The authors conducted a biomechanical study to determine whether C-1 ring integrity is important in maintaining normal occiput-C-2 separation, specifically when the anterior arch is transected to provide access to the dens during an odontoidectomy procedure.

Six human cadaveric occiput-C3 specimens were loaded under axial compression, and the bilateral horizontal separation of the C-1 lateral masses and the vertical compression of the occiput relative to C-2 were recorded. Specimens were first studied after odontoidectomy without C-1 ring transection, then after C-1 anterior arch transection, and finally after C-1 lamina transection.

With applied compressive load corresponding to three times the weight of the head, the C-1 ring spread horizontally 1.57 ± 0.30 mm more when the anterior arch of C-1 was transected than when left intact, resulting in 0.74 ± 0.44 mm collapse in the occiput-C-2 vertical separation. After laminar transection, the C-1 ring spread 6.55 ± 2.29 mm more than when it was intact. The resultant vertical separation was a 3.37 ± 1.89-mm collapse in the occiput-C-2. All changes in C-1 spreading and the occiput-C-2 collapse were statistically significant (p < 0.05, paired Student's t-tests). The C-1 ring continuity prevents horizontal spreading caused by the wedging of C-1 between the occiput and C-2 and thus prevents cranial settling. Therefore, to prevent the subsequent development of disease related to cranial settling, the authors recommend that the surgeon resect part of C-1 only if necessary during odontoidectomy.

Key Words * craniovertebral junction * lateral mass offset * odontoidectomy * dens

When they affect the craniovertebral junction (CVJ), various diseases such as rheumatoid arthritis, achondroplasia, Paget's disease, congenital anomalies, and trauma can require spinal decompressive surgery to be performed via a transoral odontoidectomy. Results from clinical and in vitro studies have shown that an odontoidectomy creates a severe ligamentous instability.[4,5] However, based on the bony morphology of the CVJ (Fig. 1) and the fact that the ring of C-1 is often transected anteriorly to provide access to the dens, there also appears to be the potential for an osseous instability of the CVJ after
odontoidectomy. The angled joint interfaces between the occiput-C1 and C1-2 cause the C-1 lateral masses to act as wedge spacers between the occiput and C-2 and provide the means for transfer of compressive force outward radially to the ring of C-1. This radial force should be inconsequential normally, but analysis of preliminary research has indicated that with even a single break in the continuity of the C-1 ring, the lateral force transferred from axial compression can cause the C-1 ring to spread, allowing the occiput to migrate caudally toward C-2 (that is, cranial settling). Neurosurgeons are concerned with this biomechanical response to compression because, due to gravitational effects on the head and muscle contraction, axial compression is the main mode of loading at the CVJ in the upright neutral position.

![Fig. 1. Computerized tomographic coronal reconstruction of the normal osseous structure of the CVJ showing the wedge-shaped configuration of the C-1 lateral masses.](image)

Spreading of C-1 and subsequent cranial settling can cause serious complications. A decrease in the height of the upper cervical spine complex can cause the spinal cord to kink or fold within the spinal canal. This kinking may be associated with tethering of the spinal cord and medulla due to tension over the dentate ligaments,[15] and this finding may explain some cases of deterioration after odontoidectomy or other upper cervical spine surgeries.[1,7] Increased C-1 lateral mass offset can also cause torsion of the vertebral arteries, which can contribute to neurological degradation.[8,16]

Although an anterior transection of the ring of C-1 during odontoidectomy is a common procedure, there is an alternative odontoidectomy procedure in which the anteroinferior C-1 arch is partially resected to gain access to the dens.[14] The ring of C-1, however, is not disrupted. It is not known whether this technique prevents C-1 ring spreading or cranial settling.

To our knowledge, no studies have focused specifically on how the C-1 ring contributes to the stability of the CVJ. In this study, therefore, we have investigated the importance of the integrity of the C-1 ring in maintaining the normal separation between the occiput and C-2 in vitro. First, we examined whether an odontoidectomy that leaves the C-1 ring mostly intact allows less vertical migration to occur than when the C-1 anterior arch is transected. We also examined whether subsequent disruption of the C-1 lamina further destabilizes the CVJ.

**MATERIALS AND METHODS**

**Cadaver Preparation**

Seven human upper cervical spine specimens (the occiput-C-3) were obtained en bloc during routine
autopsy procedures. Of these, one specimen (obtained from an 18-year-old male cadaver) was excluded because a congenital cleft in the posterior tubercle of C-1 was found. The specimens, then, consisted of five men and one woman (mean age at the time of death, 63.8 years; range 53-77 years). Examination of clinical reports and radiological studies revealed no disease affecting the bone and joint structure of the CVJ. These specimens had been used in a previous study in which we compared the biomechanical effects of different instrumentation methods after odontoidectomy-induced instability of the upper cervical spine.[11] After conducting the previous research, the specimens were mostly devoid of soft tissues, but the ring of C-1 was continuous, and the atlantoaxial joint surfaces were intact. Because in the current study we focus on bone deformation, the condition of the soft tissues was unimportant. Specimens were stored at -20°C and thawed in a saline solution at 25°C on the day of testing.

**Biomechanical Testing**

The C-3 vertebra was potted in a cylindrical, aluminum, loading fixture in which wood screws were embedded in methylmethacrylate to provide a flat surface for loading. The skull base was inverted and affixed to the base of the loading apparatus by using an angle vise. The specimen was oriented in a position that directed gravitational preload axially along its neutral orientation. Specimens were tested mechanically with the skull base attached rigidly to the base of the apparatus while loads were applied to C-3 (Fig. 2).

![Fig. 2. Photograph showing the test apparatus in which a specimen has been mounted for testing. Loads were applied to C-3 through a ball-shaped interface against a flat surface. Displacements of the occiput, C-2, and the left and right halves of C-1 were measured from three optical markers rigidly attached to each osseous structure.](image)

Because the primary loading modality used to induce cranial settling is axial compression, this is the loading mode we chose to study. Other loading modalities, such as loads to induce bending or twisting, would also be expected to induce horizontal spreading of C-1 (especially during flexion). However, these loads and angular motions were not studied because their contribution specifically to cranial settling
would be difficult to quantify and the response to these other loading modalities would be governed by a combination of osseous and ligamentous resistance rather than purely osseous resistance.

By using a servohydraulic test machine (Fig. 2), axial forces were applied to C-3 through a nonfixed rounded interface. Three preconditioning cycles were applied where loads of 120 N were held for 60 seconds. After allowing 60 seconds for creep, data were recorded while loads were applied quasistatically between 0 N and 120 N in 20-N increments. Each loading increment was held for 45 seconds. A 40-N load was chosen to approximate the weight of the human head, and a 120-N load was used to approximate the loads that might be present during muscle contraction.

During loading, three-dimensional spinal movement was measured using an optical tracking system (Optotrak 3020; Northern Digital, Waterloo, Ontario, Canada). Infrared-emitting diodes were rigidly attached to the ends of 1.25-mm end-threaded stainless steel surgical guide wires that had been inserted into three locations in the skull base and three locations in the C-2 vertebral body and cut to an average of 4 cm. Three infrared-emitting diodes were similarly attached to the left lateral mass of C-1, as well as to the right lateral mass of C-1 to track the two halves separately as two rigid bodies. By using a digitizing probe (an accessory to the Optotrak system), a Cartesian coordinate system was established at each spinal level with respect to its neutral orientation.[2] The positive x axis was oriented medially to left laterally, the positive y axis caudally to cranially, and the positive z axis posteriorly to anteriorly.

The linear displacement of a point on the medial midheight left lateral mass of C-1 was established with the digitizing probe and tracked relative to the right lateral mass of C-1. Additionally, the digitizing probe was to identify a point on the anteroinferior margin of the foramen magnum and to track that point relative to C-2. The results were given in terms of the C-1 coordinate system.

All specimens were tested in three phases: 1) after an odontoidectomy procedure in which the entire odontoid process and the transverse ligament were removed and at least 50% of the inferior portion of the C-1 anterior arch was left intact (that is, the control phase in which transections of C-1 were not performed);[14] 2) after transection of the C-1 anterior arch to simulate the more radical odontoidectomy technique;[3] and 3) after transection of the C-1 lamina.

Statistical Analysis

In each phase of testing, we measured the linear vertical motion of the occiput relative to C-2 and the offset of the C-1 lateral masses, and these results were analyzed using one-tailed paired Student's t-tests to determine whether significantly more motion was present after transection. In all cases, p values of less than 0.05 were considered statistically significant.

RESULTS

After transection of the anterior C-1 arch, applied loads moderately increased the spreading of the C-1 ring (Fig. 3 upper). Subsequent transection of the lamina increased the spreading of the ring even more when loads were applied. The increases in ring spreading after one and two transections corresponded to moderate and large increases in vertical migration of the occiput relative to C-2 (Fig. 3 lower).
Fig. 3. Graphs. Upper: Load-displacement curve showing the mean lateral position of the left half of C-1 relative to the right half at each load applied. Lower: Load-displacement...
curve showing the mean vertical position of the anteroinferior margin of the foramen magnum relative to C-2 at each load applied. CO= occiput.

When compared at normal head weight (Fig. 4 upper, Table 1) and at maximum load (approximately three times the head weight; Fig. 4 lower, Table 1), the increases in both horizontal spreading and vertical compression from intact ring to anterior transection and from anterior transection to anterior and posterior transection were statistically significant (p < 0.05).
Both lateral spreading of the C-1 ring and vertical compression demonstrated moderately linear responses after the first loading step, indicating constant stiffness (Fig. 3). With the ring of C-1 intact, the mean stiffness of horizontal ring spreading was extreme (1600 ± 930 N/mm). The stiffness of vertical compression across the occiput-C-2 was 130 ± 28 N/mm. After anterior transection of the C-1 arch was performed, the mean stiffness of horizontal ring spreading decreased significantly to 118 ± 33 N/mm. The mean stiffness of vertical compression decreased significantly to 82 ± 25 N/mm. Values for vertical and horizontal stiffness were significantly lower after anterior transection than those obtained when the ring was intact. After transection of the lamina, the stiffness of vertical compression changed little (average 82 ± 12 N/mm). After transection of the lamina, the stiffness of horizontal spreading increased significantly to a mean of 210 ± 67 N/mm.

**DISCUSSION**

**C-1 Wedge Behavior**

The occurrence of the statistically significant C-1 bilateral offset after C-1 anterior arch transection and a further offset after C-1 lamina transection can be understood by examining the coronal geometry and anatomy of the CVJ (Fig. 1). In the coronal plane, the the occiput-C-2 complex has an X-like configuration. Unlike the subaxial spine, the upper cervical spine does not posess intervertebral discs. Therefore, if the neck posture is such that the posterior arch of C-1 does not make contact with the skull base or the C-2 posterior elements, the entire compressive load across C-1 is supported by the C-1 lateral masses. The lateral force transferred from compression must be borne by the anterior and posterior arches of C-1 and, likely to a lesser extent, by the transverse ligament. An odontoidectomy in which the C-1 anterior arch is transected and the odontoid and transverse ligament are removed destroys two of...
these three load-bearing horizontal structures. The posterior arch of C1, which has a thin cross-sectional area, must then alone resist the lateral force that vertical compression exerts.

Fig. 5. Coronal representation of the CVJ demonstrating the angles and dimensions considered in a geometrical analysis of the wedge effect of C-1 during axial compression between the occiput and C-2. Upper: Before compression, the inferosuperior separation between the occiput and C-2 is $v_1$, and the horizontal separation between the lateral masses of C-1 is $h_1$. Lower: While under compression, the lateral masses displace laterally, allowing axial migration of the occiput toward C-2. The inferosuperior separation between the occiput and C-2 is $v_2$, and the horizontal separation between the lateral masses of C-1 is $h_2$. The difference in distance between $v_1$ and $v_2$ is $\Delta v$, and the difference between $h_1$ and $h_2$ is $\Delta h$. The angle alpha is the atlantooccipital joint angle, and the angle beta is the atlantoaxial joint angle.

It is possible to estimate the lateral force and the potential increase in lateral mass offset distance (Fig. 5). This geometrical analysis has two angles of interest: the atlantooccipital angle, alpha, which is 27.5° on average,[13] and the atlantoaxial angle, beta, which is 20.0% on average.[5] Dimensions of interest are the lateral mass offset increase, $\Delta h$, and the increased compression across the occiput-C-2, $\Delta v$. These four terms are related by the equation:

$$\Delta v = \frac{\Delta h}{2} (\tan \alpha + \tan \beta)$$

For the average values of alpha and beta, $\Delta v = 0.44 \Delta h$. As an example, the increase in vertical compression across the occiput-C-2 would be 0.88 mm for horizontal C-1 ring spreading of 2 mm. In the
six specimens studied, the joint angles averaged from direct goniometrical measurements were alpha = 31.8°, beta = 22.7°. For the measured horizontal spread of 1.56 mm at full compression, the predicted vertical compression increase was 0.81 mm, which is reasonably close to the observed average value of 0.70 mm. After transection of both the anterior and posterior arches of C-1, the predicted increase in vertical compression for the measured horizontal spreading of 6.55 mm was 3.40 mm, which agrees well with the observed mean value of 3.37 mm.

Clinically, these angles and dimensions can be estimated by examining radiographs or computed tomographic scans. For a given amount of C-1 lateral mass offset, combined alpha and beta angles that are greater than normal predict greater than normal wedging action with greater potential vertical translation across the occiput-C-2. For example, if both alpha and beta are 5° greater than average, vertical translation for 2 mm of horizontal C-1 ring spreading should be 1.10 mm instead of the previous value of 0.88 mm.

**C-1 Laminectomy**

The increase in C-1 lateral mass offset permitted a significant concomitant increase in vertical compression across the occiput-C-2 after odontoidectomy in which the C-1 anterior arch was transected and a further increase in concomitant vertical compression after C-1 lamina transection. As the C-1 ring integrity decreased, vertical compression increased. This further increase reflected the left and right halves of C-1 becoming completely independent masses, the motions of which were limited only by the remaining soft tissues. The stiffness of ring spreading increased because the posterior tubercle could no longer act as a pivot point for the ring spreading. Instead of swinging open like a mouth, the separation of the two halves was more linear.

**Clinical Recommendations**

The integrity of the C-1 ring should be kept in mind during preoperative planning for a transoral odontoidectomy, particularly in patients who have undergone a prior C-1 laminectomy. In such cases, surgeons should try to avoid complete transection of the anterior C-1 arch. Congenital anomalies that interfere with C-1 integrity, such as that found in the specimen with the cleft posterior tubercle excluded from this study, can be diagnosed easily by computerized tomography scanning of the CVJ or other radiographic means.[6] Surgeons should inspect radiographs carefully for any anomaly that could affect the integrity of C-1.

After odontoidectomy, fusion can be performed by using a variety of occipitocervical plate and rod constructs[9] or transarticular screw fixation techniques combined with C1-2 tension-band techniques.[10] When the anterior arch of C-1 has been transected, the center of rotation for the mouthing action, which occurs when C-1 spreads, is near the region in which posterior hardware would be applied. Hence, posterior fixation would be expected to provide little resistance against C-1 lateral mass separation and would stabilize only the posterior column. In such a case, C-1 spreading and cranial settling theoretically could still occur by the same mechanism even after fixation has been performed. Transarticular screw fixation would most likely be the preferred procedure because the buttress created by transarticular screws should limit horizontal translation of the lateral masses and concomitant vertical migration. Further research is needed regarding the best method for obtaining fixation in patients who have undergone odontoidectomy with and without C-1 transection.

**Study Limitations**
In this study we did not investigate the contribution of muscles to CVJ stability. As described in the report by Panjabi,[12] muscles are an important part of the spine stabilizing system. The presence of active muscles surrounding C-1 would probably have prevented some spreading of C-1 and thus, some vertical compression. Furthermore, no instrumentation systems were tested to determine the best method for fixating C-1. Although different devices have been tested to determine their performance during bending and rotation, the devices have not been compared in terms of their ability to prevent spreading of the C-1 ring. A final limitation of this study is that the optoelectronically measured changes in the occiput-C-2 separation were not correlated to radiographically measured changes. Therefore, it is not known how precisely the clinician can measure in patients the C-1 spreading and cranial settling quantified in this study.

CONCLUSIONS

The integrity of the C-1 ring is critical to the stability of the CVJ. When the C-1 ring is transected, the lateral masses displace laterally, causing cranial settling and overt spinal instability. The structural and mechanical abnormalities create a high risk of neurological sequelae. Whenever possible, the C-1 ring should be only partially resected during an odontoidectomy. Transection should be avoided. When the C-1 anterior arch must be transected, transarticular screw fixation or occipitocervical fixation is recommended.

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