Magnetic Resonance Imaging of the Craniovertebral Junction Ligaments: Normal Anatomy and Traumatic Injury

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J Neurol Surg B 2016;77:388–395.

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Abstract

Keywords

- trauma
- ligaments
- cervical spine
- craniovertebral junction
- alar ligament
- cruciate ligament

The superb stability and flexibility of the craniovertebral junction (CVJ) are enabled by the ligaments that connect the occipital bone and the C1 and C2 vertebral bodies. Radiographically, these ligaments are best assessed with magnetic resonance imaging (MRI), which has excellent soft tissue contrast, but typically poor spatial resolution. With the advent of advanced MRI techniques, including volumetric sequences, high spatial resolution and contrast resolution can both be attained, allowing for detailed analysis of the ligaments, particularly in trauma settings. We have instituted a cervical spine trauma protocol which utilizes a high resolution (1-mm voxel) volumetric proton density sequence to detect injuries to the ligaments of the CVJ in all trauma patients who receive a cervical spine MRI in our emergency room. In this article, we review techniques for imaging the ligaments at the CVJ, the normal imaging anatomy and the function of the CVJ ligaments, and their appearance in cases of traumatic injury.

Introduction

The craniovertebral junction (CVJ) is made up of components of the occipital bone and condyles (C0), and the C1 (atlas) and C2 (axis) vertebral elements. Several important ligaments help hold these osseous structures together, including the cruciate ligament, the paired alar ligaments, the tectorial membrane, the apical ligament, and the anterior and posterior atlanto-occipital membranes. The unique structure of the osseous elements and the horizontal orientation of their articulations allow significant movement, with the majority of flexion and extension of the cervical spine occurring at C0–C1, and most axial rotation of the cervical spine occurring at C1–C2. As a result, the stability of these uniquely shaped joints is highly dependent on the CVJ ligaments.¹

Despite the importance of ligaments in conferring stability while facilitating considerable movement at the CVJ, injuries to the CVJ have historically been classified by osseous fractures. Ligamentous injuries at the CVJ can occur without associated fractures, thus, there is increasing recognition of their critical importance in CVJ instability. Even in the

absence of fractures, ligamentous injuries can cause the osseous structures to lose normal anatomic relationships under physiologic stress, which may lead to ongoing pain and further injury.

In this article, we will familiarize the reader with magnetic resonance imaging (MRI) techniques optimized for imaging the CVJ ligaments. We will review the normal imaging appearance of each ligament while discussing its role in stability at the CVJ. Finally, we will review several examples of injury patterns to these ligaments.

Imaging of the Craniovertebral Junction Ligaments

The appropriate imaging screening of the upper cervical spine in trauma patients remains a controversial topic.² Obtunded patients in whom the injury mechanism is not known further complicate the decision-making process in how to proceed with imaging.^{3,4} Recent guidelines published by the Eastern Association for the Surgery of Trauma recommend conditional removal of cervical spine collar in obtunded patients

with normal high-quality CT, acknowledging that the appropriate management of stable ligamentous injuries identified on MRI alone remains ill-defined in practice and in the literature.⁵

Plain film (X-rays) imaging of the CVJ is a fast and relatively accessible way to assess alignment. Because dynamic views can easily be taken, stability can also be assessed and integrity of ligamentous structures can be inferred. However, the ligaments themselves cannot be seen on plain radiographs, which are limited by poor soft tissue contrast resolution and lack of cross-sectional information. The advent of multi-detector computed tomography (CT) revolutionized the assessment of the CVJ, particularly in trauma situations. Subtle fractures, abnormal alignment, and even some soft-tissue pathology can be easily and quickly identified. The speed of CT acquisition also makes it ideal for trauma situations, where rapid and widely available imaging options are usually the optimal choice. Still, in some cases, subtle ligamentous injury can be overlooked.

MRI has more recently come into play to assess the ligaments at the CVJ. MRI is limited because it is less available than CT and typically has a long acquisition time (3–6 minutes per sequence, 30–45 minutes total). The spatial resolution, particularly for fractures, is also not as good as CT, and often axial imaging stops caudal to the CVJ, precluding multiplanar assessment of the atlantoaxial and atlanto-occipital joints. However, newly available high-resolution three-dimensional (3D) imaging can provide unique and useful information about the integrity of the CVJ ligaments, and can be used to confirm suspected ligamentous injury or as a troubleshooting tool in patients with pain and clinical signs of instability but no evidence of fracture.

Timing of MRI of potentially injured craniovertebral ligaments is debated. However, it should be performed as soon as possible in suspected CVJ ligament injuries.⁶ This is in part to determine as soon as possible the extent and severity of injury to help triage for potential surgical intervention. Perhaps more importantly, earlier imaging maximizes the sensitivity of MRI to the injury. Increased water content from edema is the primary means by which MRI helps identify injured tissue. As time progresses, the water within injured edematous ligaments is reabsorbed, thus decreasing the sensitivity of detection.

Once the decision is made to obtain an MRI, the quality of imaging is also extremely important and varies significantly depending on field strength (minimum of 1.5 T is recommended), coil (a dedicated head, neck, and spine coil is ideal), and the pulse sequences of the MR scanner being used. Reports have been made that in a high percentage of patients, the CVJ ligaments cannot be seen on routine MRI of the cervical spine. This likely has to do with suboptimal technique and field of view, with exclusion of the CVJ on axial sequences, large slice thickness (> 3 mm), and low MR magnet field strength (< 1.5 T).

For optimal scanning of the CVJ, high-resolution imaging is preferred, which requires a slightly longer scan time due to decreased slice thickness, large matrix size, and high-spatial

resolution. Reducing the field of view to the CVJ can be helpful to reduce scan time.⁷ We have found that a high resolution, 3D volumetric proton density sequence with variable flip angle, called Cube (GE Healthcare, Chicago, Illinois, United States) or SPACE (Siemens, Berlin, Germany), works best. This sequence modulates the refocusing flip angle, which extends and reshapes the signal curve, and parallel imaging acquisition reduces phase encoding needed for a large 3D dataset. The isotropic voxels allow for reconstruction in any plane, and the improved spatial resolution (small voxel size) gives superior anatomical detail over that of conventional MRI. The resolution also allows differentiation in variability in signal of the ligaments.

Normal Imaging Anatomy of Craniovertebral Ligaments

The majority of flexion and extension of the cervical spine occurs at the articulation between the occipital condyles ("C0") and the lateral masses of C1, and the majority of cervical rotation occurs at the articulation between the lateral masses of C1 and C2.

The most important ligaments for stability are the cruciate ligament and the alar ligaments.^{8,9} Secondary stability is provided by the posterior longitudinal ligament and its cranial extension, the tectorial membrane. The anterior atlantoaxial and atlanto-occipital membranes, membranous extensions of the anterior longitudinal ligament,^{9,10} and the posterior atlantoaxial and atlanto-occipital membrane tend to follow the tectorial membrane in injury patterns and do little to provide stability. Finally, providing minimal support and not very important for stability is the apical ligament.⁸

Cruciate Ligament

The cruciate ligament is composed of horizontal (transverse) and vertical components. The transverse (atlantal) ligament arises from tubercles of atlas, and holds dens against anterior arch. This ensures stable physiologic axial rotation of C1 on C2 as well as stability of C1 and C2 with lateral bending. It holds the dens against the anterior arch of C1 like a seatbelt, and it is the most important ligament in preventing abnormal anterior or posterior translation and subsequent spinal cord compression. The vertical component of the cruciate ligament is a thin band of fibers oriented in the craniocaudal direction and attaching to the posterior aspect of the dens and the clivus, beneath the posterior longitudinal ligament and tectorial membrane.¹⁰

On MRI, the transverse band is best visualized in the axial plane (→ Fig. 1). However, because most axial cervical spine MRI sequences do not extend up to the atlas, and it is often difficult to distinguish from the posterior longitudinal ligament on standard sagittal T2-weighted imaging, visualization of the cruciate ligament can be difficult. When it is included, it is typically dark on T2-weighted and proton density imaging, although it can increase in signal intensity (become brighter) with aging. The vertical component cannot be seen distinct from the tectorial membrane and posterior longitudinal ligament on MRI (→ Fig. 1).

Fig. 1 Transverse component of the cruciate ligament. Axial proton density CUBE image (A) shows the curved black structure, which represents this transverse band (white arrows). Sagittal reformat of proton density CUBE sequence (B) shows the transverse band (long white arrow) between the dens (star) and the tectorial membrane (short black arrowheads) and posterior longitudinal ligament (long black arrows).

Alar Ligaments

The paired alar ligaments, from the latin root “ala,” meaning wing-like, extend superolaterally from the dens to attach to the medial aspects of the bilateral occipital condyles (► **Fig. 2**). These limit axial rotation and side bending, while allowing flexion and extension.^{11,12} For vertical distraction to occur at the atlanto-occipital junction, the tectorial membrane and the alar ligaments must be partially or completely disrupted.

On MRI, they are best seen in the sagittal and coronal planes. Most standard cervical spine MRIs include a sagittal T2-weighted image, and the alar ligaments can be seen as small black ovals just lateral to the tip of the dens. However,

they are slightly better seen in coronal plane, which is the reason high-resolution imaging (which can be reconstructed in any plane) is helpful. In the coronal plane, they are seen as black bands extending superolaterally from the tip of the dens to the occipital condyles. There is some variability in the width and angulation of the ligaments, but the majority are black on proton density and T2-weighted imaging.^{13,14}

Posterior Longitudinal Ligament and Tectorial Membrane

The posterior longitudinal ligament runs along the dorsal aspect of the vertebral bodies and becomes the tectorial

Fig. 2 Alar ligaments. Proton density CUBE images of the alar ligaments in reformatted sagittal (top row, A–C) and coronal (bottom row, D–F) planes, with (A–C) showing the right alar ligament in the plane on (D–F). The right alar ligament is indicated by the white arrows on sagittal views (A–C). The left alar ligament is also seen on coronal views (D–F, arrows).

Fig. 3 Tectorial membrane (white arrows) and contiguous posterior longitudinal ligament (black arrows).

membrane as it extends cranially from C1 (►Fig. 3). The tectorial membrane is fixed to the dorsal axis body, expanding as it ascends, attached to the basilar groove of the occipital bone, in front of the foramen magnum, where it blends with the cranial dura mater.¹⁰ These limit both flexion and rotation of the CVJ.

On MRI, the tectorial membrane is best seen in the sagittal plane. Most standard cervical spine MRIs include a sagittal T2-weighted sequence. Either this sequence or the sagittal plane 3D proton density sequence is best to evaluate the integrity of the tectorial membrane.

Capsular Joint Ligaments

Joint capsular ligaments stabilize the articulation between the occipital condyles and the upper surface of the lateral masses of C1, and between the lower surface of the lateral masses of C1 and the upper surfaces of the lateral masses of C2. The unique shape of the articulations allows for significant mobility, specifically flexion and extension at C0–C1, and transverse rotation at C1–C2. The configuration and flexibility of the ligaments allows for these movements while providing some stability.

The joint capsules are best seen in the coronal or sagittal planes, on T2- or proton density imaging. Typically, at these joints, there are two effaced dark structures, with little or no bright signal between them. Rarely are the joint capsules themselves seen as injured; rather, fluid within the joint indicates some degree of inflammation or injury.

Anterior Longitudinal Ligament

The anterior longitudinal ligament (ALL) lies along the anterior vertebral bodies and terminates along the anterior margin of the clivus.¹⁵ Components of the ALL at the CVJ are the anterior atlantoaxial ligament, which connects C2 and C1, and the anterior atlanto-occipital membrane which connects C1 and the clivus (►Fig. 4). The posterior atlanto-occipital membrane connects the posterior occiput to the posterior arch of C1. These play a limited role in CVJ stability.¹⁶

On MRI, these structures are best visualized on the sagittal T2- or a sagittal proton density sequence. They are typically low in signal intensity (dark) on T2- or proton density.

Apical Ligament

The apical ligament extends from the tip of the dens to the basion (►Fig. 4). This ligament does not provide much in terms of stability. Injuries to this ligament in and of themselves are not known to happen and would have no consequence given its limited functionality.¹⁰

Fig. 4 (A) Sagittal proton density Cube image demonstrates the anterior atlanto-occipital membrane (short white arrow). (B) Sagittal T2-weighted image demonstrates the apical ligament (long white arrow) and the posterior atlanto-occipital membrane (short white arrow).

Fig. 5 A 29-year-old man who tripped over his flip-flops and fell down a flight of stairs¹² landing on his head. Presented with neck, back, and head pain with some left upper and bilateral lower extremity tingling. Initial CT scan showed a tiny bony fragment at the site of insertion at C1 of the transverse ligament on the right (A, black arrow). MRI demonstrated prevertebral edema, and mild edema at C1 at the transverse ligament attachment (not shown). High-resolution MRI performed the next day demonstrated hyperintensity of the right transverse ligament fibers and widening of the joint space between the dens and the right lateral mass of C1 (B, white arrow). CT, computed tomography; MRI, magnetic resonance imaging.

The apical ligament is difficult to visualize on MRI due to its small size and because it is surrounded by fat. It is best seen in the sagittal plane on T2-weighted or proton density sequences.

Magnetic Resonance Imaging of Craniovertebral Ligament Injuries

Preferred techniques and indications for MRI of the CVJ in trauma patients has already been discussed. Early imaging (within 72 hours) is important to because the primary means by which injury is identified is the increased T2 signal caused by

increased water content in the acutely injured structure. As time passes, this decreases, and makes identifying injury more challenging. Considerable experience as well as knowledge of the breadth of normal imaging is needed on the part of the interpreting physician even in cases of early imaging, because of anatomic variation and signal variations in the ligaments.

Cruciate Ligament

Due to its inflexible structure, injuries of the cruciate ligament typically result in complete failure, an “all or none” phenomenon. Still, there is some variation in injury pattern, and MRI can be used to distinguish between these. There is a classification

Fig. 6 A 54-year-old man who walked into traffic and was struck by a vehicle traveling 40 mph. He hit the windshield and went over the top of the car. Loss of consciousness and GCS 12 on arrival. Admitted to trauma ICU in c-collar and complained of persistent C spine pain despite negative cervical spine CT. Due to additional injuries, MRI could not be performed until 2 days after he was admitted, and high-resolution PD imaging demonstrated an epidural hematoma at the CVJ and bright signal where the transverse band of the cruciate ligament should be (A, black arrow), and cruciate ligament band tears, more pronounced on the right than left (B, white arrows). Tectorial membrane remained intact. CT, computed tomography; CVJ, craniovertebral junction; GCS, Glasgow coma scale; ICU, intensive care unit; MRI, magnetic resonance imaging; PD, proton density.

Fig. 7 A 12-year-old girl struck by an automobile while riding her bicycle. The vehicle was traveling at unknown speeds and left the scene. The patient was found by a passing motorist and intubated at the scene for decreased level of consciousness. The patient complained of significant persistent neck pain. Due to additional injuries, including pneumothorax and bowel injury, MRI of the cervical spine was obtained 2 days after admission. Coronal 3D proton density Cube sequence demonstrated bilateral alar ligament tears, with increased signal in the bilateral ligaments (A, black arrow). Upon retrospective review, tiny avulsed bony fragments were seen at the attachments of the alar ligaments to the dens on the CT performed on admission (B, black arrow). 3D, three-dimensional; CT, computed tomography; MRI, magnetic resonance imaging.

system for cruciate ligament injuries, ranging from avulsions at the atlantal tubercle (► **Fig. 5**) and complete disruption of the ligament (► **Fig. 6**), which can be differentiated on CT and MRI.¹⁷

Alar Ligaments

Injuries to the alar ligament (one or both) occur in cases of high-speed impact, and typically result in tearing of the ligament near its attachment to the occipital condyle, the weakest part of the ligament.¹⁸ As previously discussed, this ligament is best seen in the coronal plane, which allows for visualization of the entire length of the ligament on one image. Coronal imaging is also preferred because alar ligaments demonstrate variations in orientation and signal, with a minority of patients having

intrinsic relative bright T2 signal in the ligament.^{14,19} The coronal imaging plane allows for comparison between the two ligaments, which should be symmetric in orientation and signal in any individual patient. That said, in cases of bilateral ligamentous injury, assuming that symmetry indicates lack of injury can be misleading (► **Fig. 7**). Unilateral alar ligament avulsion can be easier to identify (► **Fig. 8**). Typically, acutely injured ligaments demonstrate relatively increased (bright) signal on T2 and proton density imaging.

Tectorial Membrane

Tectorial membrane rupture is typically accompanied by alar and transverse (cruciate) ligament injuries, and occurs in

Fig. 8 A 22-year-old man who was an unrestrained front seat passenger in a high speed (> 55 mph) motor vehicle collision. The patient sustained significant additional injuries, and had cervical spine tenderness but no fractures on CT. CT (A) demonstrated widening of the right occipitoaxial and atlantoaxial joint spaces (A, black arrows), with normal joint spaces on the left side (A, white arrows). Coronal 3D proton density Cube (B) demonstrated complete avulsion of right alar ligament (B, black arrow) and intact left alar ligament fibers (B, white arrow). CT, computed tomography.

Fig. 9 A 9-year-old boy who was struck in a crosswalk by a car traveling at 25 mph, and thrown onto the hood of the car. He had an initial GCS of 14, amnesic to the event with back and hip pain. CT showed widening of all of the CVJ joints, and MRI was performed immediately. Sagittal high-resolution PD Cube sequence demonstrated stripping of the tectorial membrane (long white arrows) from its attachment to the dorsal clivus (star), as well as disruption at the cranial aspect (black arrow). The anterior atlanto-occipital membrane and the apical ligament are also torn (short white arrows) with CVJ bony articulation widening. CT, computed tomography; CVJ, craniovertebral junction; GCS, Glasgow coma scale; MRI, magnetic resonance imaging; PD, proton density.

situations of high-velocity trauma (i.e., automobile accidents) where there is hyperflexion and anterior translation at the CVJ.²⁰ Isolated injuries can occur, more often in children.

Fig. 10 A 9-year-old girl who was an unrestrained passenger in a truck which was rear-ended while pulling over. She was ejected from the vehicle and found on scene with GCS of 3. MRI on arrival to emergency department revealed atlanto-occipital dislocation with tectorial membrane disruption. Posterior spinal fusion from occiput to C2 subsequently performed. Sagittal T2-weighted MRI demonstrated complete disruption of tectorial membrane at rostral aspect of clivus (black arrow), with retraction of the membrane (white arrow) and widening of the CVJ bony articulations (not shown). CT, computed tomography; CVJ, craniovertebral junction; GCS, Glasgow coma scale; MRI, magnetic resonance imaging.

When these catastrophic injuries do occur, they can result in craniocervical dislocation, with separation of the occiput from the upper cervical spine and subsequent spinal cord or brain stem injury (→ **Figs. 9 and 10**).²¹

Fig. 11 A 12-year-old boy with neck pain after falling off of trampoline. He presented 1 week after the injury with persistent neck pain and fixed turn of his head to the right (8023616). Plain film open mouth odontoid view shows right lateral subluxation of the lateral masses of C1 relative to C2, and asymmetry of the atlantodental interval (A, black arrows). Sagittal T2-weighted MRI demonstrates bilateral C1–C2 capsular ligament injury with bright signal within the joint (B and C white arrows).

Capsular Ligaments

The joints of the CVJ are synovial joints, and the capsular ligaments contain these joints at the C0–C1 and C1–C2 articulations. Injury to the capsular joints typically occurs with rotatory subluxation, usually in the setting of rotation with hyperflexion, resulting in neck pain and “fixation” of the head in a turned orientation.²² Injuries to these ligaments are best seen on T2-weighted or proton density imaging, and are demonstrated by bright signal representing fluid within the joint, which may also show some expansion (►Fig. 11). Typically these injuries are treated conservatively, and some recent literature suggests that MRI may help direct duration of external fixation.²³

Conclusion

MRI of the CVJ after trauma is highly valuable to assess the severity and extent of injury to the major stabilizing ligaments. High-resolution volumetric imaging is particularly helpful to assess subtle injury, and to easily delineate normal and abnormal ligamentous anatomy, particularly in obtunded trauma patients or patients with persistent neck pain after negative initial imaging (plain film and/or CT).

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