Anatomy and biomechanics of the craniovertebral junction

Alejandro J. Lopez, BS,¹ Justin K. Scheer, BS,¹ Kayla E. Leibl, BS,¹ Zachary A. Smith, MD,¹ Brian J. Dlouhy, MD,² and Nader S. Dahdaleh, MD¹

¹Department of Neurological Surgery, Northwestern University, Feinberg School of Medicine, Chicago, Illinois; and ²Department of Neurological Surgery, The University of Iowa, Carver School of Medicine, Iowa City, Iowa

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.

<http://thejns.org/doi/abs/10.3171/2015.1.FOCUS14807>

KEY WORDS craniovertebral junction; occipitocervical; spine; biomechanics; anatomy; fixation

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.⁶³ 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.^{44,53,64} 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 oc-

cipital 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.⁴⁷

The foramen magnum 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.^{5,23}

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 condyle⁴⁰ (Figs. 1 and 2).

The posterior atlantooccipital membrane joins the pos-

ABBREVIATION CVJ = craniovertebral junction; Oc = occiput.

SUBMITTED November 30, 2014. **ACCEPTED** January 29, 2015.

INCLUDE WHEN CITING DOI: 10.3171/2015.1.FOCUS14807.

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

FIG. 1. Posterior view of the CVJ after resection of the tectorial membrane. Copyright Nader S. Dahdaleh. Published with permission.

terior arch of the atlas to the occiput by entering the foramen magnum and attaching posteriorly to the squamous occipital bone that constitutes the posterior ring of the foramen magnum.⁴⁸ 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 stability of the CVJ.^{29,34,35}

Ceylan et al. analyzed the denticulate ligaments of the spinal column and found regional differences.⁴ The cervical 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.^{8,61} The odontoid process and horizontal facets permit rotation of the skull, the predominate 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 bounding the dens posteriorly.⁴³ Inferior and superior crura arise from the transverse ligament as it crosses the dens, attaching 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 cranium. The alar ligaments are also critical to maintaining stability at the CVJ^{6,15} (Fig. 1).

FIG. 2. A midsagittal section of the CVJ. Copyright Nader S. Dahdaleh. Published with permission.

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^{54,57,62,63} (Fig. 2).

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.⁵⁶

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.³⁴

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.¹⁰ 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 articulation, 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 renamed the accessory atlantoaxialoccipital ligament.¹² The accessory atlantoaxial ligament is maximally tense during contralateral rotation and flexion of the cranium, but CVJ instability does not result from its disruption.⁵⁸

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.⁴⁶

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 atlantooccipital 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.^{38,45,52}

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°.⁴⁴ 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.^{14,15,20}

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.⁵³ 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.⁶⁴ 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.^{13,33}

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.⁴⁴

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.^{13,17,20,64} The capsular joints of the occipital condyles and the atlanto-

toaxial zygapophysial joints resist compression.⁶⁴ 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.¹⁰ The most commonly encountered traumas occur during motor vehicle accidents, falls, diving accidents, and gunshot wounds.⁶ Fracture-dislocation or occipitocervical dissociation at the CVJ is a leading cause of death in motor vehicle accidents.⁶ 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.⁶ Ruptures of the cruciate ligament can be further classified as ligamentous disruption versus avulsion of the atlantal tubercle.^{11,12,24} 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.^{10,12,31} Failure of the tectorial membrane has also been associated with flexion in front-end motor vehicle collisions³⁵ and may lead to dural tears, as the superior-most aspect is continuous with the dura.^{10,16} Isolated tectorial membrane failure contributes minor instability in flexion and extension.^{29,42,62}

Hyperextension may lead to fracture of the atlas at the posterior ring or fracture of the axis at the pars interarticularis or the odontoid.² 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.⁶ Failure of an alar ligament is most likely to occur near the condylar insertion⁵¹ and introduces instability in rotation and an increase in flexion, extension, and lateral bending.¹⁵ Isolated rupture of the alar ligament is rare but has been associated with hyperflexion paired with rotation in all reported cases.⁶⁵ Unfortunately, evaluation of the alar ligaments by MRI is complicated by their size and anatomical conformation.^{3,50} Avulsion of a synovial joint capsule causes only a mild increase in rotatory motion;⁸ 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.³¹

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.^{37,55,59}

When evaluating trauma to the CVJ, current guidelines recommend initial evaluation by CT followed by MRI to assess ligamentous injury.⁷ T2-weighted MRI obtained

TABLE 1. Physiological ranges of motion at the CVJ

Motion	Oc–C1	C1–2
Flexion/extension	23°–24.5°	10.1°–22.4°
Lateral bending	3.4°–5.5°	6.7°
Axial rotation	2.4°–7.2°	23.3°–38.9°

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.³⁹ Disruption of the ligamentous structures is sufficient to cause instability at the CVJ; additionally, these ligaments are irreparable once torn.¹⁹ 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.^{15,30,35,51}

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.^{38,54} 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.^{26,32,41} 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.¹ 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.⁴⁹ In addition, the location of the occiput screws have been biomechanically studied with little effect on the range of motion.¹ 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 screws¹ (Fig. 3).

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-

FIG. 3. Images obtained in a 30-year-old patient with chronic atlantoaxial rotatory subluxation. **A:** Lateral radiograph showing occipitocervical fusion using an occipital plate, C-2 pars interarticularis screws, and subaxial lateral mass screws. **B and C:** Note the bicortical occipital screws on the sagittal (B) and coronal (C) CT reconstructions.

pared with the wiring techniques.^{10,54} The C-1 lateral mass screws are long (19.1–25.9 mm), and generally, bicortical purchase is recommended.^{28,64} (Fig. 4). 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 1 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 artery⁶⁴ (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.^{22,36}

Occipitoatlantal Segment (Oc–C1)

Generally, the occipitoatlantal segment is not fixated alone due to the large moment arm created by the cranium on C-1.⁵⁴ 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.⁶⁴ These techniques are simple with low morbidity.⁶⁰ 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 in 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.⁶⁰

Another option involves the use of transarticular screws.^{21,25,64} 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.²⁵ Biomechanically, this technique increases stiffness in rotation but is poor in flexion-extension.²¹ 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.³² This is further evidence that the occipitoatlantal segment is in-

FIG. 4. Images from a 50-year-old patient with a C-2 Type II odontoid fracture. **A:** Lateral radiograph showing atlantoaxial fusion. **B:** Note the C-1 lateral mass screw trajectory and C-2 pars interarticularis following sagittal CT reconstruction. **C and D:** Note the bicortical C-1 lateral mass screw trajectory on the axial CT reconstruction (C) as well as the C-2 pars interarticularis screw trajectory (D).

FIG. 5. Images obtained in a patient with a complex combined C-1 and C-2 fracture. **A and B:** Lateral (A) and anteroposterior (B) radiographs showing C-1 to C-4 posterior fusion utilizing C-1 lateral mass screws and C-2 translaminal screws. **C:** Note the translaminal C-2 screw trajectory on the axial CT reconstruction.

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.^{25,27,38} One may also use a construct with C-1 lateral mass screws and C-2 translaminal screws, but they have been shown to not have equivalent stiffness.¹⁸

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.⁶⁴ 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.³² 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.³² It is important to note, however, that polyaxial screws tend to be subject to backout and uneven loading of the fixation points.⁶⁴ 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.⁶⁴

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.

References

- Anderson PA, Oza AL, Puschak TJ, Sasso R: Biomechanics of occipitocervical fixation. *Spine (Phila Pa 1976)* **31**:755–761, 2006
- Beckner MA, Heggeness MH, Doherty BJ: A biomechanical study of Jefferson fractures. *Spine (Phila Pa 1976)* **23**:1832–1836, 1998
- Borchgrevink G, Smevik O, Haave I, Haraldseth O, Nordby A, Lereim I: MRI of cerebrum and cervical column within two days after whiplash neck sprain injury. *Injury* **28**:331–335, 1997
- Ceylan D, Tatarlı N, Abdullaev T, Seker A, Yıldız SD, Keleş E, et al: The denticulate ligament: anatomical properties, functional and clinical significance. *Acta Neurochir (Wien)* **154**:1229–1234, 2012
- Chethan P, Prakash KG, Murlimanju BV, Prashanth KU, Prabhu LV, Saralaya VV, et al: Morphological analysis and morphometry of the foramen magnum: an anatomical investigation. *Turk Neurosurg* **22**:416–419, 2012
- Clark CR, White AA III: Fractures of the dens. A multicenter study. *J Bone Joint Surg Am* **67**:1340–1348, 1985
- Como JJ, Diaz JJ, Dunham CM, Chiu WC, Duane TM, Cappella JM, et al: Practice management guidelines for identification of cervical spine injuries following trauma: update from the Eastern Association for the Surgery of Trauma Practice Management Guidelines Committee. *J Trauma* **67**: 651–659, 2009
- Crisco JJ III, Oda T, Panjabi MM, Bueff HU, Dvorák J, Grob D: Transections of the C1–C2 joint capsular ligaments in the cadaveric spine. *Spine (Phila Pa 1976)* **16** (10 Suppl):S474–S479, 1991
- Currier BL, Maus TP, Eck JC, Larson DR, Yaszemski MJ: Relationship of the internal carotid artery to the anterior aspect of the C1 vertebra: implications for C1–C2 transarticular and C1 lateral mass fixation. *Spine (Phila Pa 1976)* **33**:635–639, 2008
- Debernardi A, D'Aliberti G, Talamonti G, Villa F, Piparo M, Collice M: The craniovertebral junction area and the role of the ligaments and membranes. *Neurosurgery* **68**:291–301, 2011
- Dickman CA, Sonntag VK: Injuries involving the transverse atlantal ligament: classification and treatment guidelines based upon experience with 39 injuries. *Neurosurgery* **40**:886–887, 1997
- Dickman CA, Spetzler RF, Sonntag VKH (eds): *Surgery of the Craniovertebral Junction*. New York: Thieme, 1998
- Dvorak J, Panjabi MM: Functional anatomy of the alar ligaments. *Spine (Phila Pa 1976)* **12**:183–189, 1987
- Dvorak J, Panjabi MM, Novotny JE, Antinnes JA: In vivo flexion/extension of the normal cervical spine. *J Orthop Res* **9**:828–834, 1991

15. Dvorak J, Schneider E, Saldinger P, Rahn B: Biomechanics of the craniocervical region: the alar and transverse ligaments. **J Orthop Res** 6:452–461, 1988
16. Farley FA, Gebarški SS, Garton HL: Tectorial membrane injuries in children. **J Spinal Disord Tech** 18:136–138, 2005
17. Fielding JW, Cochran Gv, Lawsing JF III, Hohl M: Tears of the transverse ligament of the atlas. A clinical and biomechanical study. **J Bone Joint Surg Am** 56:1683–1691, 1974
18. Finn MA, Fassett DR, Mccall TD, Clark R, Dailey AT, Brodke DS: The cervical end of an occipitocervical fusion: a biomechanical evaluation of 3 constructs. Laboratory investigation. **J Neurosurg Spine** 9:296–300, 2008
19. Frank C, Amiel D, Woo SL, Akeson W: Normal ligament properties and ligament healing. **Clin Orthop Relat Res** (196):15–25, 1985
20. Ghanayem AJ, Zdeblich TA, Dvorak J: Functional anatomy of joints, ligaments, and discs, in Clark CR, Ducker TB, Cervical Spine Research Society Editorial Committee (eds): **The Cervical Spine**, ed 3. Philadelphia: Lippincott-Raven, 1998, pp 45–52
21. Gonzalez LF, Crawford NR, Chamberlain RH, Perez Garza LE, Preul MC, Sonntag VKH, et al: Craniovertebral junction fixation with transarticular screws: biomechanical analysis of a novel technique. **J Neurosurg** 98 (2 Suppl):202–209, 2003
22. Gorek J, Acaroglu E, Berven S, Yousef A, Puttlitz CM: Constructs incorporating intralaminar C2 screws provide rigid stability for atlantoaxial fixation. **Spine (Phila Pa 1976)** 30:1513–1518, 2005
23. Govsa F, Ozer MA, Celik S, Ozmutaf NM: Three-dimensional anatomic landmarks of the foramen magnum for the craniovertebral junction. **J Craniofac Surg** 22:1073–1076, 2011
24. Greene KA, Dickman CA, Marciano FF, Drabier J, Drayer BP, Sonntag VK: Transverse atlantal ligament disruption associated with odontoid fractures. **Spine (Phila Pa 1976)** 19:2307–2314, 1994
25. Grob D: Transarticular screw fixation for atlanto-occipital dislocation. **Spine (Phila Pa 1976)** 26:703–707, 2001
26. Maher TR, Yeung AW, Caruso SA, Merola AA, Shin T, Zipnick RI, et al: Occipital screw pullout strength. A biomechanical investigation of occipital morphology. **Spine (Phila Pa 1976)** 24:5–9, 1999
27. Hanson PB, Montesano PX, Sharkey NA, Rauschnig W: Anatomic and biomechanical assessment of transarticular screw fixation for atlantoaxial instability. **Spine (Phila Pa 1976)** 16:1141–1145, 1991
28. Harms J, Melcher RP: Posterior C1-C2 fusion with polyaxial screw and rod fixation. **Spine (Phila Pa 1976)** 26:2467–2471, 2001
29. Harris MB, Duval MJ, Davis JA Jr, Bernini PM: Anatomical and roentgenographic features of atlantooccipital instability. **J Spinal Disord** 6:5–10, 1993
30. Heller JG, Amrani J, Hutton WC: Transverse ligament failure: a biomechanical study. **J Spinal Disord** 6:162–165, 1993
31. Hodak JA, Mamourian A, Dean BL: Radiologic evaluation of the craniovertebral junction, in Dickman CA, Spetzler RF, Sonntag VKH (eds): **Surgery of the Craniovertebral Junction**. New York: Thieme, 1998, pp 81–102
32. Hurlbert RJ, Crawford NR, Choi WG, Dickman CA: A biomechanical evaluation of occipitocervical instrumentation: screw compared with wire fixation. **J Neurosurg** 90 (1 Suppl):84–90, 1999
33. Iai H, Moriya H, Goto S, Takahashi K, Yamagata M, Tamaki T: Three-dimensional motion analysis of the upper cervical spine during axial rotation. **Spine (Phila Pa 1976)** 18:2388–2392, 1993
34. Jea A, Tatsui C, Farhat H, Vanni S, Levi AD: Vertically unstable type III odontoid fractures: case report. **Neurosurgery** 58:E797, 2006
35. Krakenes J, Kaale BR, Moen G, Nordli H, Gilhus NE, Rorvik J: MRI of the tectorial and posterior atlanto-occipital membranes in the late stage of whiplash injury. **Neuroradiology** 45:585–591, 2003
36. Lehman RA Jr, Dmitriev AE, Wilson KW: Biomechanical analysis of the C2 intralaminar fixation technique using a cross-link and offset connector for an unstable atlantoaxial joint. **Spine J** 12:151–156, 2012
37. Levine AM, Edwards CC: Fractures of the atlas. **J Bone Joint Surg Am** 73:680–691, 1991
38. Menezes AH, Traynelis VC: Anatomy and biomechanics of normal craniovertebral junction (a) and biomechanics of stabilization (b). **Childs Nerv Syst** 24:1091–1100, 2008
39. Mirvis SE, Shanmuganathan K: Trauma radiology: Part V. Imaging of acute cervical spine trauma. **J Intensive Care Med** 10:15–33, 1995
40. Muthukumar N, Swaminathan R, Venkatesh G, Bhanumathy SP: A morphometric analysis of the foramen magnum region as it relates to the transcondylar approach. **Acta Neurochir (Wien)** 147:889–895, 2005
41. Oda I, Abumi K, Sell LC, Haggerty CJ, Cunningham BW, McAfee PC: Biomechanical evaluation of five different occipito-atlanto-axial fixation techniques. **Spine (Phila Pa 1976)** 24:2377–2382, 1999
42. Oda T, Panjabi MM, Crisco JJ III, Oxland TR: Multidirectional instabilities of experimental burst fractures of the atlas. **Spine (Phila Pa 1976)** 17:1285–1290, 1992
43. Oda T, Panjabi MM, Crisco JJ III, Oxland TR, Katz L, Nolte LP: Experimental study of atlas injuries. II. Relevance to clinical diagnosis and treatment. **Spine (Phila Pa 1976)** 16 (10 Suppl):S466–S473, 1991
44. Panjabi M, Dvorak J, Duranceau J, Yamamoto I, Gerber M, Rauschnig W, et al: Three-dimensional movements of the upper cervical spine. **Spine (Phila Pa 1976)** 13:726–730, 1988
45. Parke WW: The vascular relations of the upper cervical vertebrae. **Orthop Clin North Am** 9:879–889, 1978
46. Rennie C, Haffajee MR, Ebrahim MA: The sinuvertebral nerves at the craniovertebral junction: a microdissection study. **Clin Anat** 26:357–366, 2013
47. Rhoton AL Jr: The foramen magnum. **Neurosurgery** 47 (3 Suppl):S155–S193, 2000
48. Rhoton AL Jr, de Oliveira E: Anatomical basis of surgical approaches to the region of the foramen magnum, in Dickman CA, Spetzler RF, Sonntag VKH (eds): **Surgery of the Craniovertebral Junction**. New York: Thieme, 1998, pp 13–57
49. Roberts DA, Doherty BJ, Heggeness MH: Quantitative anatomy of the occiput and the biomechanics of occipital screw fixation. **Spine (Phila Pa 1976)** 23:1100–1108, 1998
50. Ronnen HR, de Korte PJ, Brink PR, van der Bijl HJ, Tonino AJ, Franke CL: Acute whiplash injury: is there a role for MR imaging?—a prospective study of 100 patients. **Radiology** 201:93–96, 1996
51. Saldinger P, Dvorak J, Rahn BA, Perren SM: Histology of the alar and transverse ligaments. **Spine (Phila Pa 1976)** 15:257–261, 1990
52. Schiff DC, Parke WW: The arterial supply of the odontoid process. **J Bone Joint Surg Am** 55:1450–1456, 1973
53. Selecki BR: The effects of rotation of the atlas on the axis: experimental work. **Med J Aust** 1:1012–1015, 1969
54. Steinmetz MP, Mroz TE, Benzel EC: Craniovertebral junction: biomechanical considerations. **Neurosurgery** 66 (3 Suppl):7–12, 2010
55. Theodore N, Aarabi B, Dhall SS, Gelb DE, Hurlbert RJ, Rozzelle CJ, et al: Occipital condyle fractures. **Neurosurgery** 72 (Suppl 2):106–113, 2013
56. Tubbs RS, Grabb P, Spooner A, Wilson W, Oakes WJ: The apical ligament: anatomy and functional significance. **J Neurosurg** 92 (2 Suppl):197–200, 2000

57. Tubbs RS, Kelly DR, Humphrey ER, Chua GD, Shoja MM, Salter EG, et al: The tectorial membrane: anatomical, biomechanical, and histological analysis. **Clin Anat** **20**:382–386, 2007
58. Tubbs RS, Salter EG, Oakes WJ: The accessory atlantoaxial ligament. **Neurosurgery** **55**:400–404, 2004
59. Tuli S, Tator CH, Fehlings MG, Mackay M: Occipital condyle fractures. **Neurosurgery** **41**:368–377, 1997
60. Vender JR, Rekito AJ, Harrison SJ, McDonnell DE: The evolution of posterior cervical and occipitocervical fusion and instrumentation. **Neurosurg Focus** **16**(1):E9, 2004
61. VonTorklus D, Gehle W: **The Upper Cervical Spine. Regional Anatomy, Pathology, and Traumatology. A Systemic Radiological Atlas and Textbook.** New York: Grune & Stratton, 1972
62. Werne S: Studies in spontaneous atlas dislocation. **Acta Orthop Scand Suppl** **23**:1–150, 1957
63. White AA III, Panjabi MM: The clinical biomechanics of the occipitoatlantoaxial complex. **Orthop Clin North Am** **9**: 867–878, 1978
64. Wolfla CE: Anatomical, biomechanical, and practical considerations in posterior occipitocervical instrumentation. **Spine J** **6** (6 Suppl):225S–232S, 2006
65. Wong ST, Ernest K, Fan G, Zovickian J, Pang D: Isolated unilateral rupture of the alar ligament. **J Neurosurg Pediatr** **13**:541–547, 2014

Author Contributions

Conception and design: Dahdaleh, Lopez, Scheer. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Dahdaleh. Administrative/technical/material support: Dahdaleh. Study supervision: Dahdaleh.

Correspondence

Nader S. Dahdaleh, Department of Neurological Surgery, Northwestern University, Feinberg School of Medicine, 676 N. St. Clair St., Ste. 2210, Chicago, IL 60611. email: nader.dahdaleh@northwestern.edu.