Anatomy and biomechanics of the craniovertebral junction

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The craniovertebral junction (CVJ) has unique anatomical structures that separate it from the subaxial cervical spine. In addition to housing vital neural and vascular structures, the majority of cranial flexion, extension, and axial rotation is accomplished at the CVJ. A complex combination of osseous and ligamentous supports allow for stability despite a large degree of motion. An understanding of anatomy and biomechanics is essential to effectively evaluate and address the various pathological processes that may affect this region. Therefore, the authors present an up-to-date narrative review of CVJ anatomy, normal and pathological biomechanics, and fixation techniques.

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The craniovertebral junction (CVJ)—defined as the occiput, atlas, and axis—is a complex area that houses vital neural and vascular structures while achieving the most mobility of any segment within the spine. It represents the transition between the brain and cervical spine. The majority of the spine’s rotation, flexion, and extension occur between the occiput, the atlas, and axis. The biomechanics of motion and stability at the CVJ are unique at each vertebra and segment. An understanding of the complexities of the CVJ anatomy and biomechanics is necessary to effectively evaluate and treat the various pathological processes that may affect this region. Recent developments in fixation technologies and minimally invasive surgical approaches to the CVJ have encouraged further characterization of its anatomy. The purpose of this narrative review is to provide an up-to-date overview of CVJ anatomy, normal and pathological biomechanics, and fixation techniques.

Anatomy

The Occipitoatlantal Segment (Oc–C1)

Examining the CVJ craniocaudally, the occipital bone contributes the clivus, the foramen magnum, and the occipital condyles. The clivus gives horizontal support to the pons before sloping inferiorly and posteriorly to form the anterior-most foramen magnum or basion. A 1-cm resection of the inferior clivus would reveal the pontomedullary junction, a valuable surgical landmark.

The posterior atlantooccipital membrane joins the posterior boundary of the foramen magnum. This permits caudal continuation of the brainstem through the skull inferiorly as the medulla, which enters the vertebral canal as the spinal cord. The squamous portion of the occipital bone completes the posterior boundary of the foramen, the posterior-most point of which is the opisthion. Morphometric studies of the foramen magnum have described distinct shapes, including round, egg-shaped, tetragonal, oval, irregular, hexagonal, and pentagonal.

The occipital condyles form bilateral inferior convexities that allow articulation with the atlas, and circumscribe the anterior half of the foramen magnum. The atlas receives the lateral-turned occipital condyles into superomedially facing concave articular surfaces on the superior aspect of the C-1 lateral masses, permitting flexion and extension of the cranium. The hypoglossal canal carves ventrally through the basilar occiput, medial and superior to the occipital condyle (Figs. 1 and 2).

The posterior atlantooccipital membrane joins the pos-
terior arch of the atlas to the occiput by entering the fora-
men magnum and attaching posteriorly to the squamous
occipital bone that constitutes the posterior ring of the
foramen magnum. The vertebral arteries puncture this
membrane, joining the basilar artery via bilateral canals
that also permit exit of the first cervical nerve root. The
dura mater lies immediately deep to the membrane. The
atlantooccipital membrane contributes little to the stabil-
ity of the CVJ.

Ceylan et al. analyzed the denticulate ligaments of the
spinal column and found regional differences. The cer-
vical spine, particularly at the first denticulate ligament,
featured widened triangular extensions and more robust
collagen tissues, presumably to compensate for increased
motion at this area.

The Atlantoaxial Segment (C1–2)
The atlas lacks a vertebral body and instead articulates
with the odontoid process or dens, a bony protuberance
extending superiorly from the vertebral body of the axis.
The atlas also communicates inferiorly with the axis by
flat, wide articular facets. The odontoid process and
horizontal facets permit rotation of the skull, the predomi-
nate motion of the C1–2 vertebral junction.

The transverse ligament of the atlas constrains the dens
within 3 mm of the anterior ring of the atlas by bound-
ing the dens posteriorly. Inferior and superior crura arise
from the transverse ligament as it crosses the dens, attach-
ing to the body of C-2 and the anterior foramen magnum,
respectively. Taken altogether, the transverse ligament and
its crura form the cruciform or cruciate ligament (Fig. 1).
The transverse ligament contributes substantially to the
stability of the CVJ, preventing the dens from folding into
the midbrain during flexion (Fig. 2).

The alar ligaments arise from the anterolateral aspect
of the dens and attach to the medial aspect of the occipital
condyles, inferior to the foramen magnum. The primary
function of the alar ligaments is to restrict rotation of the
cranial. The alar ligaments are also critical to maintain-
ing stability at the CVJ (Fig. 1).
Ventral to the spinal cord, the tectorial membrane extends superiorly as a continuation of the posterior longitudinal ligament. Beginning at the posterior vertebral body of C-2, the tectorial membrane fans out laterally over the dens and associated ligaments, attaching to the superior surface of the clivus before incorporating with the intracranial dura mater. The role of the tectorial membrane is controversial. It has been proposed to function in restricting flexion, restricting extension, or protecting the dura from the dens.

The apical ligament of the dens (or apical odontoid ligament) extends from the superior-most point of the dens to attach to the inside of the anterior ring of the foramen magnum. Proposed to be vestigial, the ligament was absent in 20% of specimens examined by Tubbs et al. and does not possess sufficient integrity to impact even physiological forces of flexion or extension.

The anterior atlantooccipital membrane joins the anterior tubercle of the atlas to the basilar occiput and is continuous with the articular joint capsules. It contributes little, if at all, to the stability of the CVJ.

Ligaments of the Combined CVJ
Several extrinsic ligaments promote stability but do not contribute unique mechanics to the motion of the CVJ and will not be discussed, including the anterior longitudinal ligament, the ligamentum flavum of C1–2, and the nuchal ligament. Lateral to the spinal cord, the atlantoaxial and occipitoatlantal articulations occur at synovial joints, the capsules of which are composed of ligamentous fibers. The joint capsules proceed anteriorly along the occipital condyles of the occipitoatlantal junction and the paired zygapophysial facets of the atlantoaxial joint, joining ventrally to the anterior atlantooccipital membrane.

The accessory atlantoaxial ligaments circumscribe the anterolateral vertebral canal bilaterally, proceeding from the medial ring of C-2 to the medial ring of the foramen magnum. For this reason, this ligament has been proposed to be named the accessory atlantoaxialoccipital ligament. The accessory atlantoaxial ligament is maximally tense during contralateral rotation and flexion of the cranium, but CVJ instability does not result from its disruption.

Nerve Routes
The CVJ houses the transition from the brainstem to the spinal cord. The major concern of instability in the CVJ is stenotic injury to the spinal cord and its derivatives. The C-1 nerve exits superior to the atlas, by route of a groove in the posterior ring formed by the elevation of the superior articular surface. The vertebral artery shares this groove, the roof of which is formed by the posterior occipitoatlantal ligament. The C-2 nerve similarly exits posterior to the superior articular facet of the axis but more laterally than C-1. Distal branches of the C-2 and C-3 nerve roots course superiorly and medially, passing superficial to the posterior CVJ as the greater, lesser, and third occipital nerves.

Rennie et al. charted the origins and pathways of the upper cervical sinuvertebral nerves by microdissection.

The C2–3 sinuvertebral nerves mediate pain sensation from the CVJ's ligaments, soft tissues, and dura mater. C-1 also contributes sensation to a small degree at the atlanto-occipital joint.

Vascular Supply
Arising from the subclavian artery, the bilateral vertebral arteries progress cephalad via the transverse foramina of the cervical spine. After exiting the transverse foramina of C-1, the vertebral arteries course along the superior surface of the posterior ring of the atlas before turning ventrally to puncture the atlantooccipital membrane medial to the superior articular facet.

Blood supply to the CVJ is accomplished by extensions of the vertebral artery from the subaxial spine. The anterior and posterior ascending arteries branch from the vertebral artery at C2–3, entering the vertebral column and giving supply to the axis before anastomosing to form the apical odontoid arcade that supplies the atlas and dens. The occipital artery completes the superior portion of the arcade with minor contributions from arteries of the skull base.

Physiological Biomechanics
The occipitoatlantal junction contributes 23°–24.5° of flexion/extension of the skull and the atlantoaxial joint provides an additional 10.1°–22.4°. At the occipitoatlantal junction, the abutment of the dens against the foramen magnum prevents supraphysiological flexion, whereas odontoid contact with the tectorial membrane has been proposed to limit extension. The transverse ligament prevents pathological flexion of the atlantoaxial segment while extension is inhibited by the bony elements of the atlantoaxial joint facets.

Physiological motion of the cervical spine can accomplish 90° of rotation from the midline. The atlantoaxial junction contributes 25°–30°, at which point the motion occurs through subaxial segments. Atlantoaxial rotation of more than 30° can cause stretching and kinking of the contralateral vertebral artery. Acute rotation of more than 45° may occlude the ipsilateral vertebral artery. The bone facets of the atlantoaxial junction will permit up to 40° rotation before locking, contributing a major restriction to overrotation. The contralateral alar ligament and the ipsilateral transverse ligament also resist pathological rotation with support from the joint capsules of the occipitoatlantal and atlantoaxial junctions.

The occipital condyles restrict lateral bending of the occipitoatlantal junction to 3.4°–5.5° in either direction. The atlantoaxial segment reaches 6.7° before the alar ligaments discourage further motion.

Movement in the other planes of motion is minimal at the CVJ, including translation, distraction, and compression. Ligamentous as well as osseous structures are responsible for this stability. The transverse ligament, alar ligaments, and capsular joints resist anterior translation in the sagittal plane while the occipital condyles and the contact of the dens with the atlas and foramen magnum constitute bone barriers against posterior translation.
to axial zygapophysial joints resist compression. Distraction is not a physiological motion of the CVJ (Table 1).

**Biomechanics of Simple CVJ Pathology**

In response to trauma, the CVJ exhibits predictable patterns of failure based on the mechanism of injury. The most commonly encountered traumas occur during motor vehicle accidents, falls, diving accidents, and gunshot wounds. Fracture-dislocation or occipitocervical dissociation at the CVJ is a leading cause of death in motor vehicle accidents. Multiple mechanisms have been proposed to explain these patterns, such as whiplash and flexion-distraction injury. We will discuss supraphysiological motion in the cardinal motions of the CVJ, which can be consolidated into an understanding of more complex models of spinal insult.

Pathological flexion increases tension on the transverse ligament, resulting in failure of either the cruciate ligament or the odontoid waist. Ruptures of the cruciate ligament can be further classified as ligamentous disruption versus avulsion of the atlantal tubercle. During in vitro testing, the cruciate ligament was found to be so taut that catastrophic failure occurs upon any tear, described as the “all or none” phenomenon. Failure of the tectorial membrane has also been associated with flexion in front-end motor vehicle collisions and may lead to dural tears, as the superior-most aspect is continuous with the dura. Isolated tectorial membrane failure contributes to catastrophic instability in flexion and extension.

Hyperextension may lead to fracture of the atlas at the posterior ring or fracture of the axis at the pars interarticularis or the odontoid. Shearing injury may occur to the ligaments of the anterior CVJ, including the alar ligaments, accessory atlantoaxial ligaments, cruciform ligament, and tectorial membranes.

Supraphysiological rotation at the atlantoaxial junction can predict, or even diagnose, alar ligament disruption. Failure of an alar ligament is most likely to occur near the condylar insertion and introduces instability in rotation and an increase in flexion, extension, and lateral bending. Isolated rupture of the alar ligament is rare but has been associated with hyperflexion paired with rotation in all reported cases. Unfortunately, evaluation of the alar ligaments by MRI is complicated by their size and anatomical conformation. Avulsion of a synovial joint capsule causes a mild increase in rotatory motion; however, a rupture of the joint capsule warrants investigation of the more critical ligaments as it has been associated with disruption of the transverse atlantal and alar ligaments.

Traumatic compression of the CVJ commonly causes osseous pathology at the occipitoatlantal junction, provided that forces are not redirected into flexion, extension, or lateral bending at the cervical spine. Axial loading has been associated with burst fractures of the atlas and with occipital condyle fractures, which can be subclassified into typically stable bone fractures or unstable mixed ligamentous and bone injuries.

When evaluating trauma to the CVJ, current guidelines recommend initial evaluation by CT followed by MRI to assess ligamentous injury. T2-weighted MRI obtained within 72 hours of injury is the preferred modality for diagnosing soft-tissue injury. After 72 hours, decreased tissue edema may lead to overlooked ligamentous damage. Disruption of the ligamentous structures is sufficient to cause instability at the CVJ; additionally, these ligaments are irreparable once torn. The most critical ligaments to evaluate for stability in the CVJ are the transverse ligament of the cruciform complex, the alar ligaments, and the tectorial membrane.

### CVJ Fixation

Due to the complex anatomical nature as well as the significant mobility of the CVJ, fixation of this region remains at times a challenging decision and a difficult execution. A wide variety of fixation methods exist and may include a combination of the following: screws, rods, wires/cables, bone grafts, hooks, or plates. Furthermore, arthrodesis is also a challenge as there is little space and bone surface for sufficient bone grafting.

Fixation of the CVJ to the occiput can be accomplished via small bur holes and wire or a combination of screws and plates, which allows for fixation to the cervical spine through connection of rods or additional plates in the spine. Bur holes with wire are not currently used as often, as the screw/rod/plate constructs have shown to be biomechanically superior in terms of screw pullout strength and stiffness. The screws used in the CVJ are generally a larger diameter than the cervical screws with a smaller pitch and blunt tips to prevent piercing the dura. They can be unicortical or bicortical, but the bicortical screws have been shown to have a higher pullout strength than unicortical screws. The screws may be placed in the midline keel or parasagittally. There is a wide variation in thickness of the occiput bone, and the strength of screw fixation has been shown to be proportional to the bone’s thickness.

In addition, the location of the occiput screws have been biomechanically studied with little effect on the range of motion. Therefore, the location of the screws depends on the individual patient anatomy as well as the type of occipital plates used. For the “T“- or “Y“-shaped plates, the screws are placed along the midline; otherwise, they may be placed parasagittally in line with the cervical screws.

Fixation in the cervical spine can be a combination of a number of methods as well, usually with the intention of connecting to the occiput fixation. The screws used in the cervical spine are generally polyaxial and placed into the lateral masses of the vertebrae. Fixation to C-1 is a bit unique due to the special anatomy of C-1. The two most common forms of C-1 fixation include sublaminar wiring and lateral mass screws. The lateral mass screws offer significant biomechanical stability and pullout strength com-

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**TABLE 1. Physiological ranges of motion at the CVJ**

<table>
<thead>
<tr>
<th>Motion</th>
<th>Oc–C1</th>
<th>C1–2</th>
</tr>
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<tbody>
<tr>
<td>Flexion/extension</td>
<td>23°–24.5°</td>
<td>10.1°–22.4°</td>
</tr>
<tr>
<td>Lateral bending</td>
<td>3.4°–5.5°</td>
<td>6.7°</td>
</tr>
<tr>
<td>Axial rotation</td>
<td>2.4°–7.2°</td>
<td>23.3°–38.9°</td>
</tr>
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pared with the wiring techniques. The C-1 lateral mass screws are long (19.1–25.9 mm), and generally, bicortical purchase is recommended. One very important consideration when placing C-1 lateral mass screws is the location of the internal carotid arteries. The arteries are located very close to the C-1 lateral masses and when using bicortical purchase, the risk of arterial injury on one side is 46% according to a study.9

Fixation to C-2 can be similar to C-1, but again, there are anatomical differences to consider. Sublaminar wires can also be placed. Regarding the screw options, C-2 pars interarticularis screws can be used, but bicortical purchase is generally not used in an attempt avoid a possible aberrant vertebral artery (Fig. 4). Unlike C-1, C-2 has anatomical pedicles allowing for a second option for screw placement. The C-2 pedicle screws can be placed similar to the technique used for the lumbar spine, but much more care needs to be taken due to the smaller size of the pedicles. Recently, a third option for C-2 screw placement includes intralaminar or translaminar screws (Fig. 5). These screws are placed near the spinous process of C-2 and are placed along the lamina. Biomechanically, both pedicle and intralaminar screw placement are similar.

Occipitoatlantal Segment (Oc–C1)

Generally, the occipitoatlantal segment is not fixated alone due to the large moment arm created by the cranium on C-1. However, there are situations in which the occiput and atlas can be fixated using the above listed devices, usually due to isolated instability. The first situation can be bone and wire techniques to simultaneously restrict the motion of this segment and provide a bone graft. These techniques are simple with low morbidity. They involve small bur holes in the occiput, through which wire can be passed and connected to the lamina of the atlas. A bone graft is placed between the posterior arch of C-1 and the base of the occiput. Fusion rates have been reported up to 89%, but the construct is not immediately stable, and patients are required to remain in a halo for 12 weeks.

Another option involves the use of transarticular screws. Similar to the above construct, this is usually reserved for isolated Oc–C1 instability and is not easily incorporated into multisegment constructs. Self-tapping lag screws are placed into the lateral masses of C-1 that travel up to the occipital condyles. Biomechanically, this technique increases stiffness in rotation but is poor in flexion-extension. Thus, this technique should be used in conjunction with supplemental fixation to allow for sufficient stability.

Occiput to Atlantoaxial Segment (Oc–C2)

The occiput to atlantoaxial region is classically difficult to fixate as both the occipitoatlantal and atlantoaxial segments are highly mobile in flexion and extension, and additionally the atlantoaxial segment is very mobile in axial rotation. Any number of combinations of the previously mentioned techniques can be used. Occipitocervical fixation constructs consist of points of fixation along the occiput, C-1, and C-2, with connection to some type of longitudinal element. These longitudinal elements span the segments in the CVJ and allow them to be rigidly fixated.

Since the primary motion of the occipitoatlantal segment is flexion-extension, screw-based constructs that incorporate C-2 are necessary. Biomechanically, Hurlbert et al. found that only constructs with screw fixation of C-2 in addition to C-1 had greater stiffness in flexion-extension when compared with normal motion segments. This is further evidence that the occipitoatlantal segment is in-
adequate to fully stabilize this joint in flexion-extension without added support.

Similarly, as the dominant motion of the atlantoaxial segment is axial rotation, specific techniques for rigid fixation need to take this into account. Screw constructs have been shown to be biomechanically superior to wiring techniques and include C-1 lateral mass screws with C-2 pedicle screws, or C1–2 transarticular screws. One may also use a construct with C-1 lateral mass screws and C-2 transaminar screws, but they have been shown to not have equivalent stiffness.

To develop a strong CVJ construct, the longitudinal elements should be able to have multiple points of fixation along the junction, interface with all of the fixation points, have the ability to interface with the thickest regions of bone in the suboccipital region, and have the ability to be crosslinked. Various types of longitudinal elements are available and may include rods, structural bone grafts, reconstruction plates, and hybrid devices combining plates and rods in preformed shapes. As with all spinal instrumentation, it is critical to choose the type of longitudinal element that best suits the individual patient’s needs based on the goal of surgery and the patient’s anatomy.

From a biomechanical perspective, constructs that include wiring techniques coupled to rods have been shown to loosen with cyclic loading. With loosening, the wires slide along the rods, ultimately causing a loss of rigidity. Screw-based constructs offer more support and are resistant to this type of scenario. It is important to note, however, that polyaxial screws tend to be subject to backout and uneven loading of the fixation points. These polyaxial screws are generally interfaced with plates. Screws that interface with rods usually have solid, immovable heads and spread the loads more evenly over the fixation points.

Conclusions

The CVJ possesses unique anatomical and biomechanical properties that distinguish it from the subaxial spine. These specializations allow for large degrees of motion while maintaining stability but present unique challenges to fixation. While well characterized, the value of new surgical approaches and fixation methods in the CVJ encourage further study of the anatomy and biomechanics of this region.

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