw paths directly on either fresh or dry specimens would likely not be feasible. Therefore, different entry points and trajectories were compared using the same patients with CT imaging, rather than between different subjects.

Also, use of the computer workstation allowed for

\textbf{Fig. 10.} Drawings (A and D) and CT scans (B, C, and E) of C-2. Drawings demonstrate the axis (C-2) from superior (A) and lateral (D) views with the pars interarticularis demarcated by the shaded region. Computed tomography scans of the axis in axial (B and C) and sagittal (E) planes. In panels B and E, the pars interarticularis is demarcated by the shaded region. In panel C, the C-2 pedicles are shaded.

\textbf{Fig. 11.} Axial CT image demonstrating asymmetry of the left and right transverse foramina. In this individual case, the VA on the left loops more medially than the right. This effectively "thins out" the left pedicle, resulting in asymmetrical pedicle dimensions (\textit{bold line}), while the pars appears relatively symmetric (\textit{dotted lines}).
consistent, precise placement of specifically defined entry points using the computer workstation line measurement tool function. By constructing multiplanar CT images and cross-referencing axial, sagittal, and coronal images, we were also better able to define screw end points based on the internal circumferential boundaries of the transverse foramen within the axis. Alternatively, defining the same exact screw end points on cadaveric specimens would likely require sectioning of the specimen, which could potentially degrade the consistency and exactness of manually acquired measurements.

Another limitation of using cadaveric specimens is the possibility of overrepresentation of elderly patients, which may introduce morphological changes secondary to age-related processes such as arthritis, degeneration, or bone mineral density loss. Alternatively, using CT data provided us with a broad range of adult ages (mean 46 ± 17 years, range 19–88 years).

Lastly, this study is limited because it only examined the clinical anatomy of the atlantoaxial complex. Where-as it appears that using Entry point B with a trajectory directed toward the posterior aspect of the C-2 superior facet provides the longest pars dimension for screw insertion, this trajectory may not be possible in all patients. This entry site and trajectory are referenced from a standard transarticular screw entry point at the inferior aspect of the C-2 lateral mass. To achieve such a steep trajectory with this entry point, a much larger incision or a more caudal separate stab incision is frequently necessary to gain the appropriate angulation with the drill or screw driver, as is commonly performed with transarticular screws. This trajectory also may not be possible in patients with an exaggerated thoracic kyphosis. As such, these anatomical constraints of using this entry point and steep trajectory must be weighed against the relative benefit of using a longer screw for C-2 pars fixation.

Conclusions

Various techniques are available for screw fixation of C-2. Transarticular and C-2 pedicle screws demonstrate a potential risk for violation of the transverse foramen and VA injury. Pars screws are an alternative method for fixation of C-2 with less risk of VA injury. Anatomical evaluation using CT suggests that 99% of paretic interarticularis are at least 14 mm in length when using a conventional transarticular screw entry point, 3-mm rostral to the inferior edge of the lateral mass with a trajectory directed toward the superior facet-pars junction. If a standard C-2 pedicle screw entry point in the upper one-fourth of the C-2 lateral mass is used for C-2 pars screw insertion, one should note that as many as 13% of pars may have a length < 14 mm to the transverse foramen. Ultimately, given the vital neurovascular structures inherent to this region, careful preoperative evaluation of patient imaging and surgeon preparation is necessary to determine the appropriate screw insertion technique and implant length. Adjunctive measures such as intraoperative 3D navigation or alternative techniques such as intralaminar screws may be necessary for patients with particularly difficult or aberrant C-2 and VA anatomy.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: DJ Hoh, CY Liu, MY Wang. Acquisition of data: DJ Hoh. Analysis and interpretation of data: DJ Hoh. Drafting the article: DJ Hoh. Critically revising the article: DJ Hoh. Revised final version of the manuscript and approved it for submission: DJ Hoh, CY Liu, MY Wang. Statistical analysis: DJ Hoh.

References


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