Craniovertebral junction fixation with transarticular screws: biomechanical analysis of a novel technique

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Object. The authors compared the biomechanical stability resulting from the use of a new technique for occipitocervical motion segment fixation with an established method and assessed the additional stability provided by combining the two techniques.

Methods. Specimens were loaded using nonconstraining pure moments while recording the three-dimensional angular movement at occiput (Oc)-C1 and C1–2. Specimens were tested intact and after destabilization and fixation as follows: 1) Oc–C1 transarticular screws plus C1–2 transarticular screws; 2) occipitocervical transarticular (OCTA) plate in which C1–2 transarticular screws attach to a loop from Oc to C-2; and (3) OCTA plate plus Oc–C1 transarticular screws.

Occipitocervical transarticular screws reduced motion to well within the normal range. The OCTA loop and transarticular screws allowed a very small neutral zone, elastic zone, and range of motion during lateral bending and axial rotation. The transarticular screws, however, were less effective than the OCTA loop in resisting flexion and extension.

Conclusions. Biomechanically, Oc–C1 transarticular screws performed well enough to be considered as an alternative for Oc–C1 fixation, especially when instability at C1–2 is minimal. Techniques for augmenting these screws posteriorly by using a wired bone graft buttress, as is currently undertaken with C1–2 transarticular screws, may be needed for optimal performance.

KEY WORDS • transarticular screw • occipital condyle • craniocervical junction • atlas • axis • biomechanical study

The CVJ is composed of the occipital bone, the atlas (C-1), and the axis (C-2). This osseous complex allows significant mobility while maintaining biomechanical stability. Traumatic instability of the CVJ can be catastrophic. Survivors are prone to suffering repeated luxations and often suddenly die of complications related to such instability. Progressive neurological deterioration occurs when this instability is caused by slower processes such as infections, inflammatory diseases, metabolic disorders, or congenital conditions.

According to Grob, et al., the ideal system for fixing the unstable CVJ must meet the following requirements: 1) the system should fix only the involved segments; 2) no hardware should be inserted into the spinal canal; 3) the system should provide immediate reduction of the deformity after surgery until fusion develops without requiring postoperative orthoses; and 4) the system should be effective even if the laminae are absent. Available systems for fixing the CVJ do not meet these requirements.

Systems for fixing the CVJ can be classified into two general groups: wire-based and plate and screw-based hardware. Typically, the former requires suboccipital wiring to tie hardware and grafts to the skull and sublaminar wiring to tie hardware and grafts to the spine. In the latter, occipital screws are required to affix the hardware to the skull and lateral mass pedicle, or transarticular screws are required to affix hardware to the spine. These existing procedures have several limitations.

Screw fixation provides superior biomechanical stability compared with nonscrew-based techniques, theoretically leading to higher rates of fusion. One limitation of using the suboccipital bone as an anchorage point is that because its thickness varies, inadequate bone purchase and eventual screw pullout can result. Occipital screws also are associated with the potential complication of epidural bleeding.

The suboccipital and sublaminar single- or multithreaded wiring technique may be dangerous when the spinal canal is narrowed by degenerative spondylotic processes or a pathological mass. The insertion of wiring is also associated with intrinsic risks. The absence of laminae due to trauma, disease, or previous surgery is a contraindication to sublaminar wiring. Wire fixation can fail because it provides less rigidity than screw and plate-augmented fusion.

The authors of previous anatomical studies of the occipital condyle have elucidated the possibility of fixing the CVJ with a transarticular screw from the C-1 lateral mass into the condyle of the occiput (Fig. 1). This method resembles the widely accepted technique described by Magerl and Seemann for fixing C1–2 with transarticular screws to treat atlantoaxial instability. The use of Oc–C1...
transarticular screws had not been described in the literature when we began to study them. Recently, however, Grob successfully treated traumatic occipitoatlantal dislocation by placing Oc–C1 transarticular screws reinforced with an inverted Y-shaped plate anchored caudally with C1–2 transarticular screws.

Occipitoatlantal transarticular screws offer an advantage when only the Oc–C1 motion segment is unstable. In such cases, Oc–C1 transarticular screws could be used to limit motion only at the affected segment, a feature of the aforementioned ideal fixation construct. The other techniques for occipitoatlantal fixation require the construct to be extended beyond the involved segment, limiting the normal ROM of the subjacent cervical spine and possibly accelerating degeneration at these subjacent levels. Most notably, axial rotatory motion at C1–2, which accounts for more than 50% of the axial rotation movement of the head and neck, is lost when these other constructs are placed.

Earlier, we studied the feasibility of using the occipital condyle as an anchorage point to fix the CVJ. Computerized tomography reconstructions of the CVJ were used to determine the proper length of the screw and to ascertain the relation of the tentative trajectory with respect to the hypoglossal canal, which was potentially threatened. In preliminary studies we found that a screw 28 to 32 mm long was appropriate to preserve the integrity of the hypoglossal canal.

The next logical step was to study the biomechanical soundness of Oc–C1 transarticular screws. We therefore performed an experiment in which we used human cadaveric specimens to quantify the stability provided by this system in vitro. Using standard flexibility testing methods, we compared the effects of transarticular screw fixation with a system previously shown to provide the best stability of four occipitocervical fixation devices compared in laboratory tests. The previously proven device, the OCTA system (Spinal Concepts, Inc., Austin, TX), provided Oc–C2 fixation by rigidly connecting the heads of C1–2 transarticular screws to a contoured loop attached to the skull base (Fig. 2). Additional tests were performed to evaluate the performance of both devices combined (OCTA together with Oc–C1 transarticular screws).

**Materials and Methods**

**Specimen Preparation**

Eight specimens (skull base–C3) were obtained from fresh-frozen (unembalmed) human cadavers. There were seven males and one female (mean age at death 48.9 years; range 35–65 years). Based on clinical records and careful inspection, no specimen was found to have CVJ disease. Specimens were kept frozen at −20°C until needed for testing, when they were thawed at 25°C (in normal 0.9% saline solution).

After thawing, specimens were dissected. A straight saw was used to make a coronal cut in front of the CVJ, 2 cm anterior to the cervical spine. This cut allowed all skull base structures to be discarded, leaving isolated the occipitocervical complex. Mandibles were disarticulated and discarded. All remaining muscle was removed, leaving the ligaments, joints, and osseous structures intact. During biomechanical testing, specimens were wrapped in saline-soaked gauze to prevent dehydration.

Household wood screws were inserted partially into the exposed C-3 endplate and facet articulations. The screw heads were embedded in polymethylmethacrylate poured into a cylindrical fixture for application of loads. Holes were drilled in the skull base to allow it to be fastened to the base of the testing apparatus. Testing of specimens required 2 to 3 days. At the end of each testing day specimens were refrozen at −20°C. Biomechanical properties are not adversely affected when specimens are handled in this manner.

Before performing any surgical procedures, a custom mold was fashioned for each specimen (Fig. 3) by using fast-curing rubber (3110 RTV Silicone Rubber with F catalyst; Dow Corning, Midland, MI). The mold of the specimen in its preoperative condition provided a means for returning the specimen to its normal alignment and neutral posture after all ligaments were sectioned.

**Surgical Techniques**

Craniovertebral instability was induced surgically and was created with the intention of destabilizing both Oc–C1 and C1–2. With a No. 11 surgical blade, a cut was made anterior to the CVJ at the space between the basion and the C-1 anterior arch to section the tectorial membrane and apical ligament. This cut was extended on both sides of the dens to section the alar ligaments bilaterally. Once all ligaments were sectioned, a Type II fracture of the dens was simulated using a high-speed pneumatic drill with a 1.8-mm-diameter bit (Medtronic Midas Rex, Fort Worth, TX). Overt instability was evident after these destabilizing procedures.

Before initiating the screw insertion procedure, each specimen was placed in its custom mold to restore its normal alignment. Using C-arm fluoroscopic guidance, a 1.5-mm-diameter end-threaded stainless-steel guide wire was drilled from C-1 into the occipital condyle using a pneumatic drill (Triton; Medtronic Midas Rex). The
entry point for the guide wire was the midpoint of the posterior aspect of the C-1 lateral mass, underneath the sulcus arteriosus (Fig. 1). The middle aspect of the occipital condyle was used as an initial target for the guidewire trajectory. The trajectory was monitored on anteroposterior and lateral fluoroscopic imaging until the wire tip reached a point 1 cm rostral to the tip of the odontoid process. The guidewire was directed medially 10 to 20˚ across the occipital condyle; this trajectory was monitored on the anteroposterior fluoroscopic image on which it is possible to observe the exact location of the hypoglossal canal (Fig. 4).

Once an adequate position of the guidewire was evidenced on fluoroscopy, a pilot hole was made approximately 30 mm deep by using a 2.7-mm-diameter cannulated bit placed over the guidewire. The portion of the pilot hole through C-1 and proximal to entry into the occipital condyle (~ 12 mm deep) was widened using a 4-mm bit to allow the outer threads of the screws to pass freely through C-1 and to create a lag effect (compressing C-1 against Oc). Custom-made lag screws were used to reapproximate the gap that was created at the occipitoatlantal joint after the ligaments were sectioned. Cannulated, self-tapping 4-mm-diameter lag screws 28- to 32-mm long were used (Medtronic Sofamor Danek, Memphis, TN). The lengths of the screws were chosen to avoid damaging the hypoglossal canal.

Transarticular atlantoaxial screws were inserted using a cannulated technique similar to the aforedescribed method for Oc–C1 to help establish the appropriate trajectory. Fully threaded titanium lag screws (40-mm length, 4-mm diameter) were used; these screws were the same customized screws as used with the OCTA system, as described in Biomechanical Testing. Special screws were used both as stand-alone C1–2 transarticular screws and for attaching to the loop portion of the OCTA plating system. These screws have a linkage that allows the screw heads and the metal loop that is attached to the skull base to be rigidly interconnected (Fig. 2). Four screws connected the loop to the skull base: two in the midline at the vertex of the loop and two near the posterior rim of the foramen magnum where the bone width is adequate for good screw purchase.
Biomechanical Testing

The biomechanical flexibility tests were similar to earlier work. Each prepared specimen was mounted, inverted on an angle vise on the base of the loading apparatus, and positioned so that the gravitational preload could be oriented axially along the spine in its neutral orientation. Specimens underwent torque (pure moment) loading within the physiological range by using a nonconstraining system of cables and pulleys controlled by a servohydraulic testing machine. Loads were applied quasi-statically to the fixture on C-3 in 0.25-Nm increments to a maximum load of 1.5 Nm. The direction of the load was aligned to induce flexion, extension, lateral bending, and axial rotation. The use of pure moments is advantageous because the load is evenly distributed to each level, allowing direct comparison between levels and ensuring consistency in loading conditions between surgical states.

At each level, specimen motion was tracked stereophotometrically in three dimensions by using a noncontacting optical tracking system (Optotrak 3020; Northern Digital, Waterloo, ON, Canada). Three 1.25-mm-diameter stainless-steel guidewires were inserted in the skull base, C-1 lateral masses, and vertebral bodies of C-2 and C-3. After the guide wires were cut to 4 to 7 cm, infrared-emitting diodes were glued to the free ends. A cartesian coordinate system was assigned to each level (Oc–C1, C1–2, and C2–3). Angles between levels in flexion, extension, lateral bending, and axial rotation were calculated using the tilt-twist technique. Rotational data were evaluated to quantify the ROM, NZ, and EZ.

All specimens were tested before any intervention (normal condition). After the CVJ ligaments were cut to mimic an odontoid Type II fracture, specimens were so unstable that they could not be tested without risking further tearing of soft tissues. All specimens were tested in each of the following configurations of hardware attachment: 1) Oc–C1 transarticular screws and C1–2 transarticular screws; 2) OCTA plating system; and 3) OCTA plus Oc–C1 transarticular screws. Hence, comparisons were performed among fixation devices spanning 1) occiput to C-1 and C-1 to C-2; 2) occiput to C-2 and C-1 to C-2; and 3) occiput to C-1, C-1 to C-2, and occiput to C-2.

After nondestructive flexibility testing, specimens underwent load-to-failure testing during flexion to evaluate weak points where the hardware system would fail under extreme circumstances. Specimens were loaded using the same apparatus as for nondestructive testing but with stronger cables and pulleys. The piston of the servohydraulic test frame was raised at a constant cable uptake rate corresponding to approximately 1.5˚/second (C-3 relative to occiput) until failure as noted by visible disruption of the specimen.

Statistical Analysis

Two-tailed paired Student t-tests were performed to compare the two different hardware systems studied (Oc–C1 screws combined with C1–2 screws and OCTA plate). One-tailed paired Student t-tests were conducted to evaluate whether stability was enhanced by additional hardware (Oc–C1 transarticular screws added to OCTA). Significance was assumed at a probability value less than 0.05. Statistical comparisons were made in each loading modality (flexion, extension, lateral bending, and axial rotation) and for each parameter studied (NZ, EZ, and ROM). Because of the small numbers of specimens and large number of comparisons, the probability of statistical error was high. Therefore, these statistical data should only be considered as an index for clarifying where the differences in stability might be greatest among the different configurations of instrumentation.

Additional Tests

After instrumentation was placed, all specimens underwent CT scanning in which multiplanar reconstructions were obtained to eval-
and 19 particular screws combined with C1–2 transarticular screws occurred at the atlantoaxial joint. No changes were found in the shape of the occipitoatlantal screws or in the OCTA plate after hardware removal. The holes at the screw–bone interface, however, were widened in all specimens, especially at the C1–2 joint.

Computerized Tomography Analysis

Sixteen sides were studied using CT scanning, and in all specimens the hypoglossal canal was uninterrupted during its full course inside the occipital condyle. No fractures were identified. Using the aforedescribed trajectory, the screws were located inside the bone in all but one side (6.25%). In that case, the screw crossed the occipitoatlantal joint too far ventrally to capture the occipital condyle effectively.

Anatomical Dissections

Inspection after testing demonstrated the integrity of all osseous elements. Screw insertion created no fractures, and the integrity of the hypoglossal canal was evident on disarticulated specimens. In one instrument-treated specimen, CT scanning revealed that the C1–2 screws were bent. After loading to failure, one of these screws was broken.

Discussion

Biomechanical Implications

After insertion of occipitoatlantal transarticular screws, stability at this junction was similar to that observed during lateral bending and axial rotation provided by attaching the OCTA plate. Results, however, were inferior during flexion–extension tests. These findings are similar to the results of biomechanical studies involving C1–2 transarticular screws. Naderi, et al.,24 have demonstrated that C1–2 transarticular screws performed well in resisting lateral bending and axial rotation but that they required a posterior buttress (wired bone graft) to reduce flexion–extension movement.

The addition of occipitoatlantal transarticular screws to the OCTA construct significantly further reduced occipitoatlantal motion without altering atlantoaxial stability. The magnitude of this reduction, however, was very small: mean ROM of 0.46° reduced to 0.11° during unilateral lateral bending, and mean ROM of 0.81° reduced to 0.17° dur-

\[ \begin{align*}
\text{Loading Mode} & \quad \text{Normal Motion (°)} & \quad \text{Oc–C1 + C1–2 Screws} & \quad \text{OCTA Plate} & \quad \text{OCTA Plate + Oc–C1 Screws} \\
\text{Oc–C1} & \text{flexion} & 14.5 \pm 2.2 & 0.264 \pm 0.231 & 0.044 \pm 0.028 & 0.006 \pm 0.006 \\
& \text{extension} & 16.4 \pm 2.3 & 0.195 \pm 0.112 & 0.060 \pm 0.027 & 0.006 \pm 0.005 \\
& \text{lateral bending} & 2.5 \pm 0.7 & 0.225 \pm 0.135 & 0.198 \pm 0.111 & 0.050 \pm 0.029 \\
& \text{axial rotation} & 3.4 \pm 1.5 & 0.271 \pm 0.194 & 0.259 \pm 0.149 & 0.049 \pm 0.023 \\
\text{C1–2} & \text{flexion} & 10.9 \pm 1.1 & 0.203 \pm 0.111 & 0.052 \pm 0.068 & 0.039 \pm 0.019 \\
& \text{extension} & 5.7 \pm 1.1 & 0.404 \pm 0.270 & 0.090 \pm 0.168 & 0.065 \pm 0.038 \\
& \text{lateral bending} & 2.3 \pm 1.9 & 0.033 \pm 0.034 & 0.028 \pm 0.027 & 0.034 \pm 0.069 \\
& \text{axial rotation} & 36.1 \pm 4.0 & 0.006 \pm 0.004 & 0.001 \pm 0.001 & 0.002 \pm 0.002 \\
\end{align*} \]

* Values are presented as the means ± standard deviation.
Screw fixation of the craniovertebral junction

### TABLE 2

**Summary of probability values derived from occipitoatlantal and atlantoaxial biomechanical testing**

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<th>Hardware Configurations</th>
<th>p Value</th>
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<th>EZ</th>
<th>ROM</th>
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* Indicates a value that was not statistically significant (p > 0.05).

After all tests were completed, it was determined that the screw was not well placed in the occipital condyle of one specimen. Such an error could have been avoided had we used computer-assisted image guidance of the type often performed to place cervical pedicle screws.29 This adjunct provides the surgeon with the best possible gauge of the appropriate trajectory.

### Study Limitations

Load-to-failure tests usually resulted in failures at the
potting fixture, which indicated that the specimens were inadequately potted for such high loads. Quantitative values found during load-to-failure tests were therefore meaningless and indicated only that the loads that were used were probably supraphysiological.

Our results provide evidence that occipitoatlantal transarticular screws would be effective in treating an isolated Oc–C1 injury. In this study, however, an extensive injury was created across the entire occipitoatlantoaxial complex. Therefore, the degree of C1–2 stability conferred by Oc–C1 transarticular screw fixation of an isolated occipitoatlantal injury is unknown. Future studies involving this fixation technique should attempt to identify which types of instability affect Oc–C1 with minimal effect on C1–2 stability. Occipitoatlantal transarticular screws would be best indicated for these types of instability.

Future Direction

We have described the technique and biomechanical implications of this new fixation method. In ongoing research, we plan to determine the degree of additional stability provided by a posterior bone graft that simultaneously provides a scaffold for fusion. Normally, because bone grafts placed between the skull base and the upper cervical spine are not under compressive loading, they can easily dislodge with unrestricted motion. Occipitoatlantal transarticular screws significantly reduce movement during lateral bending and axial rotation, requiring another method to achieve stability during flexion and extension. As has been shown when C1–2 transarticular screws are used in combination with an interspinous graft, posterior grafts perform well in resisting flexion and extension. We hope to achieve similar results at the occipitoatlantal joint. Computerized tomography guidance will be used to improve purchase into the occipital condyle.

Conclusions

Transarticular screw fixation of the occipitoatlantal motion segment can provide immediate rigid fixation while avoiding the need to introduce hardware into the spinal canal. It involves only the compromised segments and spares the C1–2 mobility. This procedure adequately reduces motion with respect to normal movement and after severe instability. Fulfillment of these conditions makes this system a good alternative in cases of occipitoatlantal dislocation when it is infeasible to include the suboccipital bone and C-1 and C-2 posterior elements in the fixation construct.

Occipitoatlantal transarticular screws did not perform as well as the OCTA plate in immobilizing Oc–C1, especially during flexion and extension. This finding is similar to the results of placing C1–2 screws without a posterior wired interspinous bone graft. A posterior bone graft placed between the suboccipital bone and the C-1 arch would reduce the hinge effect by acting as a buttress and would simultaneously serve as a scaffold for fusion.

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References

Screw fixation of the craniovertebral junction


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Addendum

During the preparation and revision of this manuscript, we treated a 17-year-old patient with an occipitoatlantal dislocation sustained in a severe motor vehicle collision (Fig. 6 left). After 7 months of follow up, he is asymptomatic and radiography demonstrated excellent fusion (Fig. 6 right).

Fig. 6. Left: Preoperative coronal computerized tomography reconstruction revealing widening between the occipital condyle and the lateral mass of the axis. Right: Postoperative lateral radiograph demonstrating the position of the screw and the solid bone fusion in the back, held with sublaminar wiring.