Ligaments of the craniocervical junction

A review

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The specialized ligaments of the craniocervical junction must allow for stability yet functional movement. Because injury to these important structures usually results in death or morbidity, the neurosurgeon should possess a thorough understanding of the anatomy and function of these ligaments. To the authors’ knowledge, a comprehensive review of these structures is not available in the medical literature. The aim of the current study was to distill the available literature on each of these structures into one offering. (DOI: 10.3171/2011.1.SPINE10612)

Key Words • anatomy • skull base • neurosurgery • craniocervical junction • craniovertebral junction • ligaments

The CCJ contains the complex transition from the skull to the spine. It is composed of 2 joints—the atlantooccipital and the atlantoaxial joints—and houses the spinal cord, multiple cranial nerves, and many important blood and lymphatic vessels that supply the head and neck.44,45,66 This CCJ must protect its contents while simultaneously allowing significant mobility. The 2 most prominent and arguably the most important ligaments of the CCJ are the transverse and alar ligaments. These ligaments have been the focus of much study, but the other accessory ligaments of the CCJ have been vastly ignored and are absent in many textbooks dedicated to this topic.70–76 The reason for this may be the detailed dissection needed to view the ligaments or the lack of knowledge about the ligaments’ morphology. Regardless of the reason, it is important to study these small ligaments to better understand the CCJ and complications that arise from injury to the area. In the present article, we review the literature on the accessory ligaments and membranes focusing on the anatomy, biomechanics, pathology, radiology, and surgical aspects of each. Search engines such as PubMed and various germane textbooks were used, searching for salient chapters and terms such as the following: ligaments, neck, occipital, atlas, axis, connective tissues, anatomy, biomechanics, pathology, C-1, C-2, membrane, craniocervical junction, and craniovertebral junction.

Biomechanics of CCJ

The CCJ is composed of 2 major joints: the atlantooccipital and the atlantoaxial joints. These joints are responsible for the majority of the movement of the cervical spine and operate on different biomechanical principles. The mechanical properties of the atlantooccipital joint are primarily determined by bony structures, whereas the mechanical properties of the atlantoaxial joint are mainly determined by ligamentous structures.57,86 The prominent movements at the atlantooccipital joint are flexion and extension. The various movements at this joint occur because the condyles glide in the sockets of the atlas.44 Panjabi et al.55 found the atlantooccipital joint to be responsible for 27.1° of flexion and 24.9° of extension. They also noted that about 8° of axial rotation can take place at this joint, as well as minimal lateral and axial rotation and anteroposterior translation.41,50 Steinmetz et al.62 reported similar values, with a mean movement of 23°–24.5° of flexion/extension, whereas axial rotation was limited to 2.4°–7.2°. They reported that flexion was limited by impingement of the odontoid process on the foramen magnum, and extension was restricted by the

Abbreviations used in this paper: AAO = anterior atlantooccipital; CCJ = craniocervical junction; LAO = lateral atlantooccipital; PAO = posterior atlantooccipital; TOL = transverse occipital ligament; VA = vertebral artery.
tectorial membrane. Lateral flexion is strongly inhibited at the atlantooccipital joint by the contralateral alar ligament.8,10,15,21,39,44,67

The primary movement at the atlantoaxial joint is axial rotation. Steinmetz et al.67 reported that the mean axial rotational movement was between 23.3° and 38.9°. Menezes and Traynelis44 noted that axial rotation beyond 30°–35° can cause VA occlusion. Flexion and extension at the atlantoaxial joint range from 10.1° to 22.4° and are limited by the transverse ligament and tectorial membrane, respectively. Lateral bending is restricted to 6.7° by the contralateral alar ligament, and some very minimal anteroposterior translation may occur at this joint.50,56

Although these 2 joints function differently, they must act in unison to ensure optimal stability and mobility at the CCJ.

**Transverse Ligament**

**Anatomy**

The transverse ligament of the atlas is the key component of the cruciform ligament and is one of the most important ligaments in the body (Figs. 1 and 2). It is the largest, strongest, and thickest craniovertebral ligament (mean height/thickness 6–7 mm).11 The superior and inferior limbs of the cruciform ligament are extremely thin and offer no known craniovertebral stability. The transverse ligament maintains stability at the CCJ by locking the odontoid process anteriorly against the posterior aspect of the anterior arch of C-1, and it divides the ring of the atlas into 2 compartments: the anterior compartment houses the odontoid process, and the posterior compartment contains primarily the spinal cord and spinal accessory nerves. The transverse ligament runs posterior to the odontoid process of C-2 and attaches to the lateral tubercles of the atlas bilaterally. A synovial capsule is located between the odontoid process and the transverse ligament. The ligament also has a smooth fibrocartilaginous surface to allow the odontoid process to glide against it. The tectorial membrane, epidural fat, and dura mater are located dorsal to the transverse ligament.11 A previous quantitative anatomical study conducted by Tubbs et al.66 examined 50 dried adult C-1 vertebrae to determine dimensions of the transverse ligament tubercles. They found that all specimens contained single bilateral tubercles with similar dimensions on the left and right sides. The tubercles had a mean width and height of 5 and 6 mm, respectively. The intertubercular distance ranged from 14 mm to 16.5 mm (mean 15.2 mm).

**Biomechanics**

The transverse ligament is the major stabilizing ligament at the atlantoaxial joint. The atlantoaxial joint is responsible for about 47° of rotation at the neck. The transverse ligament permits rotation to occur while the alar ligaments prevent excessive rotation.8,11,12 Fielding et al.21 conducted a study to test the biomechanics of the transverse ligament and other atlantoaxial ligaments. They found that the transverse ligament was most vulnerable to rupture under either rapid or slow loading forces. Tears in the ligament can occur centrally or lateral at the bony tubercle where the ligament attaches to the atlas.11 The biomechanical data reported by Fielding et al. demonstrated that the transverse ligament is the primary defense against anterior subluxation of the atlas on the axis and that it is relatively inelastic, only allowing C-1 to subluxate approximately 3–5 mm before rupturing. They also concluded that the accessory ligaments of the atlantoaxial joints (namely, the alar ligaments) serve as secondary restrictions of the atlas to anterior shift.21

**Alar Ligament**

**Anatomy**

The alar ligament attaches the axis to the base of the skull (Figs. 1 and 2). Although most researchers agree that the ligament attaches to the lateral aspects of the odontoid process, there is some discrepancy as to where it attaches on the skull. Some investigators claim that the cranial attachment is on the anterolateral part of the fora
mer magnum, whereas others believe the attachment is on the medial aspect of the occipital condyles.53,55,70 The ligaments run from the posterolateral aspect of the odontoid process, laterally forming an angle ranging from 125° to 210° with a mean of 154°.36 An MR imaging study conducted by Pfirrmann and colleagues58 found that the alar ligament was oriented caudocranially in about half of the cases and horizontally in the other half. Cattyrsse and associates8 used 3D digitizing stylus technology to further characterize the alar ligament in 20 human cadavers. They found the that mean length and diameter of the alar ligament were 8.8 and 7.3 mm, respectively and that the shape was tubular. These measurements were consistent with the findings of previous studies, but other authors reported the shape of the ligament to be more elliptical or rectangular.57 An MR imaging study of the craniovertebral ligaments conducted by Krakenes et al.35 indicated that the cross-sectional shape of the alar ligament could be round, ovoid, or winglike. Additionally, they reported that the ligament is thicker medially. It was their opinion that variation in cross-sectional shape is important to note because it is a common anatomical variation.

**Biomechanics**

The alar ligaments function as stabilizing structures of the atlantoaxial joint and act to limit axial rotation and lateral bending on the contralateral side.5,10,15,21,39,44,67 They are the only ligaments, except the transverse ligament, that are strong enough to stabilize the CCJ and prevent anterior displacement of the atlas. If the transverse ligament ruptures, the alar ligaments become responsible for preventing atlantal subluxation. Fielding and coworkers21 reported that the alar ligaments alone are not as strong as the transverse ligament. Following the rupture of the transverse ligament, a mean force of 72 kg was needed to stretch the alar ligament to create a predental space of 12 mm, and any subluxation greater that 12 mm caused the alar ligament to rupture. Similarly, Dvorak et al.19 noted that the transverse ligament could withstand a load of 350 N, whereas the alar ligament could only withstand 200 N before rupturing.

The alar ligament limits the axial rotation on the
Contralateral side to about 90°. Damage to this ligament results in further axial rotation, which can result in compression or damage to the VA or the spinal accessory nerves. Alar ligament injury often occurs in motor vehicle collisions and is believed to be a cause of whiplash-associated disorders.

### Transverse Occipital Ligament

**Anatomy**

The TOL is a small accessory ligament of the CCJ that is located posterolateral to the alar ligaments and odontoid process (Figs. 1 and 3). It attaches to the inner aspect of the occipital condyles, posterolateral to the alar ligament, superior to the transverse ligament, and extends horizontally across the foramen magnum. Tubbs et al. have identified the TOL in 7 (77.8%) of 9 human cadavers. The mean width, length, and thickness of the ligament were 3.4, 19.4, and 1.3 mm, respectively. Statistical analysis found no significant difference in the width, length, or thickness based on sex. In 2005, Ackerman and Cooper found the TOL in only 2 bodies (8.3%) of 24 and observed that it was attached to both the odontoid process and the alar ligaments (MJ Ackerman, MH Cooper, unpublished work [presented at the 4th Joint Meeting of the American Association of Clinical Anatomists and the British Association of Clinical Anatomists, 2005]). Dvorak et al. stated that the TOL is only present in about 10% of the population, whereas Lang identified the TOL in approximately 40% of their specimens. The discrepancies in the occurrence of the TOL in specimens could be due to the proximity and similar morphology to the alar ligament. Clinically, the TOL may be encountered during a transoral odontoidectomy.

**Biomechanics**

The TOL is thought to have similar functions to the alar ligaments in helping to stabilize the CCJ. Lang believed the TOL represented the uppermost fibers of the alar ligament that sometimes crossed the midline. However, Tubbs et al. did not consistently find a connection between the TOL and the odontoid process or alar ligaments. When attached to the alar ligament, the possible functions of the TOL include providing additional support in stabilizing lateral bending, flexion, and axial rotation of the head. The TOL may also prevent posterior displacement of the apical ossicles of the odontoid process, as the transverse ligament ends inferior to the apex of the odontoid process.
Accessory Atlantoaxial Ligament

**Anatomy**

The accessory atlantoaxial ligament is an important but often ignored ligament that inserts medially onto the dorsal surface of the axis and courses laterally and superiorly to insert posterior to the transverse ligament on the lateral mass of the atlas (Figs. 1 and 2).\(^6,^8\) Despite its importance, it is neglected by most anatomical texts. Woodburne and Burkel\(^7\) simply stated that this ligament passes from the back of the lateral mass of the atlas downward and medial to the back of the body of the axis. The ligament runs anterior to the tectorial membrane and is sometimes called the “accessory part of the tectorial membrane.”\(^7\) Tubbs et al.\(^4\) studied 10 cadavers to clarify the anatomy and biomechanics of this ligament. Their findings confirmed the presence of the atlantoaxial ligament in all specimens and the ligament as a separate entity from the tectorial membrane. The mean length and width of the ligament were 29 and 5.5 mm, respectively. Interestingly, there was a cephalic extension of this ligament to the occipital bone just posterior to the attachment of the alar ligament. Therefore, this structure may be important for conveying blood supply to the odontoid process.\(^6\) Tubbs et al.\(^4\) suggested that this ligament could more appropriately be named the accessory atlantoaxial-occipital ligament to represent its anatomical attachments.

**Biomechanics**

Although there are no biomechanical studies on the function of the accessory atlantoaxial ligament, several authors think that its functions similarly to the alar ligament in maintaining stability at the CCJ, as well as limiting axial rotation of the head. Tubbs et al.\(^7\) found that axial rotation of the head between 5° and 8° caused maximal tension in the contralateral accessory atlantoaxial ligament. The ligament also resisted flexion maximally between 5° and 10° and was lax in normal extension of the spine. The accessory atlantoaxial ligament coupled with the alar ligament maintained proper atlantal-axial-occipital alignment by forming a halter for the odontoid. The alar ligaments resisted rotation of the atlas and occipital bone in the coronal plane through the apex of the odontoid process, whereas the accessory atlantoaxial ligament resisted this motion again in the coronal plane.\(^2,^4\) Yuksel et al.\(^9\) conducted an imaging study focused on the accessory atlantoaxial ligament and found that the atlantooccipital portion of the ligament connecting the occiput to the atlas was significantly smaller than the atlantoaxial segment, and in some cases, the atlantooccipital segment was asymmetrical. Because of anatomical variation in the ligament, they postulated that the ligament plays a larger role in limiting articulation at the atlantoaxial junction than at the atlantooccipital junction.

Lateral Atlantooccipital Ligament

**Anatomy**

The LAO ligament is another ligament of the CCJ that has been neglected in the literature (Figs. 4 and 5). It runs just lateral to the anterior atlantooccipital membrane, attaching to the anterolateral aspect of the transverse process of the atlas, and inserting onto the jugular process of the occipital bone.\(^5,^9\) This ligament runs immediately posterior to the rectus capitis lateralis muscle and has fibers that extend in the opposite direction to the muscle (that is, muscle runs lateral to medial and ligament runs medial to lateral). Additionally, the LAO ligament relates posteriorly to the VA and anteriorly to the jugular vein as it exits the jugular foramen.\(^5\) Tubbs et al.\(^7\) studied the LAO ligament in 20 human cadavers to elucidate the anatomy and function of the ligament and found the LAO ligament was present bilaterally in all bodies. The mean length, width, and thickness of this ligament were 22, 5, and 2 mm, respectively. The tensile strength of the LAO ligament was found to be 37.5 N. Surgically, the LAO ligament may be encountered during lateral approaches to the CCJ, as the rectus capitis lateralis can be identified using this landmark.\(^6,^5\)

**Biomechanics**

Although no studies have tested the biomechanical function of the LAO ligament, data from Tubbs et al.\(^7\) suggested that the ligament plays a role in limiting lateral flexion of the head. Lateral flexion of the head occurs almost exclusively in the subaxial spine, although Panjabi et al.\(^5\) reported that lateral flexion of the atlantooccipital joint may range from 8° to 40°.\(^5\) The mean tensile strength of 37.5 N is relatively substantial and indicates that this ligament may play a role in maintaining stability at the CCJ. When the LAO ligament was transected in cadavers, Tubbs et al.\(^7\) observed an increase in lateral flexion of the contralateral side of 3°–5°. Additionally,
Craniocervical junction ligaments

the LAO ligament may play a small role in limiting axial rotation of the atlantooccipital joint. Tubbs et al. noted tautness of the LAO ligament on contralateral rotation of the head on the atlas. Dvorak et al.14 reported that axial rotation at the atlantooccipital joint of greater than 5° indicates hypermobility.

**Barkow Ligament**

**Anatomy**

The Barkow ligament is a horizontal band attaching onto the anteromedial aspect of the occipital condyles anterior to the attachment of the alar ligaments (Figs. 6 and 7). This ligament is located just anterior to the superior aspect of the dens with fibers traveling anterior to the alar ligaments, but there is no attachment to these structures. The Barkow ligament has been rarely described. Lang38 depicted the ligament in a drawing but made no mention of its function or significance. Interestingly, Lang showed the ligament attaching onto the internal aspect of the anterior arch of C-1 and then blending with the anterior atlantooccipital membrane as it attaches to the anterior rim of the foramen magnum.70 In a study of occipital condyle fractures, Tuli et al.78 noted that the Barkow ligament is one of the superficial structures that maintain the occipitoatlantoaxial joint. Tubbs et al.70 found the ligament to be present in 12 (92.3%) of 13 cadavers, observing an attachment between the Barkow ligament and the anterior atlantooccipital membrane at the midline in 9 specimens (75%). The mean length, width, and thickness were found to be 2.5, 4, and 3.5 mm, respectively. They also reported the mean tensile strength to be 28 N, and the ligament was found to be smaller than the transverse ligament but having a similar course.

**Biomechanics**

The Barkow ligament may function to support the CCJ, limiting extension of the atlantooccipital joint, and may assist the transverse ligament in containing the odontoid process. Tubbs et al.70 noted that the only movement that caused tautness of the Barkow ligament was extension of the atlantooccipital joint. As the head was extended, the Barkow ligament was stretched against the odontoid process, and therefore, resistance to this movement was provided. Interestingly, the transverse ligament must be intact for the Barkow ligament to function properly. The ligament may inhibit lateral displacement of a unilateral occipital condyle fracture.

**Apical Ligament**

**Anatomy**

The apical ligament, also known as the middle odontoid ligament or suspensory ligament, attaches the tip of the odontoid process to the basion (Fig. 1). The ligament runs in the triangular area between the left and right alar ligaments known as the supraodontoid space (apical cave)28 and travels just posterior to the alar ligaments and just anterior to the superior portion of the cruciform ligament. In an earlier study, Hecker30 found the ligament ranged in length from 10.5 to 11.5 mm and in width from 3 to 5 mm. Panjabi et al.57 later found the length of

![Fig. 4. Anterior drawing noting the jugular foramen (a) and its relationship to the lateral atlantooccipital ligament (b). For reference, note the anterior longitudinal ligament (c) and the rectus capitis lateralis (d).](image)

![Fig. 5. Cadaveric dissection noting the right lateral atlantooccipital (LAO) ligament. Note the jugular foramen (JF) and atlas (C1).](image)
the apical ligament to be 23.5 mm, describing the ligament as broad and fan shaped at its insertion onto the basion. They also reported the ligament as tightly adherent to the overlying tectorial membrane. More recently, Tubbs et al.71 conducted a cadaveric study focusing on the apical ligament and found the mean length and width to be 7.5 and 5.1 mm, respectively. They also observed the ligament to be straight at the midline with no fanning between the attachment points. They did not observe any connection between the alar or cruciform ligaments, or the tectorial membrane. An area between the apical ligament and the superior crus of the cruciform ligament was routinely found to be filled with connective tissue, fat, and a small venous plexus. Interestingly, they found the ligament to be present in only 80% of the cadavers.

Biomechanics

There is discrepancy over the biomechanical function of the apical ligament. Ebraheim et al.16 attributed the stability of the CCJ to the transverse, alar, and apical ligaments. Grabb and colleagues25 added the apical ligament, anterior and posterior atlantooccipital membranes, and the tectorial membrane as crucial elements for providing CCJ stability. Contrary to the aforementioned findings, in their cadaveric study, Tubbs et al.71 observed no significant function of the apical membrane. They found that in 87% of cases, the ligament was lax while the head was in the neutral position and they could not produce any tautness following cranial distraction. This ligament’s lack of function is further supported by the fact that 20% of the specimens were devoid of the ligament, and there were no tubercles on the basion or the odontoid tip that would allow for chronic pulling by the ligament.71 Some claim that the ligament simply represents rudimentary notochord tissue.9,23,30,79

Tectorial Membrane

Anatomy

The tectorial membrane is a thin structure at the CCJ that serves as the posterior border to the supraodontoid
Craniocervical junction ligaments

space\(^2\) (Fig. 8). It runs posterior to the cruciform ligament, and the accessory atlantoaxial ligament runs along its lateral border. The tectorial membrane is composed of 2–3 distinct layers that run the length of the ligament and then fuse together at the posterior longitudinal ligament. The outermost layer is the widest and attaches as far laterally as the hypoglossal canals. The second layer is thicker and runs from the clivus to the body of the axis. A small bursa is often present between the 2 layers over the odontoid process. The third layer is the deepest and is discontinuous as it attaches to the clivus above and then becomes frayed in the area over the odontoid apex. Nerves and vessels often run between the different layers of the tectorial membrane.\(^2\) Descriptions of the tectorial membrane are insufficient and inconsistent with regard to anatomy and function. Some authors have reported that this membrane is an accessory ligament that restricts flexion. Others described it as a primary stabilizer of the CCJ, resisting extension.\(^\text{20,35,79}\) Authors variably described the tectorial membrane as a strong collagenous ligament\(^3\) or a weak band\(^1\) that attaches cranially to the clivus or the anterior aspect of the foramen magnum.\(^4\) One traditional description of the tectorial membrane is as follows: “the membrane tectoria is a broad ligamentous sheet which is attached below to the back of the body of the axis, where it is continuous with the posterior longitudinal ligament. It extends upwards covering the odontoid process and the anterior margin of the foramen magnum, and is attached above to the upper surface of the occipital bone in front of the foramen magnum.” Werne\(^8\) has also described the tectorial membrane as the well-developed superior continuation of the deeper layer of the posterior longitudinal ligament. Tubbs et al.\(^7\) found the tectorial membrane to extend superiorly to the level of the internal auditory meatus, which was approximately at the site of the sphenoooccipital synchondrosis medially and the jugular foramen laterally. The mean length, width, and thickness of this membrane were 6, 3, and 1 mm, respectively. Tubbs et al. also found the tectorial membrane to be in intimate contact with the posterosuperior dura mater and anteriorly with the accessory atlantoaxial and cruciform ligaments. The tectorial membrane firmly adhered to the cranial base and body of the axis but not to the posterior odontoid process.\(^7\) Surgically, the tectorial membrane would be encountered rarely. Procedures in which the inferior clivus or anterior foramen magnum is removed (for example, in chordomas), if extradural in nature, would involve resecting parts of the tectorial membrane.\(^7\)

**Biomechanics**

There are many different arguments as to what function the tectorial membrane plays in maintaining cranio-cervical stability and inhibiting movement of the CCJ. Werne\(^8\) concluded that the tectorial membrane restricts extension at the atlantooccipital joint and flexion/extension at the atlantoaxial joint. Oda et al.\(^2\) however, found that this membrane restricts flexion between the occiput, atlas, and axis and has no limiting effect on extension. Some authors have found that the tectorial membrane plays a substantial role in maintaining stability at the CCJ, especially in limiting flexion.\(^29,34\) Others have concluded that the tectorial membrane limits extension and that transection of the tectorial membrane increases flexion at both the atlantooccipital and atlantoaxial joints.\(^30,57,84\) Krakenes et al.\(^3\) found that, with isolated sectioning of the tectorial membrane, instability was appreciated only in flexion. VanGilder et al.\(^7\) stated that the function of the tectorial membrane in preventing flexion relies on a competent odontoid process that tightens this membrane during flexion. A more recent study conducted by Tubbs et al.\(^3\) found that the tectorial membrane did not directly inhibit cervical flexion but rather prevented the odontoid process from impinging into cervical canal. They found that flexion of the CCJ made the tectorial membrane fully taut at 15°, and extension made the tectorial membrane fully taut at 20°. The tensile strength of this ligament was found to be 76 N. The tectorial membrane could not be made taut with any lateral flexion or axial rotation of the joint.

**Posterior Atlantooccipital Membrane**

**Anatomy**

The PAO membrane is a broad, thin ligament that attaches the posterior arch of the atlas inferiorly to the posterior rim of the foramen magnum superiorly (Fig. 9). It is continuous with the posterior atlantoaxial membrane and then the ligamentum flavum inferiorly.\(^7\) This structure has been noted by several authors to extend laterally over the atlantooccipital joint capsules.\(^9\) The PAO membrane
runs adjacent to the rectus capitis posterior minor posteriorly and the dura mater anteriorly. Several authors have noted connection or interdigitation of the PAO membrane with both the rectus capitis posterior minor muscle and the spinal dura mater. A study conducted by Hack et al. reported the presence of a connective tissue bridge joining the rectus capitis posterior minor muscle to the spinal dura in all cadaveric specimens. Zumpano and associates found this connective tissue bridge to be present in 67% of cadavers, indicating that this represents normal anatomy rather than a rare anatomical anomaly. Nash et al., expanding on these studies, reported that the PAO membrane is actually composed of the deep fascia of the rectus capitis posterior minor muscle and the vertebral vascular sheath. The PAO membrane is tendinous laterally, but the middle portion is often less obvious because of the increased amount of vascularity and connective tissue. Nash et al. found that the PAO membrane was fused with the spinal dura mater anteroinferiorly rather than attaching directly to the posterior arch of the atlas. Importantly, the VAs pierce the PAO membrane, then dura mater, to enter the posterior fossa.

**Biomechanics**

Currently there is little in the literature focusing on the biomechanics of the PAO membrane. The PAO membrane has historically been referenced as the cephalad extension of the ligamentum flavum and, hence, in antiquity was thought to play a role in craniocervical stability. However, more recent studies revealed that the PAO membrane plays an insignificant role in atlantooccipital joint stability.

**Anterior Atlantooccipital Membrane**

**Anatomy**

The AAO membrane is a thin structure that attaches the anterior aspect of the atlas to the anterior rim of the foramen magnum (Fig. 10). It is located just posterior to the prevertebral muscles of the neck and anterior to the ligament of Barkow. Tubbs et al. observed a connection of the Barkow ligament to the midline onto the AAO membrane. The AAO membrane also serves as the anterior wall of the supraodontoid space, which houses the alar, apical, and Barkow ligaments, as well as fat and veins.

**Biomechanics**

Grabb et al. grouped the AAO and PAO membranes...
Craniocervical junction ligaments

![Diagram of the craniocervical junction (CCJ)](Fig. 10. Cadaveric dissection of the anterior CCJ noting the anterior atlantooccipital (AAO) membrane. Note the relationship to the atlas (C1) and odontoid process (O).)

as soft-tissue structures critical to maintaining stability of the CCJ. Tubbs et al.70 noted that the AAO membrane may function synergistically with the Barkow ligament to limit atlantooccipital extension of the head. Additional studies are needed to further classify the biomechanical properties of this membrane.

**Nuchal Ligament**

**Anatomy**

The nuchal ligament is the cephalic extension of the supraspinous ligament extending from the C-7 spinous process to the inion of the occipital bone (Fig. 9). With the shorter spinous processes of the cervical vertebrae and the lordotic curve of the cervical spine, this ligament forms a midline septation dividing the posterior neck muscles on left and right sides. Moreover, some of these muscles attach medially to this structure.

**Biomechanics**

Intuitively, the nuchal ligament restricts hyperflexion of the cervical spine.39 Interestingly, some have identified a greater concentration of proprioceptive fibers in this structure and have opined that it may play a role in maintaining proper alignment of the cervical spine.31

**Histology of Craniocervical Ligaments**

The majority of the ligaments and soft-tissue structures of the CCJ and the odontoid process are derived from the centrum of the proatlas, which is basically the fourth sclerotome.71,79 These structures are present in the 27-mm embryo and are thought to be modified intervertebral discs.53,70,81 Histologically, these ligaments are composed mainly of collagen fibers, with minimal elastic fibers in their periphery. The degree of elastic tissue present varies from ligament to ligament. For example, the transverse and alar ligaments contain very few elastic fibers, which may explain their rigid, rather inflexible properties. The collagen fibers intersect one another at a 30° angle in the center of the ligament. Several of the ligaments contain a fibrocartilaginous portion. The fibrocartilage makeup is thought to be an adaptation caused by the constant compression upon the ligament. Tendons and ligaments that are under constant pressure or that wrap structures are often composed of fibrocartilage. Fibrocartilage is composed of large oval cells that contain an abundance of intermediate filaments. There is some evidence that fibrocartilage tendons transfer some of the force/compression to the extracellular matrix via intermediate filaments interacting with surrounding integrins. Another reason fibrocartilage is commonly found in “wraparound tendons” is because they are usually accompanied by a large amount of glycosaminoglycans, which trap water and act as a cushion under pressure.9

Immunohistochemical staining of the transverse ligament has shown the presence of collagen Type I–IV, with an abundance of collagen Type II and aggrecan only in the fibrocartilage portion of the ligament.46 The ventral side of the transverse ligament is composed of a fibrocartilaginous layer that interacts with the dorsal side of the odontoid process.11,21,62 Ligaments consisting of fibrocartilage contain certain epitopes that can act as targets for autoimmune reactions, such as rheumatoid arthritis.81 Such antigens include aggrecan, link protein, and Type II collagen, all of which are found in articular cartilage, as well as in fibrocartilaginous portions of tendons and ligaments.6

Histologically, the tectorial membrane appears different than the other ligaments of the CCJ. It is composed of bundles of parallel collagen with spindle-shaped fibrocytes interspersed. Near its attachment to the posterior axis (odontoid), collagen fibers are more homogeneous with larger nonspindled fibrocytes. At the cranial attachment of the tectorial membrane, multiple calcified areas have been noted that interdigitate with the underlying clivus, and at this location, an increase in the number of elastic fibers is seen. This might imply that the tectorial membrane, compared with the posterior longitudinal ligament, is more similar to the ligamentum flavum in which elastic fibers allow the spine to return to a neutral position more readily.73

**Pathology of the Craniocervical Junction**

There are several disease processes and common injuries that tend to affect the ligaments of the CCJ. These include rheumatoid arthritis, Down syndrome, calcium pyrophosphate dihydrate crystal deposition, and “whiplash.” Rheumatoid arthritis is the most common inflammatory disease of the spine and is mostly present in the craniocervical region, specifically in the transverse ligament.46 Rheumatoid arthritis often causes inflammation of the joints in the CCJ, as well as weakening/degradation of the transverse ligament, and therefore, instability of the atlantoaxial joint.31 This is a serious disease of the CCJ that must be monitored and treated because it can lead to
anterior subluxation of the atlas, which may require surgical fixation. Milz and coworkers conducted a study to determine if molecules commonly found in the articular cartilage (aggrecan, Type II collagen, link protein) play a role in causing rheumatoid arthritis in the CCJ. They conducted an immunohistochemical study looking for these molecules in the transverse ligament and found that such molecules were present only in the fibrocartilaginous portion of the ligament. They concluded that the presence of fibrocartilage in the ligament could predispose the CCJ to rheumatoid arthritis. Also, epitopes from the fibrocartilage cells can serve as a target for rheumatoid arthritis.

Another common pathology involving the ligaments of the CCJ is Down syndrome. The prevalence of atlantoaxial instability in children with Down syndrome is estimated to be between 9% and 30%. This instability is thought to be due to ligamentous laxity, as well as osseous structural abnormalities at the CCJ. The usual presentation is cervical myelopathy due to spinal cord compression. A study by Menezes and Ryken showed that the mean predental space in patients with Down syndrome was 8 mm in contrast to the normal 3-mm distance. Another less common pathological entity associated with the transverse ligament is calcium pyrophosphate dihydrate deposition disease, which may also present as myelopathy if this area is involved.

The PAO membrane is thought to be involved with cervicogenic headaches. This may be due to its apparent interdigitation with the pain-sensitive spinal dural layer. Studies by Nash et al. and Zumpano et al. agreed that there is a connective tissue bridge between the rectus capitis posterior minor muscle, the PAO membrane, and the spinal dura mater. This connection may serve as a point of transfer of force from the spinal column to the dura.

The prevalence of whiplash-associated disorders has drastically increased over the last 20 or so years, yet the pathogenesis of this disorder has not been fully elucidated. Whiplash-associated disorders are most commonly caused by motor vehicle collisions that transfer strong forces across the CCJ, often resulting in soft-tissue damage. Damage to the soft-tissue structures of the CCJ can alter biomechanical conditions needed for full range of motion and result in chronic neck pain and upper cervical spine instability. The alar and transverse ligaments are most likely to be injured from a whiplash-associated disorder. Trauma resulting in whiplash-associated disorders often involves the transfer of large amounts of force across the atlantoaxial joint, resulting in rupture of these 2 key ligaments. These ligaments may be more susceptible to this type of high-energy injury because of their predominate collagen makeup. They lack elastic tissue and as a result do not stretch under tension.

Imaging of the Ligamentous Structures of the CCJ

There has been an emphasis placed on improving the imaging techniques used to visualize the CCJ. Ligaments of this region are often best visualized on T2-weighted MR imaging. Grabb et al. examined MR images obtained in 5 trauma patients with suspected atlantoaxial dislocation and found that fast spin echo T2-weighted MR imaging and sagittal MR cisternography were good modalities for diagnosing ligamentous injury. Another protocol formulated by Krakenes et al. used proton density–weighted sequences as well as T1- and T2-weighted gradient echo sequences to view the craniocervical ligaments. The general consensus among various authors is that the highest-quality images of the CCJ soft tissues are produced using both coronal and sagittal T1-weighted and fast spin echo T2-weighted images. Individual ligaments are discussed in further detail below.

The integrity of the transverse ligament can be inferred via radiographs. Anterior subluxation at the C1–2 joint causes an increase in the distance of the predental space. A predental space greater than 3 mm in adults and 5 mm in children is a good indication of transverse ligament pathology, and a distance of greater than 6 mm implies rupture of the transverse ligament. Also useful for determination of transverse ligament integrity is the rule of Spence that states that if the amount of overhang of the C-1 lateral mass on the C-2 lateral mass is greater than 6.9 mm, then the transverse ligament is probably torn.

In 1 study, Krakenes et al. concluded that the alar ligament was best viewed in the coronal and sagittal planes. Their study was not controlled, and they only evaluated patients involved in a motor vehicle accident. Vetti and colleagues conducted a similar study aimed at using MR imaging to diagnose rheumatoid arthritis in the CCJ. However, several other controlled studies indicated that current MR imaging modalities cannot diagnose alar ligament lesions. These studies revealed that although alar lesions often showed high signal intensity, alar ligaments with no lesion obtained in control subjects also showed high signal intensity. This indicates that MR imaging signal intensity may not be the best method of diagnosing alar ligament lesions. Pfirrmann and associates proposed several reasons for the high signal intensity in control individuals. The alar ligaments of individuals with small amounts of epidural fat may blend with surrounding tissue (joint capsules, cruciform ligament) and thus may not be distinguished. The high prevalence of asymmetry and structural alterations of the alar ligament in asymptomatic individuals complicates the use of MR imaging to identify causes of neck pain in symptomatic individuals.

Until recently, there were no studies focusing on direct imaging techniques of the accessory atlantoaxial ligament (Figs. 1 and 2). However, in 2006, Yuksel et al. studied using MR imaging on 10 healthy volunteers to directly visualize the accessory atlantoaxial ligament. The study used 3-T whole body MR imaging, and the ligaments were viewed looking at T2-weighted fast spin echo images. These authors identified the atlantoaxial segment of the ligament in all individuals and the atlantoaxial portion of the ligament in 4 of the 10 individuals.

Radiologically, the tectorial membrane is visualized as a very low signal band on MR imaging. Adams' examined the victims of 21 fatal traffic accidents without craniovertebral dislocation and found 13 dural and tecto-
Craniocervical junction ligaments

Farley and colleagues reviewed images acquired in 3 children injured by full-frontal impact collisions and found that the tectorial membrane was injured in all. Grabb et al. used T2-weighted MR imaging to directly visualize lesions in the tectorial membrane in 5 pediatric patients who had suffered trauma. Engel et al. also used T1-weighted MR imaging to visualize the tectorial membrane and the other structures of the supradosontoid space. Bloom et al. successfully diagnosed injuries to the tectorial membrane using thin-section contiguous axial CT scans to visualize areas of discontinuity in the soft tissues.

There is currently little or no data in the literature detailing specific imaging techniques for the transverse occipital ligament, lateral atlantooccipital ligament, Barlow’s ligament, apical ligament, posterior atlantooccipital, and anterior atlantooccipital membranes (Figs. 1–3, 6, 7, 9, and 10). However, these ligaments have been mentioned in imaging studies focusing on other aspects of the CCJ. Grabb et al. successfully demonstrated tears in the apical ligament on T2-weighted images of the CCJ. Engel et al. identified the contents of the supradosontoid space using MR imaging. They successfully identified the apical ligament, as well as the alar ligaments, fat pad, and a venous plexus. Later, Saifuddin et al. conducted an imaging study of the CCJ and noted that the tectorial membrane, dura mater, and apical ligament often appeared as a single band on T1-weighted images. They were unable to identify the apical ligament in 60% of cases. These MR imaging findings agree with the observation of Tubbs et al. of a fat pad and venous plexus surrounding the apical ligament, as well the absence of the apical ligament in some individuals. Krakenes et al. conducted a study in which MR imaging in 30 volunteers identified ligaments of the CCJ. They directly visualized the PAO membrane in 22 cases; they noticed that in half of the cases, the PAO membrane fused with the spinal dura mater, and in the other half, there was a distinct fat layer between the PAO membrane and spinal dura mater. Schweitzer et al. found that the AAO membrane had greater signal intensity than the other ligaments of the CCJ. They also noted that the fascicles of the AAO membrane radiate out and appear parallel when viewed via MR imaging. Krakenes et al. conducted a similar MR imaging study and had difficulty observing the AAO membrane.

Conclusions

The ligaments of the CCJ play a vital role in maintaining structural stability in this region. A thorough working knowledge of this anatomy is, therefore, important for clinicians and surgeons who treat patients with conditions affecting this area.

Disclosure

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

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Cranio cervical junction ligaments


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