

# Ligaments of the craniocervical junction

## A review

**R. SHANE TUBBS, M.S., P.A.-C., PH.D.,<sup>1</sup> JUSTIN D. HALLOCK, M.D.,<sup>2</sup>  
VIRGINIA RADCLIFF, M.D.,<sup>1</sup> ROBERT P. NAFTEL, M.D.,<sup>1</sup> MARTIN MORTAZAVI, M.D.,<sup>1</sup>  
MOHAMMADALI M. SHOJA, M.D.,<sup>3</sup> MARIOS LOUKAS, M.D., PH.D.,<sup>4</sup>  
AND AARON A. COHEN-GADOL, M.D., M.Sc.<sup>3</sup>**

*<sup>1</sup>Section of Pediatric Neurosurgery, Children's Hospital, Birmingham, Alabama; <sup>2</sup>University of Tennessee College of Medicine, Memphis, Tennessee; <sup>3</sup>Clarian Neuroscience, Goodman Campbell Brain and Spine, Department of Neurological Surgery, Indiana University, Indianapolis, Indiana; and <sup>4</sup>Department of Anatomical Sciences, St. George's University, Grenada*

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

**T**HE 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.<sup>44,45,66</sup> 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.<sup>70–76</sup> 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.<sup>67,86</sup> 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.<sup>44</sup> Panjabi et al.<sup>55</sup> 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.<sup>41,50</sup> Steinmetz et al.<sup>67</sup> 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.<sup>8,10,15,21,22,39,44,67</sup>

The primary movement at the atlantoaxial joint is axial rotation. Steinmetz et al.<sup>67</sup> reported that the mean axial rotational movement was between 23.3° and 38.9°. Menezes and Traynelis<sup>44</sup> 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.<sup>50,56</sup> 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 craniocervical ligament (mean height/thickness 6–7 mm).<sup>11</sup> The superior and inferior limbs of the cruciform ligament are extremely thin and offer no known craniocervical 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.<sup>44</sup> The tectorial membrane, epidural fat, and dura mater are located dorsal to the transverse ligament.<sup>11</sup> A previous quantitative anatomical study conducted by Tubbs et al.<sup>76</sup> 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.<sup>8,11,12</sup> Fielding et al.<sup>21</sup> 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.<sup>11</sup> 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.<sup>21</sup>

### 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 foramen magnum, whereas others believe the attachment is on the medial aspect of the occipital condyles.<sup>15,35,70</sup> 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°.<sup>36</sup> An MR imaging study conducted by Pfirrmann and colleagues<sup>58</sup> found that the alar ligament was oriented caudocranially in about half of the cases and horizontally in the other half. Cattyrse and associates<sup>8</sup> used 3D digitizing stylus technology to further characterize the alar ligament in 20 human cadavers. They found that the 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.<sup>57</sup> An MR imaging study of the craniocervical ligaments conducted by Krakenes et al.<sup>35</sup> 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.<sup>8,10,15,21,39,44,67</sup> 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 coworkers<sup>21</sup> 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 than 12 mm caused the alar ligament to rupture. Similarly, Dvorak et al.<sup>15</sup> 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

## Craniocervical junction ligaments

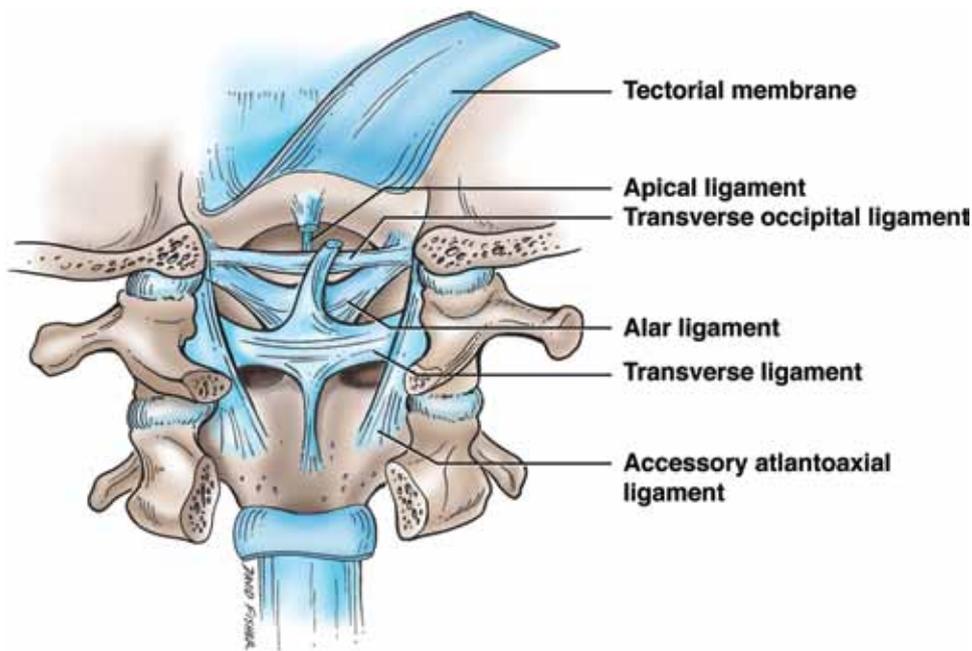


Fig. 1. Artist's drawing of the posterior CCJ illustrating its numerous specialized ligamentous structures. The tectorial membrane is reflected up and down in this drawing.

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.<sup>10,34,44,58</sup> Alar ligament injury often occurs in motor vehicle collisions and is believed to be a cause of whip-lash-associated disorders.<sup>13,32,58,81</sup>

### Transverse Occipital Ligament

#### Anatomy

The TOL is a small accessory ligament of the CCJ that is located posterosuperior to the alar ligaments and odontoid process (Figs. 1 and 3). It attaches to the inner aspect of the occipital condyles, posterosuperior to the alar ligament, superior to the transverse ligament, and extends horizontally across the foramen magnum.<sup>72</sup> Tubbs et al.<sup>72</sup> 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 Ackermann, 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.<sup>15</sup> stated that the TOL is only present in about 10% of the population, whereas Lang<sup>37</sup> 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<sup>38</sup> believed the TOL represented the uppermost fibers of the alar ligament that sometimes crossed the midline. However, Tubbs et al.<sup>72</sup> 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.<sup>72</sup>

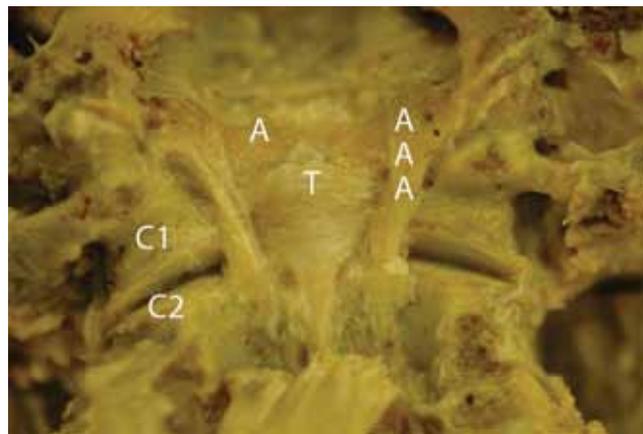


Fig. 2. Cadaveric dissection illustrating the view of Fig. 1. Note the transverse ligament (T), alar ligament (A), accessory atlantooccipital membrane (AAA), and the atlas (C1) and axis (C2).

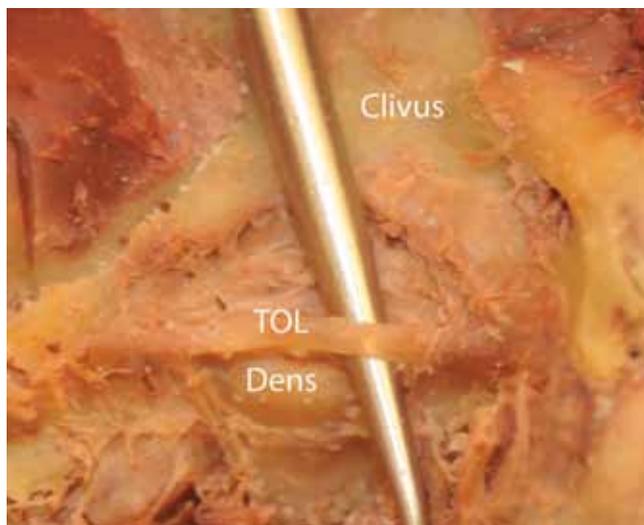


Fig. 3. Cadaveric dissection noting the transverse occipital ligament (TOL).

### 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).<sup>63,89</sup> Despite its importance, it is neglected by most anatomical texts. Woodburne and Burkel<sup>87</sup> 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.”<sup>79</sup> Tubbs et al.<sup>74</sup> 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.<sup>63</sup> Tubbs et al.<sup>74</sup> suggested that this ligament could more appropriately be named the accessory atlantal-axial-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.<sup>26,74,89</sup> Another possible function is protection and support for branches of the VA that supply the odontoid process.<sup>65</sup> Dvorak et al.<sup>15</sup> suggested that this ligament, along with the alar ligament, tectorial membrane, and joint capsule, functions to limit

axial rotation of the head. Tubbs et al.<sup>74</sup> 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.<sup>74</sup> Yuksel et al.<sup>89</sup> 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.<sup>59,75</sup> 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.<sup>75</sup> Tubbs et al.<sup>75</sup> 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.<sup>60,75</sup>

#### Biomechanics

Although no studies have tested the biomechanical function of the LAO ligament, data from Tubbs et al.<sup>75</sup> 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.<sup>56</sup> reported that lateral flexion of the atlantooccipital joint may range from 8° to 40°. 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.<sup>75</sup> observed an increase in lateral flexion of the contralateral side of 3°–5°. Additionally,

## Craniocervical junction ligaments

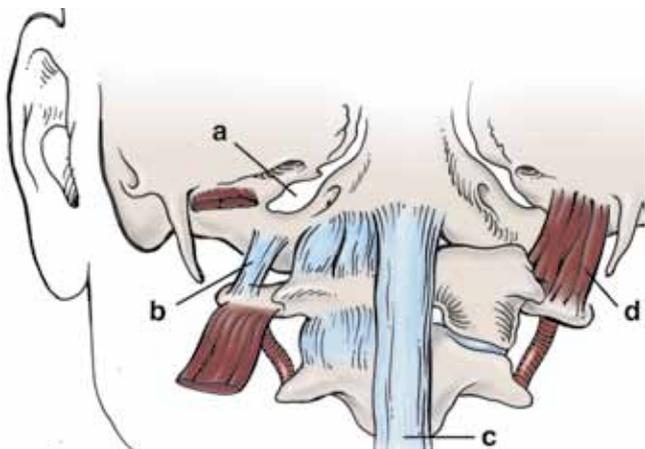


FIG. 4. Anterior drawing noting the jugular foramen (a) and its relationship to the lateral atlantooccipital ligament (b). For reference, note the anterior longitudinal ligament (c) and the rectus capitis lateralis (d).

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.<sup>14</sup> 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. Lang<sup>38</sup> 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 at-

lantooccipital membrane as it attaches to the anterior rim of the foramen magnum.<sup>70</sup> In a study of occipital condyle fractures, Tuli et al.<sup>78</sup> noted that the Barkow ligament is one of the superficial structures that maintain the occipitoatlantoaxial joint. Tubbs et al.<sup>70</sup> 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.<sup>70</sup> 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.

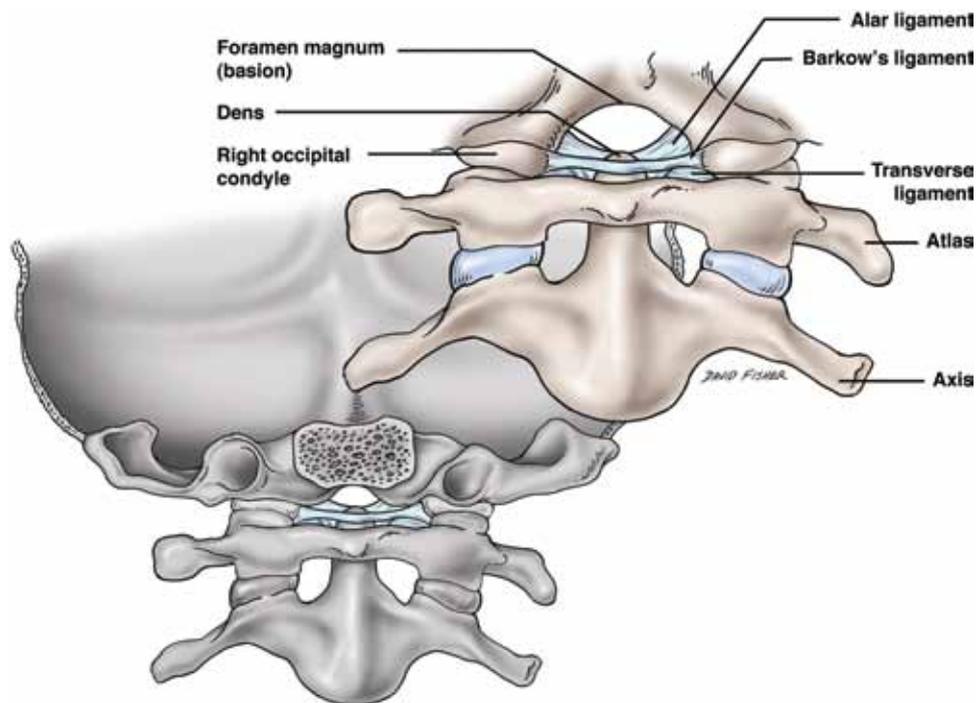
### Apical Ligament

#### 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)<sup>28</sup> and travels just posterior to the alar ligaments and just anterior to the superior portion of the cruciform ligament. In an earlier study, Hecker<sup>30</sup> found the ligament ranged in length from 10.5 to 11.5 mm and in width from 3 to 5 mm. Panjabi et al.<sup>57</sup> later found the length of



FIG. 5. Cadaveric dissection noting the right lateral atlantooccipital (LAO) ligament. Note the jugular foramen (JF) and atlas (C1).



**Fig. 6.** Anterior view of the CCJ demonstrating the Barkow ligament and its relationship to the alar ligaments. Reprinted from Tubbs RS et al: Ligament of Barkow of the craniocervical junction: its anatomy and potential clinical and functional significance. *J Neurosurg Spine* 12:619–622, 2010.

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.<sup>71</sup> 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.

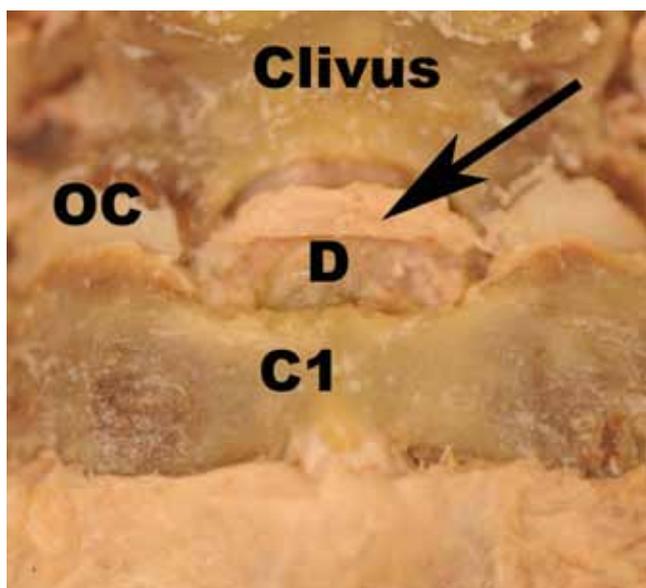
#### Biomechanics

There is discrepancy over the biomechanical function of the apical ligament. Ebraheim et al.<sup>16</sup> attributed the stability of the CCJ to the transverse, alar, and apical ligaments. Grabb and colleagues<sup>25</sup> 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.<sup>71</sup> 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.<sup>71</sup> Some claim that the ligament simply represents rudimentary notochord tissue.<sup>9,23,30,79</sup>

#### Tectorial Membrane

##### Anatomy

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



**Fig. 7.** Cadaveric dissection noting the Barkow ligament (arrow). For reference, note the right occipital condyle (OC) and dens (D).

## Craniocervical junction ligaments

space<sup>28</sup> (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.<sup>28</sup> 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.<sup>20,35,79</sup> Authors variably described the tectorial membrane as a strong collagenous ligament<sup>35</sup> or a weak band<sup>17</sup> that attaches cranially to the clivus<sup>29</sup> or the anterior aspect of the foramen magnum.<sup>34</sup> 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.”<sup>77</sup> Werne<sup>83</sup> has also described the tectorial membrane as the well-developed superior continuation of the deeper layer of the posterior longitudinal ligament. Tubbs et al.<sup>73</sup> found the tectorial membrane to extend superiorly to the level of the internal auditory meatus, which was approximately at the site of the sphenoccipital 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.<sup>73</sup> 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.<sup>73</sup>

### 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<sup>83</sup> concluded that the tectorial membrane restricts extension at the atlantooccipital joint and flexion/extension at the atlantoaxial joint. Oda et al.,<sup>52</sup> 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.<sup>29,34</sup> Others have concluded

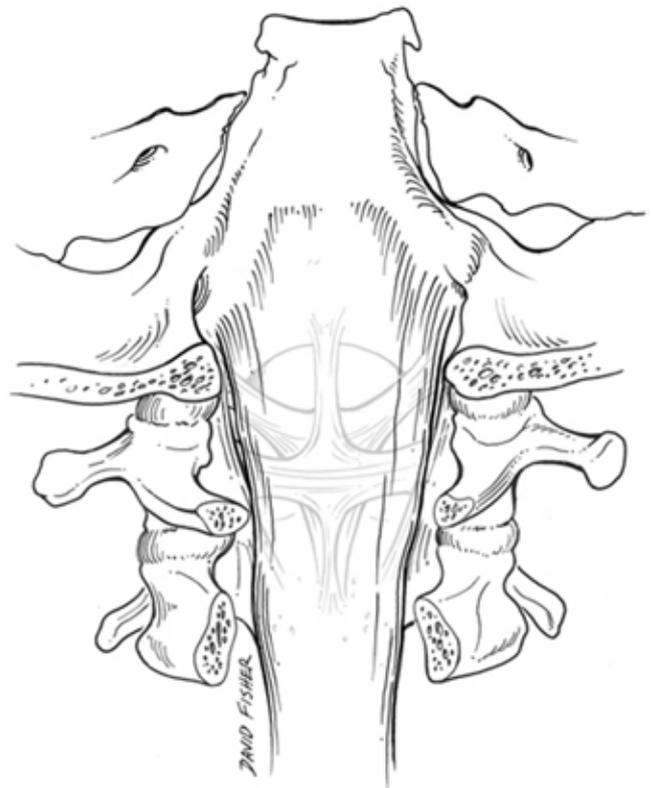


Fig. 8. Posterior view of the CCJ illustrating the relationship between the tectorial membrane (*shadowed*) and the more anterior-lying ligaments.

that the tectorial membrane limits extension and that transection of the tectorial membrane increases flexion at both the atlantooccipital and atlantoaxial joints.<sup>30,57,84</sup> Krakenes et al.<sup>34</sup> found that, with isolated sectioning of the tectorial membrane, instability was appreciated only in flexion. VanGilder et al.<sup>79</sup> 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.<sup>73</sup> 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.<sup>77</sup> This structure has been noted by several authors to extend laterally over the atlantooccipital joint capsules.<sup>90</sup> The PAO membrane

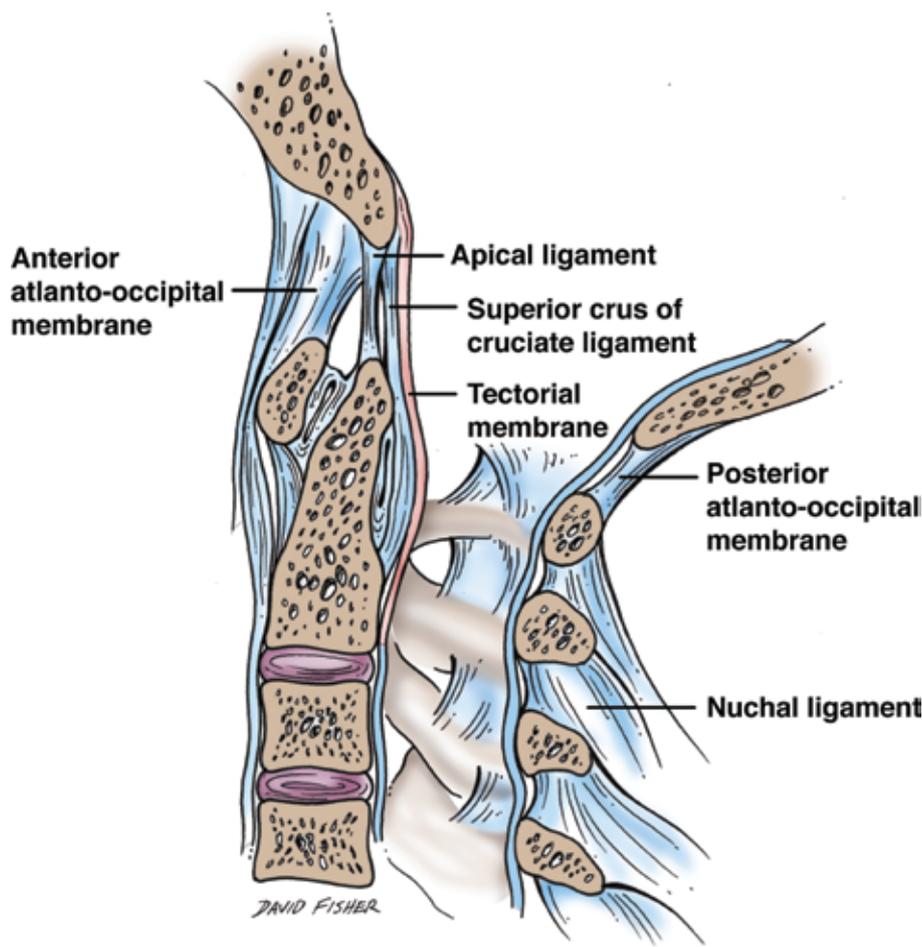


Fig. 9. Sagittal drawing of the neck and cranial base depicting the various specialized ligaments of the CCJ region.

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.<sup>27,68,85</sup> A study conducted by Hack et al.<sup>27</sup> 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<sup>90</sup> 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.,<sup>49</sup> 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.<sup>2,69</sup>

#### 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.<sup>77,88</sup> However, more recent studies revealed that the PAO membrane plays an insignificant role in atlantooccipital joint stability.<sup>5,24,29,49</sup>

### 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<sup>35,70</sup> (Fig. 10). It is located just posterior to the prevertebral muscles of the neck and anterior to the ligament of Barkow. Tubbs et al.<sup>70</sup> 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.<sup>28</sup>

#### Biomechanics

Grabb et al.<sup>25</sup> grouped the AAO and PAO membranes

## Craniocervical junction ligaments



**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.<sup>70</sup> 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 theinion 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.<sup>30</sup> 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.<sup>37</sup>

### 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.<sup>71,79</sup> These structures are present in the 27-mm embryo and are thought to be modified intervertebral discs.<sup>53,76,81</sup> 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.<sup>3</sup> 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.<sup>46</sup> The ventral side of the transverse ligament is composed of a fibrocartilaginous layer that interacts with the dorsal side of the odontoid process.<sup>11,21,62</sup> Ligaments consisting of fibrocartilage contain certain epitomes that can act as targets for autoimmune reactions, such as rheumatoid arthritis.<sup>81</sup> 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.<sup>6</sup>

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.<sup>73</sup>

### 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.<sup>36</sup> 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.<sup>31</sup> 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.<sup>6</sup> Milz and coworkers<sup>46</sup> 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, epitomes from the fibrocartilage cells can serve as a target for rheumatoid arthritis.<sup>81</sup>

Another common pathology involving the ligaments of the CCJ is Down syndrome.<sup>36,42,81</sup> 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.<sup>66</sup> The usual presentation is cervical myelopathy due to spinal cord compression.<sup>47</sup> A study by Menezes and Ryken<sup>43</sup> 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.<sup>5,54,56,90</sup> This may be due to its apparent interdigitation with the pain-sensitive spinal dural layer. Studies by Nash et al.<sup>49</sup> and Zumpano et al.<sup>90</sup> 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.<sup>13</sup> 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 the biomechanical conditions needed for full range of motion and result in chronic neck pain and upper cervical spine instability.<sup>32,39</sup> The alar and transverse ligaments are most likely to be injured from a whiplash-associated disorder (Figs. 1, 2, 6, 8, and 9). 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.<sup>6,11,21,22,39,62,81</sup>

### 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.<sup>18,35,40,66,82</sup> Grabb et al.<sup>25</sup> examined MR im-

ages obtained in 5 trauma patients with suspected atlantooccipital 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.<sup>35</sup> 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.<sup>21,25,32,33,48,58,81,82</sup> Individual ligaments are discussed in further detail below.

The integrity of the transverse ligament can be inferred via radiographs.<sup>11</sup> 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.<sup>11,21</sup> 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.<sup>34</sup> 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.<sup>34</sup> Vetti and colleagues<sup>80</sup> 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.<sup>13,48,58,81</sup> 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<sup>58</sup> 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.<sup>58</sup>

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.<sup>89</sup> 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 atlantooccipital 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.<sup>64</sup> Adams<sup>1</sup> examined the victims of 21 fatal traffic accidents without craniovertebral dislocation and found 13 dural and tecto-

## Craniocervical junction ligaments

rial membrane lesions. Farley and colleagues<sup>20</sup> 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.<sup>25</sup> used T2-weighted MR imaging to directly visualize lesions in the tectorial membrane in 5 pediatric patients who had suffered trauma. Engelman et al.<sup>19</sup> also used T1-weighted MR imaging to visualize the tectorial membrane and the other structures of the supraodontoid space.<sup>28</sup> Bloom et al.<sup>4</sup> 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.<sup>25</sup> successfully demonstrated tears in the apical ligament on T2-weighted images of the CCJ. Engelman et al.<sup>19</sup> identified the contents of the supraodontoid 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.<sup>61</sup> 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.<sup>71</sup> 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.<sup>34</sup> 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.<sup>64</sup> 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.

Author contributions to the study and manuscript preparation include the following. Conception and design: Tubbs, Shojja, Cohen-

Gadol. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Tubbs. Critically revising the article: Tubbs, Cohen-Gadol. Reviewed final version of the manuscript and approved it for submission: all authors. Study supervision: Tubbs.

### References

1. Adams VI: Neck injuries: III. Ligamentous injuries of the craniocervical articulation without occipito-atlantal or atlantoaxial facet dislocation. A pathologic study of 21 traffic fatalities. *J Forensic Sci* **38**:1097–1104, 1993
2. Akar Z, Kafadar AM, Tanriover N, Dashti RS, Islak C, Kocer N, et al: Rotational compression of the vertebral artery at the point of dural penetration. Case report. *J Neurosurg* **93** (2 Suppl):300–303, 2000
3. Benjamin M, Ralphs JR: Fibrocartilage in tendons and ligaments—an adaptation to compressive load. *J Anat* **193**:481–494, 1998
4. Bloom AI, Neeman Z, Floman Y, Gomori J, Bar-Ziv J: Occipital condyle fracture and ligament injury: imaging by CT. *Pediatr Radiol* **26**:786–790, 1996
5. Bogduk N: Anatomy of the spine, in White AH (ed): *Spine Care: Operative Treatment*. St. Louis: Mosby-Yearbook, 1995, Vol 2, p 821
6. Boszczyk AA, Boszczyk BM, Putz R, Benjamin M, Milz S: Expression of a wide range of fibrocartilage molecules at the entheses of the alar ligaments—possible antigenic targets for rheumatoid arthritis? *J Rheumatol* **30**:1420–1425, 2003
7. Brash JC, Jamieson EB: *Cunningham's Manual of Practical Anatomy*, ed 10. New York: Oxford University Press, Vol 3, 1940
8. Cattrysse E, Barbero M, Kool P, Gagey O, Clarys JP, Van Roy P: 3D morphometry of the transverse and alar ligaments in the occipito-atlanto-axial complex: an in vitro analysis. *Clin Anat* **20**:892–898, 2007
9. Clemente CD: *Anatomy: A Regional Atlas of the Human Body*, ed 4. Philadelphia: Lippincott Williams & Wilkins, 1997
10. Derrick LJ, Chesworth BM: Post-motor vehicle accident alar ligament laxity. *J Orthop Sports Phys Ther* **16**:6–11, 1992
11. Dickman CA, Mamourian A, Sonntag VK, Drayer BP: Magnetic resonance imaging of the transverse atlantal ligament for the evaluation of atlantoaxial instability. *J Neurosurg* **75**: 221–227, 1991
12. Driscoll DR: Anatomical and biomechanical characteristics of upper cervical ligamentous structures: a review. *J Manipulative Physiol Ther* **10**:107–110, 1987
13. Dullerud R, Gjertsen O, Server A: Magnetic resonance imaging of ligaments and membranes in the craniocervical junction in whiplash-associated injury and in healthy control subjects. *Acta Radiol* **51**:207–212, 2010
14. Dvorak J, Hayek J, Zehnder R: CT-functional diagnostics of the rotatory instability of the upper cervical spine. Part 2. An evaluation on healthy adults and patients with suspected instability. *Spine* **12**:726–731, 1987
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. Ebraheim NA, Lu J, Yang H: The effect of translation of the C1-C2 on the spinal canal. *Clin Orthop Relat Res* **351**:222–229, 1998
17. Edwards RJ, Britz GW, Johnston FG: Fatal instability following “odontoid sparing” transoral decompression of a periodontoid pseudotumour. *J Neurol Neurosurg Psychiatry* **73**:756–758, 2002
18. el-Khoury GY, Kathol MH, Daniel WW: Imaging of acute injuries of the cervical spine: value of plain radiography, CT, and MR imaging. *AJR Am J Roentgenol* **164**:43–50, 1995

19. Engelman ED, Schnitzlein HN, Hilbelink DR, Murtagh FR, Silbiger ML: Imaging anatomy of the crano-vertebral junction (occipito-atlanto-axial joint). **Clin Anat** 2:241–252, 1989
20. Farley FA, Gebarški SS, Garton HL: Tectorial membrane injuries in children. **J Spinal Disord Tech** 18:136–138, 2005
21. Fielding JW, Cochran GB, 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
22. Fielding JW, Hawkins RJ, Ratzan SA: Spine fusion for atlanto-axial instability. **J Bone Joint Surg Am** 58:400–407, 1976
23. Ganguly DN, Roy KK: A study on the crano-vertebral joint in the man. **Anat Anz** 114:433–452, 1964
24. Ghanayem AJ, Zdeblick T, Dvorak J: Functional anatomy of joints, ligaments, and discs, in Clark CR (ed): **The Cervical Spine**, ed 3. Philadelphia: Lippincott Williams & Wilkins, 1997, p 46
25. Grabb BC, Frye TA, Hedlund GL, Vaid YN, Grabb PA, Royal SA: MRI diagnosis of suspected atlanto-occipital dissociation in childhood. **Pediatr Radiol** 29:275–281, 1999
26. Grant J: **A Method of Anatomy, Descriptive and Deductive**, ed 2. Baltimore: Williams and Wilkins, 1940
27. Hack GD, Koritzer RT, Robinson WL, Hallgren RC, Greenman PE: Anatomic relation between the rectus capitis posterior minor muscle and the dura mater. **Spine** 20:2484–2486, 1995
28. Haffajee MR, Thompson C, Govender S: The supraodontoid space or “apical cave” at the craniocervical junction: a microdissection study. **Clin Anat** 21:405–415, 2008
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. Hecker P: Appareil ligamenteux occipito-atloïdo-axoïdien: étude d’anatomie comparée. **Arch Anat Histol Embryol** 1: 417–433, 1922
31. Inamasu J, Kim DH, Klugh A: Posterior instrumentation surgery for craniocervical junction instabilities: an update. **Neurol Med Chir (Tokyo)** 45:439–447, 2005
32. Kaale BR, Krakenes J, Albrektsen G, Wester K: Active range of motion as an indicator for ligament and membrane lesions in the upper cervical spine after a whiplash trauma. **J Neurotrauma** 24:713–721, 2007
33. Kim HJ, Jun BY, Kim WH, Cho YK, Lim MK, Suh CH: MR imaging of the alar ligament: morphologic changes during axial rotation of the head in asymptomatic young adults. **Skeletal Radiol** 31:637–642, 2002
34. Krakenes J, Kaale BR, Nordli H, Moen G, Rorvik J, Gilhus NE: MR analysis of the transverse ligament in the late stage of whiplash injury. **Acta Radiol** 44:637–644, 2003
35. Krakenes J, Kaale BR, Rorvik J, Gilhus NE: MRI assessment of normal ligamentous structures in the craniovertebral junction. **Neuroradiology** 43:1089–1097, 2001
36. Krauss WE, Bledsoe JM, Clarke MJ, Nottmeier EW, Pichellmann MA: Rheumatoid arthritis of the craniovertebral junction. **Neurosurgery** 66 (3 Suppl):83–95, 2010
37. Lang J: Craniocervical region, osteology, and articulations. **Neuro-Orthopedics** 1:67–92, 1986
38. Lang J: **Skull Base and Related Structures**. Stuttgart: Schattauer, 1995
39. Maak TG, Tominaga Y, Panjabi MM, Ivancic PC: Alar, transverse, and apical ligament strain due to head-turned rear impact. **Spine** 31:632–638, 2006
40. Marbacher S, Lukes A, Vajtai I, Ozdoba C: Surgical approach for synovial cyst of the atlantoaxial joint: a case report and review of the literature. **Spine** 34:E528–E533, 2009
41. Martin MD, Bruner HJ, Maiman DJ: Anatomic and biomechanical considerations of the craniovertebral junction. **Neurosurgery** 66 (3 Suppl):2–6, 2010
42. Menezes AH: Craniocervical developmental anatomy and its implications. **Childs Nerv Syst** 24:1109–1122, 2008
43. Menezes AH, Ryken TC: Craniovertebral abnormalities in Down’s syndrome. **Pediatr Neurosurg** 18:24–33, 1992
44. Menezes AH, Traynelis VC: Anatomy and biomechanics of normal craniovertebral junction (a) and biomechanics of stabilization (b). **Childs Nerv Syst** 24:1091–1100, 2008
45. Menezes AH, Vogel TW: Specific entities affecting the craniocervical region: syndromes affecting the craniocervical junction. **Childs Nerv Syst** 24:1155–1163, 2008
46. Milz S, Schlüter T, Putz R, Morigl B, Ralphs JR, Benjamin M: Fibrocartilage in the transverse ligament of the human atlas. **Spine** 26:1765–1771, 2001
47. Moguel GD, Kinsella LJ: Reversal of sympathetic failure due to cervical myelopathy in a patient with Down’s syndrome. **Clin Auton Res** 13:224–226, 2003
48. Myran R, Kvistad KA, Nygaard OP, Andresen H, Folvik M, Zwart J: Magnetic resonance imaging assessment of the alar ligaments in whiplash injuries: a case-control study. **Spine** 33: 2012–2016, 2008
49. Nash L, Nicholson H, Lee AS, Johnson GM, Zhang M: Configuration of the connective tissue in the posterior atlanto-occipital interspace: a sheet platination and confocal microscopy study. **Spine** 30:1359–1366, 2005
50. Nassos JT, Ghanayem AJ, Sasso RC, Tzermiadianos MN, Voronov LI, Havey RM, et al: Biomechanical evaluation of segmental occipitoatlantoaxial stabilization techniques. **Spine** 34:2740–2744, 2009
51. Neumann D: Axial skeleton: osteology and arthrology, in **Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation**. St. Louis: Mosby, 2002, pp 251–310
52. Oda T, Panjabi MM, Crisco JJ III, Bueff HU, Grob D, Dvorak J: Role of tectorial membrane in the stability of the upper cervical spine. **Clin Biomech (Bristol, Avon)** 7:201–207, 1992
53. O’Rahilly R, Müller F, Meyer DB: The human vertebral column at the end of the embryonic period proper. 2. The occipitocervical region. **J Anat** 136:181–195, 1983
54. Olesen J: The classification and diagnosis of headache disorders. **Neurol Clin** 8:793–799, 1990
55. Panjabi M, Dvorak J, Crisco J III, Oda T, Hilibrand A, Grob D: Flexion, extension, and lateral bending of the upper cervical spine in response to alar ligament transections. **J Spinal Disord** 4:157–167, 1991
56. Panjabi M, Dvorak J, Durancieu J, Yamamoto I, Gerber M, Rauschnig W, et al: Three-dimensional movements of the upper cervical spine. **Spine** 13:726–730, 1988
57. Panjabi MM, Oxland TR, Parks EH: Quantitative anatomy of cervical spine ligaments. Part I. Upper cervical spine. **J Spinal Disord** 4:270–276, 1991
58. Pfirrmann CW, Binkert CA, Zanetti M, Boos N, Hodler J: MR morphology of alar ligaments and occipitoatlantoaxial joints: study in 50 asymptomatic subjects. **Radiology** 218:133–137, 2001
59. Pick TP, Howden R (eds): **Gray’s Anatomy, Descriptive and Surgical**. Philadelphia: Lea Brothers, 1901
60. Rhoton AL Jr: The posterior cranial fossa: microsurgical anatomy and surgical approaches. **Neurosurgery** 47 (Suppl):S5–S298, 2000
61. Saifuddin A, Green R, White J: Magnetic resonance imaging of the cervical ligaments in the absence of trauma. **Spine** 28: 1686–1692, 2003
62. Saldinger P, Dvorak J, Rahn BA, Perren SM: Histology of the alar and transverse ligaments. **Spine** 15:257–261, 1990
63. Schaeffer JP (ed): **Morris’ Human Anatomy A Complete Systematic Treatise**, ed 11. New York: The Blakiston Company, 1953
64. Schweitzer ME, Hodler J, Cervilla V, Resnick D: Craniovertebral junction: normal anatomy with MR correlation. **AJR Am J Roentgenol** 158:1087–1090, 1992
65. Sherk HH, Parke WW: Normal adult anatomy, in The Cervical Spine Research Society (ed): **The Cervical Spine**. Philadelphia: JB Lippincott Company, 1983

## Craniovertebral junction ligaments

66. Smoker WR, Khanna G: Imaging the craniocervical junction. **Childs Nerv Syst** **24**:1123–1145, 2008
67. Steinmetz MP, Mroz TE, Benzel EC: Craniovertebral junction: biomechanical considerations. **Neurosurgery** **66** (3 Suppl):7–12, 2010
68. Thompson VP: Anatomical research lives! **Nat Med** **1**:297–298, 1995
69. Tubbs RS, Ammar K, Liechty P, Wellons JC III, Blount JP, Salter EG, et al: The marginal sinus. **J Neurosurg** **104**:429–431, 2006
70. Tubbs RS, Dixon J, Loukas M, Shoja MM, Cohen-Gadol AA: Ligament of Barkow of the craniocervical junction: its anatomy and potential clinical and functional significance. **J Neurosurg Spine** **12**:619–622, 2010
71. 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
72. Tubbs RS, Griessenauer CJ, McDaniel JG, Burns AM, Kumbha A, Cohen-Gadol AA: The transverse occipital ligament: anatomy and potential functional significance. **Neurosurgery** **66** (3 Suppl Operative):1–3, 2010
73. 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
74. Tubbs RS, Salter EG, Oakes WJ: The accessory atlantoaxial ligament. **Neurosurgery** **55**:400–404, 2004
75. Tubbs RS, Stetler W, Shoja MM, Loukas M, Hansasuta A, Liechty P, et al: The lateral atlantooccipital ligament. **Surg Radiol Anat** **29**:219–223, 2007
76. Tubbs RS, Wellons JC III, Banks J, Blount JP, Oakes WJ: Quantitative anatomy of the transverse ligament tubercles. **J Neurosurg** **97** (3 Suppl):343–345, 2002
77. Tubbs RS, Wellons JC III, Blount JP, Oakes WJ: Posterior atlantooccipital membrane for duraplasty. Technical note. **J Neurosurg** **97** (2 Suppl):266–268, 2002
78. Tuli S, Tator CH, Fehlings MG, Mackay M: Occipital condyle fractures. **Neurosurgery** **41**:368–377, 1997
79. VanGilder JC, Menezes AH, Dolan KD: **The Craniovertebral Junction and Its Abnormalities**. Mount Kisco, NY: Futura Publishing Company, 1987
80. Vetti N, Alsing R, Kråkenes J, Rørvik J, Gilhus NE, Brun JG, et al: MRI of the transverse and alar ligaments in rheumatoid arthritis: feasibility and relations to atlantoaxial subluxation and disease activity. **Neuroradiology** **52**:215–223, 2010
81. Vetti N, Kråkenes J, Eide GE, Rørvik J, Gilhus NE, Espeland A: MRI of the alar and transverse ligaments in whiplash-associated disorders (WAD) grades 1-2: high-signal changes by age, gender, event and time since trauma. **Neuroradiology** **51**:227–235, 2009
82. Volle E, Montazem A: MRI video diagnosis and surgical therapy of soft tissue trauma to the craniocervical junction. **Ear Nose Throat J** **80**:41–44, 46–48, 2001
83. Werne S: Studies in spontaneous atlas dislocation. **Acta Orthop Scand Suppl** **23**:1–150, 1957
84. White AA III, Panjabi MM: **Clinical Biomechanics of the Spine**, ed 2. Philadelphia: JB Lippincott, 1990
85. Williams PL (ed): **Gray's Anatomy: The Anatomical Basis of Medicine and Surgery**, ed 38. London: Churchill Livingstone, 1996
86. Wolfla CE: Anatomical, biomechanical, and practical considerations in posterior occipitocervical instrumentation. **Spine J** **6** (6 Suppl):225S–232S, 2006
87. Woodburne RT, Burkel WE: **Essentials of Human Anatomy**, ed 9. New York: Oxford University Press, 1994
88. Yong-Hing K, Reilly J, Kirkaldy-Willis WH: The ligamentum flavum. **Spine** **1**:226–234, 1976
89. Yuksel M, Heiserman JE, Sonntag VK: Magnetic resonance imaging of the craniocervical junction at 3-T: observation of the accessory atlantoaxial ligaments. **Neurosurgery** **59**:888–893, 2006
90. Zumpano MP, Hartwell S, Jagos CS: Soft tissue connection between rectus capitus posterior minor and the posterior atlanto-occipital membrane: a cadaveric study. **Clin Anat** **19**:522–527, 2006

Manuscript submitted August 27, 2010.

Accepted January 10, 2011.

Please include this information when citing this paper: published online March 11, 2011; DOI: 10.3171/2011.1.SPINE10612.

Address correspondence to: R. Shane Tubbs, Ph.D., Pediatric Neurosurgery, Children's Hospital, 1600 7th Avenue South, ACC 400, Birmingham, Alabama 35233. email: shane.tubbs@chsys.org.