Magnetic resonance imaging of the transverse atlantal ligament for the evaluation of atlantoaxial instability

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Twelve normal human subjects and 14 patients with upper cervical spine pathology were studied with axial high-field magnetic resonance (MR) imaging to examine the transverse atlantal ligament. Gradient-echo MR imaging pulse sequences provided reliable visualization of the transverse ligament, which exhibited low signal intensity and extended behind the dens between the medial portions of the lateral masses of C-1. The MR imaging characteristics of the transverse ligament were verified in clinical studies and in postmortem specimens. The clinical MR examinations defined 27 normal ligaments, three ligament disruptions, and four stretched rheumatoid ligaments. Atlantoaxial instability associated with transverse ligament rupture or ligamentous laxity required internal fixation. In contrast, fractures of C-1 or C-2 or atlantoaxial rotatory dislocations associated with an intact transverse ligament healed without instability or nonunion. The transverse ligament is the primary stabilizing component of C-1. The treatment of atlantoaxial instability has previously been based on criteria drawn from computerized tomography or plain radiographic studies, which only indirectly assessed the probability of rupture of the transverse ligament. It is concluded that MR imaging accurately depicts the anatomical integrity of the transverse ligament. After transverse ligament failure, the remaining ligaments of the craniovertebral junction are inadequate to maintain stability. The presence of ligament disruption should be considered as a criterion for early fusion.

KEY WORDS: atlantoaxial instability, cervical spine, spinal fracture, transverse atlantal ligament, magnetic resonance imaging

Disruption of the transverse ligament of the atlas has been implicated as the most important pathological abnormality responsible for atlantoaxial instability.\textsuperscript{1,13,16,29,31,35,37} It has also been considered responsible in certain cases for nonunion of atlas and axis fractures.\textsuperscript{1,2,3,10,11,21,26,28,31,34,35} Conventional radiographic studies and computerized tomography (CT) are insufficient to demonstrate the anatomy of the transverse ligament, and the probability for ligamentous injury has been indirectly assessed from correlations of autopsy data, experimental data, and radiographic studies.\textsuperscript{13,39,36} This report delineates the normal and pathological anatomy of the transverse atlantal ligament and its direct evaluation by magnetic resonance (MR) imaging.

Clinical Material and Methods

Patient Population

Magnetic resonance imaging studies of the transverse ligament were performed in 20 normal adult humans and in 14 patients with pathology of the atlas or axis. The abnormalities included rheumatoid arthritis with symptomatic atlantoaxial instability in four cases and traumatic injuries to the atlas and/or axis in 10 cases. The medical records, imaging studies, clinical examinations, treatment, and outcome were reviewed in each case.

Magnetic Resonance Imaging Parameters

All studies were performed using a 1.5-tesla Signa MR unit.* Sagittal and axial images of the upper cervical spine and transverse ligament were acquired using a multiplanar gradient-echo technique (TR 733 msec, TE 18 msec, flip angle 20°, with a 3-mm slice) in all cases. For all normal individuals studied, an additional three-dimensional volume acquisition technique with axial reconstructions was used (TR 35 msec, TE 15

* Signa MR unit manufactured by General Electric, Milwaukee, Wisconsin.
Fig. 1. **Left**: Sagittal magnetic resonance (MR) image depicting the plane of the axial sections, parallel to the ring of C-1. **Right**: Gradient-echo axial MR image. The transverse ligament has a homogeneous low signal intensity (arrows). Note that the synovial space surrounding the dens has high signal intensity.

msec, flip angle 5°, with a 2-mm slice). Spin-echo axial scans (TR 2000 msec, TE 30/80 msec, with a 4-mm slice) were also obtained through the transverse ligament on four normal individuals.

**Postmortem Studies**

Two fresh human cadaveric specimens were imaged in the axial and sagittal planes using the same pulse sequences as above. One normal and one traumatically disrupted transverse ligament were imaged using en bloc and dissected specimens of the craniovertebral junction and upper cervical spine. These postmortem studies were correlated with the MR imaging findings of the normal and pathological transverse ligaments.

**Results**

**Imaging of the Normal Ligament**

Axial gradient-echo MR images, angled parallel to the atlas, provided the best visualization of the transverse ligament, which appeared as a structure of low signal intensity (Fig. 1). Anteriorly, the margin of the ligament was contrasted with an area of high signal intensity from the synovial joint, which was interposed between the posterior cortex of the dens and the transverse ligament. The posterior margin of the ligament was adjacent to the high signal intensity from the cerebrospinal fluid (CSF). On gradient-echo images, the ligament had a relatively homogeneous signal intensity. The ring of the atlas and the odontoid process of the axis also had low signal intensities but could be recognized by their characteristic shapes on the axial images. Sagittal images did not provide additional information concerning the ligamentous anatomy.

The axial gradient-echo sequence images were obtained rapidly (in approximately 5 minutes) and provided excellent anatomical resolution in all cases. However, the three-dimensional volume gradient-echo acquisition and spin-echo images did not demonstrate the transverse ligament as clearly as the gradient-echo images. The spin-echo images also took almost twice as long to acquire as the gradient-echo scan.

**Postmortem Examination of the Transverse Ligament**

The MR imaging appearance of the in vitro cadaveric transverse ligaments was identical to the in vivo imaging characteristics of the ligament (Fig. 2). The postmortem studies confirmed that the imaged ligamentous structure was indeed the transverse ligament. Transverse ligament disruption was verified by the postmortem examination in a 59-year-old woman who sustained an atlantoaxial subluxation in a high-speed automobile accident. Plain lateral cervical radiographs revealed a 2-cm anterior subluxation of the atlas and the MR images demonstrated disruption of the lateral portion of the ligament. The signal characteristics of the ligamentous rupture corresponded to the actual pathological characteristics (Fig. 3). The loss of anatomical continuity and the presence of an abnormal signal from the ligament were confirmed as signs of injury on MR imaging.
Imaging of Traumatic Injuries of the Atlas and Axis

Among the 10 patients with upper cervical spinal injuries, three had anterior atlantoaxial instability due to transverse ligament rupture (Fig. 4) and one had rotatory atlantoaxial fixation with an intact transverse ligament. Ligament tears appeared as regions of disruption with high signal intensity. Injuries of the transverse ligament occurred in the midportion of the ligament in one case and laterally at the site of bone insertion of the ligament in two cases. Transverse ligament disruption required internal fixation. In comparison, the patient with rotatory fixation with an intact transverse ligament recovered uneventfully after reduction of C1–2 and external immobilization.

The four atlas fractures and the two odontoid fractures were associated with an intact transverse ligament and healed without instability of nonunion. In four cases, the fractures were not displaced and were mechanically stable. Two patients with atlas fractures had radiographic C1–2 subluxations with translational instability but had an anatomically intact transverse ligament. These findings were surprising. In both of these cases, comminuted fractures of one lateral mass of C-1 occurred with displacement of bone fragments which remained attached to the site of insertion of the ligament (Fig. 5). Although the transverse ligaments were not physically disrupted, instability occurred due to physiological incompetence of the ligament. These two patients were treated with external cervical immobilization, developed osseous unions, and were without subsequent instability.

Imaging of Atlantoaxial Instability in Rheumatoid Arthritis

All four patients with rheumatoid arthritis and symptomatic atlantoaxial subluxations had myelopathy. Physiologically incompetent transverse ligaments oc-
curred with subluxations that ranged from 8 to 11 mm. In all cases, MR imaging showed stretching, distortion, thickening, and irregularity of the transverse ligaments without identifiable ligamentous disruption (Fig. 6). Three of these patients required transoral odontoidectomy for neural decompression, and all four required C1-2 fusion for treatment of the extensive instability.

Discussion

Anatomy of the Transverse Ligament

The transverse portion of the cruciate ligament is the most important ligamentous structure of the occiput-C1-2 complex.23,26 The cruciate ligament is also composed of triangular ascending and descending bands that attach to the foramen magnum and body of C-2, respectively (Fig. 7).23,26 The transverse ligament is the largest, strongest, and thickest ligament of the upper cervical spine.12,13,33-38 It is attached to the lateral masses of the atlas medially via insertions upon osseous tubercles.4 A synovial capsule separates the posterior surface of the dens from the transverse ligament. Dorsal to the transverse ligament are the tectorial membrane, a thin layer of epidermal fat, and the dura mater. The thin tectorial membrane is the rostral continuation of the posterior longitudinal ligament and is closely applied to the transverse ligament.12,30

The transverse ligament is broader centrally behind the dens than laterally, where it attaches to the tubercles of the lateral masses of the atlas.9 The central portion of the transverse ligament is 7 to 8 mm thick.37 In comparison, the midportions of the ascending and descending bands of the cruciate ligaments are 3 to 4 mm thick.37 The neck of the odontoid process is constricted where the transverse ligament passes posteriorly.6 The ligament forms a tight band behind the dens.6,13

Biomechanical Properties of the Transverse Ligament

The transverse ligament is the primary and most crucial stabilizing component of all the ligaments of the atlantoaxial complex.6,13 It confines the odontoid process within the articular notch on the anterior arch of C-1, fixes the atlas on the axis, and prevents anterior subluxation of C-1 on C-2.13 Although the transverse ligament allows normal atlantoaxial rotation to occur within a 47° range of motion,22 the alar ligaments, which are attached to the dens and occipital condyles, prevent excessive rotation.6,10,14,31,39

The physical and biomechanical properties of the transverse ligament have been investigated in normal human cadavers.12,13,33,35-38 The transverse ligament is nonelastic and rather rigid.13 It usually fails suddenly when either rapid or slow-loading forces are applied.13 In experimental injuries, the ligament can rupture in the central portion, or osteoperiosteal failure can occur at the bony tubercle where the transverse ligament inserts at the lateral mass of C-1.13,33,35 The ligament appears to be weakest at the insertion, where the gradual transition from ligament to bone occurs.12,35 However, prior to this study, the sites of ligamentous disruption have not been reported in pathological examinations after injuries.

Histologically, the transverse ligament is composed primarily of collagen fibers with very few elastic fibers.12,33 The collagen fibers cross each other in a meshwork at an angle of 30° in the central portion of the ligament.33 Ventrally toward the dens, the ligament demonstrates a transition into fibrocartilage. The relatively exclusive collagen content and the pattern of fiber orientation account for the inelasticity of the ligament.33
The transverse ligament is the strongest ligament stabilizing the atlas; severe forces are required to cause ligamentous disruption in experimental models.\textsuperscript{1,3,13,33,35,36} Using anteriorly directed force vectors at C-1, Fielding, et al.,\textsuperscript{13} observed transverse ligamentous failure in human cadavers with a mean force of 84-kiloponds (range 12 to 180 kiloponds). Spence, et al.,\textsuperscript{35} tried to simulate C-1 burst fractures by transecting the C-1 ring at four sites. Laterally directed distraction of the articular masses of C-1 in these cases caused transverse ligamentous rupture with a mean force of 580 newtons (range 380–1040 newtons).\textsuperscript{12} In other dynamic tests, the transverse ligament could withstand an average of 330 newtons of axial load.\textsuperscript{1,3,13}

After the transverse ligament ruptures, the support provided by the remaining occiput-C-1–2 ligaments, which stretch with relative ease, is inadequate to prevent significant displacement of C-1 on C-2.\textsuperscript{3,13,31,33} Minor trauma can cause late neurological sequelae or sudden death from C-1–2 subluxations.\textsuperscript{1,13,3,18}

**Radiographic Assessment of the Transverse Ligament**

The transverse ligament can only be assessed indirectly from lateral and anteroposterior spinal radiographs.\textsuperscript{24,25,35,38} On lateral views, its physiological integrity is reflected by the atlantoaxial interval, which is the distance between the posterior surface of the anterior ring of C-1 and the anterior surface of the dens.\textsuperscript{23} In adults, the atlantoaxial interval should not exceed 3 mm and does not change with flexion or extension.\textsuperscript{23,31,33} In children, this space can be as wide as 5 mm and can be mobile.\textsuperscript{23,31,35} A wide or mobile atlantoaxial interval raises the suspicion of rupture or incompetence of the transverse ligament.\textsuperscript{4,9,24,25,3}

Open-mouth views have also been used to assess the possibility of ligament rupture and instability in C-1 fractures.\textsuperscript{2,24,31,35} This strategy has been based upon the experimentally simulated C-1 burst fractures conducted by Spence, et al.,\textsuperscript{35} in which the transverse ligament ruptured when the spread of the lateral masses on open-mouth radiographic views was a mean of 6.3 mm (range 4.8 to 7.6 mm). Atlas fractures associated with more than 7-mm displacement have been considered "unstable" based upon probable ligament rupture.\textsuperscript{31,35}

**MR Assessment of the Transverse Ligament**

Based on the ability of MR imaging to demonstrate ligaments elsewhere in the body, especially the knee,\textsuperscript{18} we applied the techniques described in this report to evaluate the transverse ligament. The transverse ligament can be consistently and clearly visualized with rapidly obtained imaging sequences. The imaging anatomy corresponds to the actual anatomy of the ligament in normal and pathological specimens.

The ligament's high degree of contrast with surrounding structures permits it to be visualized consistently in normal individuals. The shape of the ligament is convex toward the dura. The low signal intensity of the transverse ligament is evident on gradient-echo images with small flip angles, reflects the ligament's dense structure. The circular zone of high intensity signal surrounding the dens on MR images is from the long relaxation time on T\(_2\)-weighted images of the synovium and synovial fluid. The CSF marks the posterior margin of the ligament and is also bright on the low flip angle gradient-echo images.

Tears of the transverse ligament appear as a loss of anatomical continuity of the ligament containing regions of high signal intensity compared with the homogeneous low signal intensity of the normal ligament on gradient-echo images. This pattern also occurs with imaging of the cruciate ligaments in the knee and the supraspinatus tendon in the shoulder.\textsuperscript{18} High signal intensity is visible within the ligament at sites of injury. Due to magnetic susceptibility effects, acute blood may appear
as a low-intensity signal on gradient-echo sequences. In theory, since the ligament also has a low-intensity signal, acute hemorrhage could be obscured. In our experience, this did not prove to be a limitation of this technique; however, further experience is needed to confirm this.

Conventional radiographs and CT are still the best modalities for evaluating osseous abnormalities; however, visualization of the transverse ligament is inconsistent using CT scanning. 14,27 Magnetic resonance imaging has become useful for evaluating the spinal cord after trauma, and visualization of the transverse ligament can now be reliably obtained using MR imaging.

Clinical Applications

Imaging of the transverse ligament provides valuable information for the prospective study of traumatic injuries of the atlas and axis. Disruption of the transverse ligament is thought to be an unstable situation that requires surgical fusion. 13,16,17,21,22,27,35,38 Since the secondary atlantoaxial ligaments are relatively weak, patients are susceptible to injury with even minor trauma. 3,31 Atlantoaxial dislocations present the risk of sudden death or late neurological sequelae. 4,11,13,21,27,30 Since our current clinical assumptions have been based on indirect inferences regarding the transverse ligament rather than direct assessment, a critical examination of our assumptions is needed.

Ruptures of the transverse ligament do not appear to heal adequately with immobilization alone; chronic atlantoaxial instability can occur in patients treated nonsurgically. 13,17,22,27,35,38 Surgery has been advocated to fuse the C-1 and C-2 vertebrae to prevent the risk of late sequelae with chronic atlantoaxial subluxations. 11,13,16,32,37,38 Translational dislocations or rotational injuries of the atlas 3,4,16,29,38 should be evaluated with MR imaging to determine the most appropriate treatment. Prospective studies need to address whether certain types of ligament injuries will heal without surgery.

Although widely displaced C-1 fractures have been assumed to have transverse ligament disruption, this association has not been proven pathologically. 7,21,22,26,28,35,37 Since almost all C-1 fractures, even those that are widely displaced, heal with just an external orthosis, 21,26,34 true transverse ligament rupture accompanying atlas fractures must either be rare or be able to heal. 27,28,35 Laxity of the transverse ligament can occur with comminuted fractures of the C-1 lateral mass, without actual ligament disruption (Fig. 5). The presence of a bone fragment remaining attached to the physiologically incompetent but anatomically intact transverse ligament can allow "healing" if an osseous union occurs. A rigid external orthosis is justified for the treatment of these "unstable" comminuted atlas fractures. Prospective studies should evaluate whether nonunion of atlas fractures or true cases of transverse ligament disruption with C-1 fractures require fusion.

Ligamentous integrity is also an important consideration in the evaluation of odontoid fractures. 26 Although most fractures of C-2 heal with rigid external immobilization, odontoid Type II fractures with extensive dens displacement are associated with a high rate of nonunion. 17,30,20,28,34 Posterior displacement or angulation of the dens are indirect manifestations of transverse ligament injury. The relationship between nonunion of odontoid fractures and transverse ligament injury needs to be evaluated directly. Magnetic resonance imaging may help to select patients prone to nonunion and identify candidates for early surgical stabilization.

Nontraumatic causes of transverse ligament failure can also be examined with MR imaging to better understand the pathology and determine treatment. Atlantoaxial instability from rheumatoid arthritis, congenital abnormalities, infection, or neoplasms may be associated with transverse ligament involvement. 3,32,35 In these cases, either severe ligament stretching or ligament disruption may be indications for arthrodesis.

Conclusions

A primary consideration for many traumatic injuries of the atlantoaxial complex is the integrity of the transverse atlantal ligament. Guidelines for the treatment of such injuries have been based on indirect inferences about ligamentous integrity from radiographic studies. Direct assessment of the integrity of the transverse ligament can be reliably and accurately performed with MR imaging. We conclude that MR imaging of the transverse ligament provides an important means to assess recommendations for therapeutic intervention.

References


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