

Effect of frameless stereotaxy on the accuracy of C1–2 transarticular screw placement

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Object. In recent studies some authors have indicated that 20% of patients have at least one ectatic vertebral artery (VA) that, based on previous criteria in which preoperative computerized tomography (CT) and standard intraoperative fluoroscopic techniques were used, may prevent the safe placement of C1–2 transarticular screws. The authors conducted this study to determine whether frameless stereotaxy would improve the accuracy of C1–2 transarticular screw placement in healthy patients, particularly those whom previous criteria would have excluded.

Methods. The authors assessed the accuracy of frameless stereotaxy for C1–2 transarticular screw placement in 17 cadaveric cervical spines. Preoperatively obtained CT scans of the C-2 vertebra were registered on a stereotactic workstation. The dimensions of the C-2 pars articularis were measured on the workstation, and a 3.5-mm screw was stereotactically placed if the height and width of the pars interarticularis was greater than 4 mm. The specimens were evaluated with postoperative CT scanning and visual inspection. Screw placement was considered acceptable if the screw was contained within the C-2 pars interarticularis, traversed the C1–2 joint, and the screw tip was shown to be within the anterior cortex of the C-1 lateral mass.

Transarticular screws were accurately placed in 16 cadaveric specimens, and only one specimen (5.9%) was excluded because of anomalous VA anatomy. In contrast, a total of four specimens (23.5%) showed significant narrowing of the C-2 pars interarticularis due to vascular anatomy that would have precluded atlantoaxial transarticular screw placement had previous nonimage-guided criteria been used.

Conclusions. Frameless stereotaxy provides precise image guidance that improves the safety of C1–2 transarticular screw placement and potentially allows this procedure to be performed in patients previously excluded because of the inaccuracy of nonimage-guided techniques.

KEY WORDS • screw fixation • frameless stereotaxy • cervical spine

ATLANTOAXIAL transarticular screw fixation was introduced in 1987 by Magerl and Seemann¹² as biomechanically superior to other techniques for atlantoaxial fusion. The procedure is technically demanding; significant anatomical variations and the inability to obtain intraoperative visualization place the VA at risk for injury. The authors of clinical reports on C1–2 transarticular screw fixation have indicated that screw misplacement occurs in up to 15% of patients, with a 4.1% rate of VA injury.^{8,11} The authors of recent anatomical studies have indicated that 20% of patients have at least one ectatic VA that may prevent safe transarticular screw placement when using standard fluoroscopic techniques.^{11,14,18}

Abbreviations used in this paper: CT = computerized tomography; LED = light-emitting diode; VA = vertebral artery; 3D = three dimensional.

Frameless stereotactic image guidance, adapted from intracranial neuronavigation, has recently been applied to procedures involving spinal fixation.⁵ This technology has the potential to improve the safety of C1–2 transarticular screw placement and to reduce the number of patients previously excluded based on unfavorable anatomy. Image guidance provides full visualization of the trajectory through the C-2 pars interarticularis in real time, allowing the surgeon to avoid the VA safely. This *in vitro* study was conducted to determine whether frameless stereotaxy would improve the accuracy of C1–2 transarticular screw placement in healthy patients as well as in those with anatomy deemed unsuitable by previous criteria for such a procedure.

Materials and Methods

Seventeen cadaveric specimens underwent preoperative spiral

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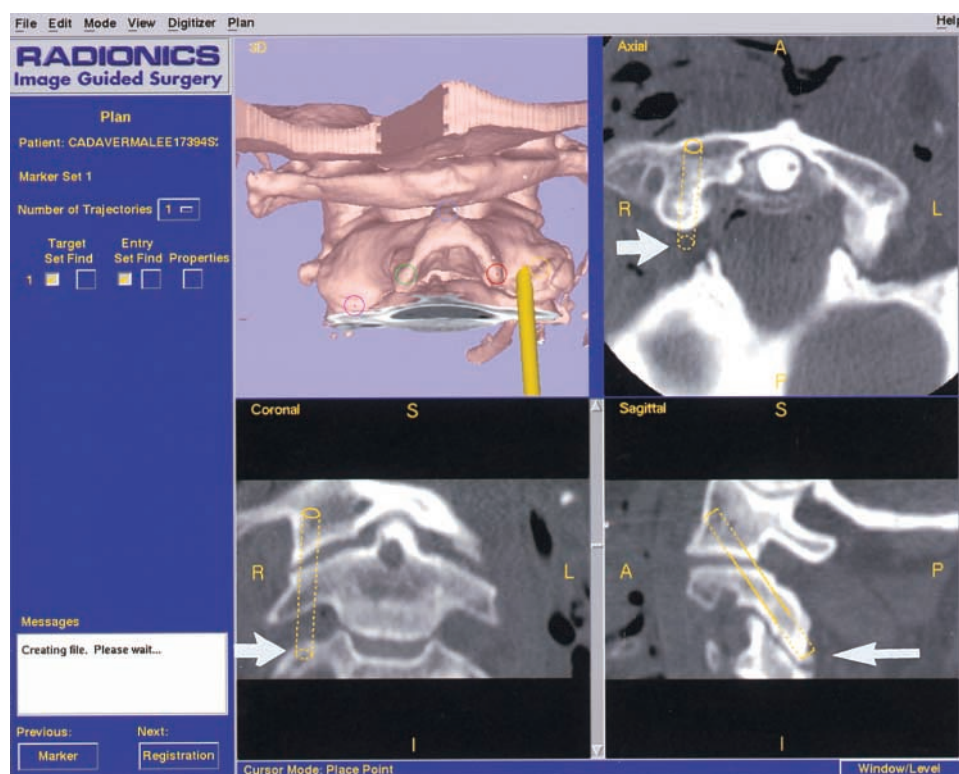


FIG. 1. Stereotactic images and 3D reconstruction (*upper left*) generated when the standard probe is placed at the entry point. The markers on the 3D reconstruction represent the five selected registration points. The stereotactic images (*upper right, lower left and right*) demonstrate the probe trajectories (*arrows*) and confirm this to be an appropriate entry point for placing a pilot hole.

CT scanning (General Electric, Milwaukee, WI). The data were obtained in 1-mm slices and transferred on digital audio tape to a workstation (Optical Tracking System Workstation; Radionics, Inc., Burlington, MA). The tracking system generated standard two-dimensional orthogonal (axial, sagittal, and coronal) scans as well as a 3D reconstruction. The dimensions of the C-2 pars interarticularis were evaluated on the workstation. A preplanned trajectory through the pars was virtually determined on the workstation, and 3.5-mm screw placement was considered feasible if the height and width of the pars articularis was greater than 4 mm along the path perpendicular to the trajectory of the screw. These criteria differ from nonimage-guided standard fluoroscopic techniques that exclude patients in whom the pars widths and/or heights are less than 5 mm¹³ or when the internal height of the C-2 lateral mass (measured from the roof of the VA groove to the endpoint of the superior facet) is less than 2 mm.¹¹

The cadaveric specimens were prepared using a standard posterior surgical exposure of the C1–2 complex. The spinal stereotactic dynamic reference frame was attached to the C-2 spinous process, and the C-2 vertebra was registered using standard point-to-point matching in which five anatomical points were used to correlate the position of the patient in the operative space with the previously obtained CT data pictured on the optical tracking system workstation. Mean registration errors of less than 1.5 mm were considered acceptable. Proper registration was verified by touching the probe to anatomical landmarks on the specimen and comparing the actual probe position with the apparent probe position on the workstation monitor (Fig. 1).

The surgical procedure was performed with real-time image-guided tracking of the drill position; to track the position of the drill, a universal instrument registration technique was used in which an instrument with a defined tip can be fitted with an LED array and calibrated for image-guided applications.¹⁰ A pneumatic surgical drill was fitted with an array of LEDs and calibrated to the frameless

stereotactic system for the surgical procedure. The drill bit tip was positioned at the standard entry point at the base of the C-2 facet and then adjusted to attain a final trajectory, as displayed on the workstation monitor, which provided safe passage of the screw through the C1–2 complex. A pilot hole was then made under real-time image guidance to maintain the trajectory, with special care taken to avoid injuring the VA (Fig. 2). The pilot hole was tapped, and a 3.5-mm screw was placed along the same trajectory. Fluoroscopic guidance was not used at any point in these procedures.

The accuracy of the screw placement was evaluated using post-operative CT scanning and physical inspection of the specimens. The intact C1–2 vertebral complex was removed from each specimen. The soft tissues were removed, and the spinal canal and VA foramen were examined under a surgical microscope for evidence of screw violation. Screw placement was considered accurate if the screw was contained within the C-2 pars interarticularis without perforation and if it traversed the C1–2 joint and its tip was in the anterior cortex of the C-1 lateral mass.

Results

Anatomically 16 of 17 specimens could safely accommodate bilateral C1–2 transarticular screw placement according to the criteria used in this study. The one specimen (5.9%) unsuitable for the procedure had bilateral VA groove erosion into the C-2 pars interarticularis, which decreased the height of the bony passage perpendicular to the trajectory of the screw to less than 4 mm. The average dimensions of the C-2 pars examined for C1–2 screw placement in this study are listed in Table 1.

Four specimens (23.5%) had critical VA groove erosion that, based on previously accepted criteria defined by

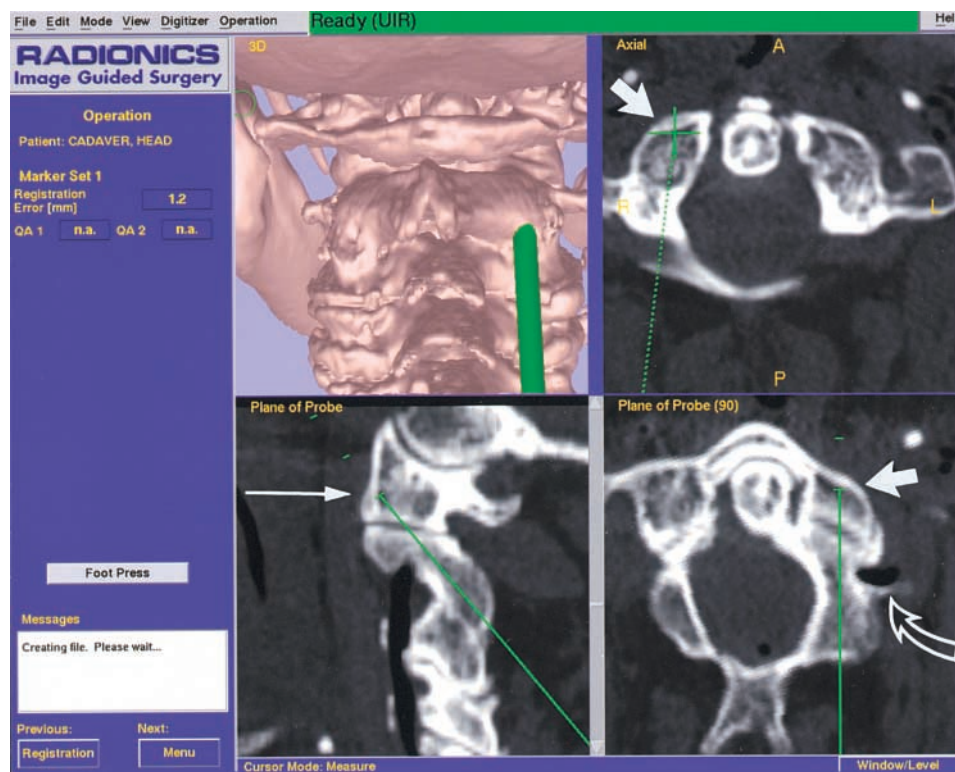


FIG. 2. The drill bit has now been stereotactically calibrated, and the endpoint of the solid line represents the tip of the drill bit (solid arrows). The surgical drill appears to have been successfully navigated. The “plane of probe (90°)” view demonstrates the medial angulation of the drill bit as it avoids the VA (open arrow).

standard, nonstereotactic, fluoroscopic techniques, precluded safe C1–2 screw placement. Included in this group is the one aforementioned specimen in which stereotactic screw placement was not attempted because of anomalous VA anatomy. Based on the stereotactic criteria as defined in this study, the remaining three specimens were deemed suitable for the procedure, and C1–2 screws were safely placed under frameless stereotactic guidance in each specimen (Fig. 3).

The C1–2 transarticular screws were placed in a total of 16 cadaveric specimens. In two specimens unilateral screw placement was performed due to technical difficulties: in one case the C-1 subluxation could not be reduced and in the other case screw fracture occurred that prevented advancement or removal of the screw after partial insertion. Both of these specimens otherwise had a C-2 pars interarticularis that would have allowed safe screw placement. All 30 screws placed in the specimens were judged on CT scans and by visual inspection to be well positioned, with no perforations or VA injuries (Fig. 3).

Based on previous criteria (height and width of the pars interarticularis > 4 mm), 23.5% of the specimens in this study would have been excluded from C1–2 screw placement on at least one side due to an ectatic VA. Using stereotactic guidance and our criteria (C-2 lateral mass height < 2 mm), there was only a 5.9% technical exclusion rate due to unsuitable vascular anatomy.

Discussion

Since the introduction of C1–2 transarticular screws in

1987, many surgeons have adopted the procedure as their preferred method of achieving atlantoaxial stabilization.^{3,16} In clinical and cadaveric studies the authors have shown that C1–2 transarticular screw fixation provides significantly greater biomechanical stability in axial rotation than conventional posterior fusion, as well as equivalent stability in lateral bending, flexion, and extension.⁷ Transarticular screws provide immediate three-column fixation and stability that obviates the need for postoperative halo vest placement for most patients. Fusion rates for C1–2 transarticular screw fixation range from 95 to 100%, which is significantly better than the 70 to 90% rate attributed to conventional posterior atlantoaxial fusion.³

Despite the known advantages, C1–2 transarticular screw fixation is technically demanding and has potentially significant risks. Grob, et al.,⁸ reported a series of 161 patients in whom C1–2 transarticular screw fixation was performed, and they found a malposition rate of 15%. Madawi, et al.,¹¹ placed C1–2 screws in 61 patients and reported a malposition rate of 14%. The risks associated with inaccurately placed screws include injury to the VA, spinal cord, or cranial nerves.^{4,11,18} The anatomy of the atlantoaxial complex varies among patients, and these anatomical variations can increase the difficulty of the procedure as well as the risk of complications.

Anatomical Exclusion Criteria in Standard C1–2 Transarticular Screw Placement

Although the exact technique of C1–2 transarticular screw placement varies slightly among surgeons, nearly

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TABLE 1

Anatomical parameters obtained in 17 cadaveric C-2 vertebrae

Parameter	Pars Width (mm)*	Internal Height of Lat Mass (mm)†	Height of Path Perpendicular to Screw (mm)*
mean	5.6	3.9	6.5
standard deviation	2.3	1.2	2.2
minimum	1.5	1.7	2.0
maximum	11.8	6.8	10.2

* Measured from the external cortical margins of the C-2 pars interarticularis along the narrowest point of screw trajectory.

† Measured from the midpoint of the superior facet to the nearest point on the inferior surface of the C-2 lateral mass or VA groove.

all agree on the need for preoperative thin-cut CT scanning with reformatted sagittal images to determine if unfavorable anatomy exists. Based on these imaging data, a number of authors have designed exclusion criteria to define which patients can undergo safe screw placement guided by standard fluoroscopy. Paramore, et al.,¹⁴ evaluated CT scans obtained in 94 consecutive patients and determined that in 18 to 23% a high-riding VA groove on at least one side of the C-2 vertebra precluded safe placement of transarticular screws. The projected screw path was determined using a standard entry point and trajectory. The entry point was 4 mm superior to the C2–3 facet and 2 to 3 mm lateral to the spinal canal. The trajectory was a straight path (that is, 0° mediolaterally) aimed toward the anterior tubercle of C-1 on lateral fluoroscopy. Madawi, et al.,¹¹ examined 25 adult cadaveric C-2 vertebrae and similarly found that in 20% of the cases the width of the C-2 pars was reduced by the VA groove unilaterally and thus prevented safe screw placement. Their criteria for determining inoperable anatomy was the maximum depth of the VA groove measured on CT scans. They measured the internal height of the C-2 lateral mass from the midpoint of the superior facet to the roof of the VA groove. Specimens with an internal lateral mass height of 2 mm or less were determined to be unsuitable for operation. The problem with this criterion is that the path of the screw does not intersect the minimal internal segment, depending on the trajectory, and therefore the C-2 pars interarticularis may safely accommodate a 3.5-mm screw by adjusting the trajectory.

Mandel, et al.,¹³ analyzed the morphological features and dimensions of 205 sets of human C-1 and C-2 vertebrae by using both direct anatomical and CT-documented measurements to anticipate which individuals would be at risk for VA injury during C1–2 transarticular screw placement. They concluded that C-2 pars interarticularis widths and/or heights of less than 5 mm were too narrow to allow safe placement of a 3.5-mm screw.

Image-Guided C1–2 Transarticular Screw Placement

Although some authors have suggested that image guidance may allow screws to be placed in cases otherwise considered unsuitable,^{1,3,6} little information has been published regarding the guidelines for stereotactic C1–2 transarticular screw placement.⁴ Welch, et al.,¹⁷ described using the stereotactic articulating arm to place C1–2 transarticular screws in four patients; however, there are

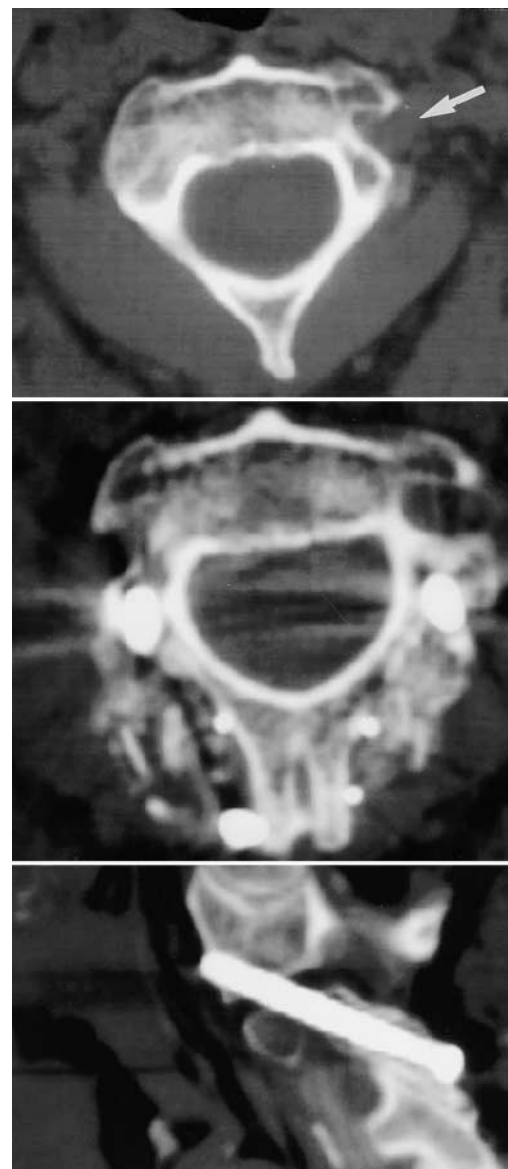


FIG. 3. Upper: Axial CT scan revealing severe erosion of the left C-2 pars interarticularis by the VA groove (arrow). Center: Axial CT scan demonstrating successful placement of a transarticular screw in the same specimen. Lower: Sagittal CT reconstruction of the cervical specimen following placement of a C1–2 transarticular screw.

significant drawbacks to their technique, as the system relied on skin fiducials for registration. The authors of previous studies have shown that because the skin is significantly more mobile in comparison with the relatively rigid bone anatomy, skin fiducials potentially increase the chance for error.^{2,15} These authors performed a surface-matching technique in which as many as 40 points were used; consequently, approximately 15 minutes were added to the operating time. The other shortcoming of this technique is that the system required a mechanical arm that provided identification of the anatomy, screw entry point, and proposed trajectory; however, the drill was placed over the wand and was not itself stereotactically guided.

As a result, fluoroscopy was required throughout all steps of screw placement.

In the present series C1–2 transarticular screws were placed using a frameless LED-based system similar to that described by Foley and Smith.⁵ The advantage of these systems include the use of any custom-made instrument that can be fitted with LEDs and used stereotactically, obviating the need for fluoroscopic guidance. In four specimens in our study we observed uni- or bilateral VA groove erosion that reduced the internal height of the C-2 lateral mass to 2 mm or less, which would have excluded them from C1–2 screw placement had the criteria established by Madawi, et al.,¹¹ been followed. Three of these specimens were deemed technically suitable based on our stereotaxy criteria, and bilateral C1–2 transarticular screw placement was successfully performed. The improved accuracy provided by frameless stereotaxy allowed 3.5-mm screws to be safely placed in specimens with C-2 pars interarticularis dimensions greater than 4 mm. This differs from previous studies in which the authors indicated that C1–2 transarticular screws should not be placed in patients in whom the C-2 pars interarticularis measures less than 5 mm.¹³

The image guidance system can display instrument positions in “plane of probe” and “plane of probe (90°)” views. These views are axial and sagittal reconstructions obtained along the plane of the instrument that allow the surgeon to navigate a drill bit in real time along a predetermined path; additionally, any necessary changes in trajectory can be made to avoid important neurovascular structures by observing the workstation screen. This fine tuning allows modifications in trajectory from a straight angle (0° mediolaterally) to an oblique trajectory while maintaining visualization of the instrument, ensuring that it does not perforate the bone cortex. Based on criteria used by Paramore, et al.,¹⁴ (standard screw pathway) and Madawi, et al.,¹¹ (measuring the internal lateral mass height at the center of the superior facet), the VA is examined at its most superior point to determine surgical feasibility. Strict adherence to these standard entry points and trajectory criteria is not necessary when using frameless stereotaxy because minor modifications in the trajectory can be made. In frameless stereotaxy the screw trajectory can be adjusted medially, navigating away from the VA. This technique may potentially be improved further by the addition of contrast-enhanced CT scans to assist in the identification of the artery. Therefore, the new frameless stereotactic criteria for surgical feasibility are the height and width of the C-2 pars interarticularis perpendicular to the best trajectory from the screw, which must be greater than 4 mm. Using these criteria, the number of patients in whom the anatomy is technically not suited for fixation is reduced from approximately 20 to 5.9%.

Technical Challenges of Image-Guided C1–2 Screw Placement

In our experience distinct anatomical landmarks for registration are easily identifiable in both the laboratory and clinical settings. Similarly, we did not identify any technical aspect of stereotactic C1–2 screw placement, including registration time, that would hinder routine clinical application.

The relationship and mobility of C-1 to C-2 is of significant concern in transarticular screw fixation. In patients with fixed, irreducible atlantoaxial subluxation, image guidance allows preoperative trajectory planning to determine whether screw placement will traverse the C1–2 joint as well as avoid the VA. In patients with a small degree of irreducible subluxation screws can be successfully placed stereotactically, whereas in those with severe cases of subluxation screw placement is contraindicated because the screw trajectory will not safely cross the C1–2 joint. Patients with a treatable subluxation should be positioned to achieve the smallest degree of angulation, and fluoroscopy should be used to supplement the image guidance procedure because the C1–2 relationship may be significantly different from that visualized on the preoperative CT scan. Future advances in image guidance technology, such as independent tracking of separate vertebral segments, will allow for accurate and safe screw placement in this circumstance without requiring fluoroscopy.

In this study, as in several clinical reports,^{9,11,16,17} 3.5-mm-diameter screws were exclusively used for fixation. Some surgeons, however, prefer 4-mm screws for atlantoaxial fixation,³ and the larger screw diameter may preclude screw placement in some cases due to screw's larger size.

Conclusions

Previously C1–2 transarticular screw placement was not considered technically feasible or safe in 20% of cases due to anomalous VA anatomy within the C-2 pars interarticularis. We conducted cadaveric studies in which we demonstrated that stereotactic guidance significantly reduces this incidence to 5.9% because of the precision afforded by this technology, which allows accurate preplanning and intraoperative trajectory modification, thereby increasing the safety of screw placement in patients requiring C1–2 fixation.

References

1. Brockmeyer DL, York JE, Apfelbaum RI: Anatomical suitability of C1–2 transarticular screw placement in pediatric patients. **J Neurosurg (Spine 1)** 92:7–11, 2000
2. Brodwater BK, Roberts DW, Nakajima T, et al: Extracranial application of the frameless stereotactic operating microscope: experience with lumbar spine. **Neurosurgery** 32:209–213, 1993
3. Dickman CA, Sonntag VK: Posterior C1-2 transarticular screw fixation for atlantoaxial arthrodesis. **Neurosurgery** 43:275–281, 1998
4. Ebraheim NA, Misson JR, Xu R, et al: The optimal transarticular C1-2 screw length and the location of the hypoglossal nerve. **Surg Neurol** 53:208–210, 1999
5. Foley KT, Smith MM: Image guided spinal surgery. **Neurosurg Clin North Am** 7:171–186, 1996
6. Fuji T, Oda T, Kato Y, et al: Accuracy of atlantoaxial transarticular screw insertion. **Spine** 25:1760–1764, 2000
7. Grob D, Crisco JJ III, Panjabi MM, et al: Biomechanical evaluation of four different posterior atlantoaxial fixation techniques. **Spine** 17:480–490, 1992
8. Grob D, Jeanneret B, Aebi M, et al: Atlanto-axial fusion with transarticular screw fixation. **J Bone Joint Surg (Br)** 73:972–976, 1991

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9. Jun BY: Anatomic study for ideal and safe posterior C1–2 transarticular screw fixation. **Spine** **23**:1703–1707, 1998
10. Kim KD, Johnson JP, Masciopinto JE, et al: Universal calibration of surgical instruments for spinal stereotaxy. **Neurosurgery** **44**:173–178, 1999
11. Madawi AA, Casey AT, Solanki GK, et al: Radiological and anatomical evaluation of the atlantoaxial transarticular screw fixation technique. **J Neurosurg** **86**:961–968, 1997
12. Magerl F, Seemann PS: Stable posterior fusion of the atlas and axis by transarticular screw fixation, in Kehr P, Weidner A (eds): **Cervical Spine I**. Vienna: Springer-Verlag, 1987, pp 322–327
13. Mandel IM, Kambach BJ, Petersilge CA, et al: Morphologic considerations of C2 isthmus dimensions for the placement of transarticular screws. **Spine** **25**:1542–1547, 2000
14. Paramore CG, Dickman CA, Sonntag VKH: The anatomical suitability of the C1–2 complex for transarticular screw fixation. **J Neurosurg** **85**:221–224, 1996
15. Roessler K, Ungersboeck K, Dietrich W, et al: Frameless stereotactic guided neurosurgery: clinical experience with an infrared based pointer device navigation system. **Acta Neurochir** **139**:551–559, 1997
16. Stillerman CB, Wilson JA: Atlanto-axial stabilization with posterior transarticular screw fixation: technical description and report of 22 cases. **Neurosurgery** **32**:948–955, 1993
17. Welch WC, Subach BR, Pollack IF, et al: Frameless stereotactic guidance for surgery of the upper cervical spine. **Neurosurgery** **40**:958–964, 1997
18. Wright NM, Laurysen C: Vertebral artery injury in C1–2 transarticular screw fixation: results of a survey of the AANS/CNS Section on Disorders of the Spine and Peripheral Nerves. **J Neurosurg** **88**:634–640, 1998

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