3 TESLA MAGNETIC RESONANCE IMAGING OF THE OCCIPITOATLANTOAXIAL REGION IN THE NORMAL HORSE

BEATRIZ GUTIÉRREZ-CRESPO, PATRICK R. KIRCHER, INES CARRERA

The aim of this study was to describe the appearance of the ligamentous structures of the occipitoatlantoaxial (OAA) region in the normal horse by 3 tesla (3T) magnetic resonance imaging (MRI). The MRI images of the longitudinal odontoid ligament, tectorial membrane, dorsal and ventral atlantoaxial ligaments, dorsal atlantooccipital membrane with its reinforcing ligaments, and the lateral atlantooccipital ligaments of 10 horse cadavers were evaluated. All ligaments and membranes were identified in all planes, except for the lateral atlantooccipital ligament in the sagittal plane due to its cranioventrolateral course. All were iso to mildly hypointense to musculature of the neck in T1W with the exception of the tectorial membrane that was moderately hypointense; moderately hypointense in PD-SPIR, and markedly hypointense (isointense to cortical bone) in T2W. The PD-SPIR was the best sequence to identify all ligaments and membranes from their cranial and caudal attachments. The longitudinal odontoid ligament, ventral atlantoaxial ligament, and reinforcing bands of the dorsal atlantooccipital membrane presented a characteristic striped heterogeneous signal behavior thought to be due to fibrocartilaginous content. The remaining ligaments and membranes showed homogeneous signal intensity. Special anatomical features in this species such as the fan-shaped longitudinal odontoid ligament, absence of the transverse ligament and presence of the ventral atlantoaxial ligament were documented. Ligamentous structures that stabilize the equine OAA region were described with MRI in this study and these findings could serve as an anatomic reference for those cases where instability of this region is suspected.

Key words: anatomy, equine, MRI, occipitoatlantoaxial.

Introduction

OCCIPITOATLANTOAXIAL (OAA) dislocation is not common in the horse; however, to date, few case reports have been published with congenital[1–6] or acquired (trauma)[7–12] primary causes. Congenital OAA malformation is rare and is described primarily in Arabian breeds,[1,2] although other breeds have also been reported over recent years.[3–6] The vertebral structures, particularly the dens, may be malformed leading to an unstable joint and subsequent sub- or luxation. In both situations (congenital or acquired causes), the instability of the atlantoaxial joint results from either laxity or disruption of the ligaments. The ligaments and membranes that provide stability to the OAA region in the horse compromise the longitudinal odontoid ligament (*lig. longitudinale dentis*), tectorial membrane (*membrane tectoria*), dorsal atlantoaxial ligament (*lig. atlantoaxiale dorsale*), ventral atlantoaxial ligament (*lig. atlantoaxiale ventrale*), the lateral atlantooccipital ligaments (*lig. laterale*), ventral atlantooccipital membrane (*membrane atlantooccipitalis ventralis*), and the dorsal atlantooccipital membrane (*membrane atlantooccipitalis dorsalis*) with its reinforcing ligaments.[13]

Atlantoaxial subluxation can be suspected clinically, but diagnostic imaging is mandatory for pre-mortem confirmation. The typical features include malalignment of the atlas and axis, with ventral displacement of the axis in most instances.[1–11] Variable degrees of axial rotation of the axis and/or atlas may be present.[10] In cases of congenital malformations, the dens may have an abnormal shape.[6] Trauma to this region may result in fractures most commonly affecting the dens of the axis.[9,11,12] In chronic cases, the instability may lead to degenerative joint disease, or even fusion and ankylosis of the joint.[8,10]

Computed tomography may provide additional information about the bony structures.[6] However, soft tissue structures, such as the supporting atlantooccipital ligaments, cannot be assessed with radiography or CT. Magnetic resonance imaging has been used to describe the OAA ligaments in people[14–16] and recently in dogs.[17] In people, absence, stretching, or disruption of the transverse ligament may be an indication for early surgical intervention.[18] In horses, different conservative or surgical treatments for the correction of OAA subluxation have been proposed.[7,10,12] The MRI diagnosis of any ligament injuries, together with secondary

From the Section of Diagnostic Imaging, Vetsuisse Faculty, University of Zürich, Winterthurerstrasse 260 8057, Zurich, Switzerland.
Address correspondence and reprint requests to Beatriz Gutierrez-Crespo, at the above address. E-mail: bgutierrez@vetclinics.uzh.ch

Received June 11, 2013; accepted for publication August 9, 2013.
doi: 10.1111/vru.12121

Vet Radiol Ultrasound, Vol. 55, No. 3, 2014, pp 278–285.

complications, such as compression of the spinal cord by bony fragments, severe displacement of the odontoid process or extradural haemorrhage, development of inflammatory pannus, or the degree of narrowing of the vertebral canal due to callus formation, could have an impact on the understanding of the pathophysiological mechanisms of instability in this region. Furthermore, MRI findings could affect the decision of which specific treatment is the most suitable for each particular case.

The aim of this study was to describe the appearance of normal ligamentous structures of the OAA region of the horse with MRI, and compare them with matched plane anatomic dissections, in order to serve as a guideline for pathological cases.

Materials and Methods

The head and neck regions were removed from the bodies (disarticulated at the level of C4–C5) of 10 horses and were used for this study. The horses were euthanized for reasons unrelated to neck pain or neurological disease.

A 3T magnet (Ingenia, Philips Medical Systems Nederland B.V., The Netherlands) was used for all MR examinations using a volume coil (*d*S Torso coil, phased-array transmit-receive, with 32 channels).

Each specimen was scanned within 24 h of euthanasia, in left lateral recumbency, with the neck and head in neutral position. Dorsal, sagittal, and transverse images were acquired. The region of interest was centered at the level of C1; the sagittal and dorsal images included rostrally the occipital bone and caudally the level of C3. The dorsal plane was planned from the sagittal images and orientated parallel to the longitudinal odontoid ligament. Transverse images were acquired from the level of the midbody of C2 to rostral to the occipital condyles in a 90° orientation with respect to the dens. Slice thickness was 4 mm, 4.4 mm interslice spacing and the field-of-view 300 mm. The sequences included were: fast spin echo T2-weighted (T2W): (TR = 4431–7385, TE = 100), number of signal average (NSA) = 3; fast spin echo T1-weighted (T1W): (TR = 721, TE = 6.5–8.2), NSA = 4; and fast spin echo proton density with fat saturation (PD-SPIR), (SPIR: spectral presaturation with inversion recovery): (TR = 3247–5691, TE = 30) and NSA = 3.

Once the MR imaging study was performed, two of the heads from horse cadavers were frozen at −30°C for at least 24 h. These specimens were sectioned using a high-speed band saw in the sagittal and transverse planes. For the sagittal section, a symmetrical single slice through the midline of the head and neck was performed. For the macroscopic transverse sections, consecutive 5-mm-thick slices of the head and neck from mid calvarium to mid axis were obtained. Another horse's head was kept in refrigeration and dissected manually by the first author with a dorsal approach.

By consensus of the two authors, the macroscopic slices, which correlate most with the MRI image with respect to the plane and section location, were selected for comparison to MRI images. The anatomical structures to identify were: longitudinal odontoid ligament, tectorial membrane, dorsal and ventral atlantoaxial ligaments, dorsal atlantooccipital membrane, and lateral atlantooccipital ligaments.

Magnetic resonance imaging images were reviewed independently by the first and last author. The ability, the best plane, and the best sequence to visualize the previously cited structures on the MRI images were recorded. In each structure visualized, the following were described: attachments, shape in the different planes (round, oval, conic, fan-like, flat, X-shaped), symmetry (asymmetric, symmetric), course of ligament fibers (parallel, V-shaped, convergent, or divergent), signal behavior (homogeneous, heterogeneous), signal intensity in all sequences compared to muscle and to cortical bone (hypointense, isointense, hyperintense). The criteria of choosing the best plane and the best sequence was made based on which one enables the complete delineation and visualization of the ligaments from both cranial and caudal attachments.

Breeds included in the study were six Swiss warmblood, three Arabic and one Haflinger. The median age was 15 years and 2 months (range 5 years and 3 months to 24 years and 7 months). The median weight was 520 kg (range 466–640 kg). There were six males and four females. All anatomic and MRI figures were labeled based on a consensus of the first and last authors.

Results

Longitudinal Odontoid Ligament

The longitudinal odontoid ligament was readily identified in 10/10 animals in all three planes (dorsal, sagittal, and transverse). The dorsal plane was the best for describing the morphology of this ligament. The longitudinal odontoid ligament had its caudal attachment at the dorsal surface of the axis' odontoid process and radiated fibers to attach cranially to the transverse rough surface of the atlas' floor, cranial to the fossa of the dens. It consisted of two strong symmetric bands of ligamentous fibers with a divergent V-shape. On the dorsal plane, this ligament was narrower at the caudal attachment point on the dens compared to its width at the cranial attachment in the atlas, adopting a fan-shaped appearance (Fig. 1). From the transverse view at the level of the dens, this ligament was seen as two symmetric oval cords that became wide and flattened cranially as they approached the rough surface on the floor of the atlas (Fig. 2). On the sagittal view the odontoid ligament showed a conical shape, with a broad base located caudally at the

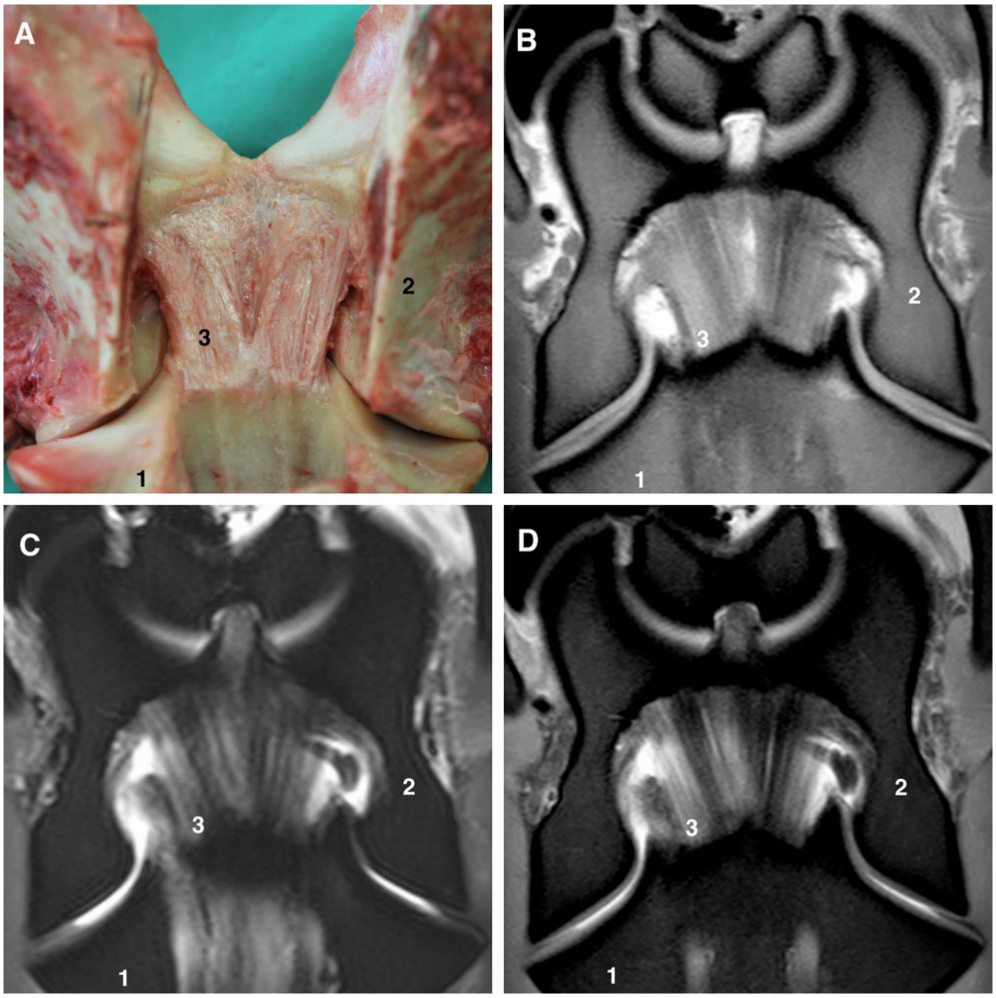

FIG. 1. Dorsal images at the level of the atlantoaxial region showing the longitudinal odontoid ligament. (A) Dissection image after removal of the dorsal arch of the atlas, (B) T1-weighted image, (C) T2-weighted image, and (D) PD-SPIR image. 1: axis; 2: atlas; 3: longitudinal odontoid ligament. A, B, C and D show the characteristic fan-shaped appearance of this ligament. In the MRI images (B, C, D); the longitudinal odontoid ligament (3) presents striped appearance, with mixed hyper and hypointense fibers compared to muscle.

level of the dens (Fig. 3). It showed heterogeneous signal intensity, with hyper- and hypointense parallel course of fibers, giving a striped appearance in all sequences. These parallel fibers showed a divergent V-shape orientation. The longitudinal odontoid ligament was identified on T1W sequences as isointense to musculature of the neck, while on PD-SPIR sequences it was moderately hypointense to muscle, and markedly hypointense to muscle in T2W sequences (isointense to cortical bone).

Tectorial Membrane

The tectorial membrane could be visualized in 10/10 horses in the transverse and sagittal plane. However, the tectorial membrane could not be differentiated from the odontoid ligament in any of the dorsal planes. The sagittal plane was the best to delineate its course. It was seen as a continuation of the dorsal longitudinal ligament of the spine, extending cranially over the longitudinal odontoid ligament to attach to the ventrolateral aspect of the foramen magnum. In T1W, and PD-SPIR images, the tectorial membrane could be seen as a thin, flat band, presenting homogeneous low signal intensity, moderately hypointense to muscle, while in T2W it was markedly hypointense (isointense to cortical bone), which made its differentiation from the longitudinal odontoid ligament difficult (Fig. 2 and 3).

Dorsal Atlantoaxial Ligament

The dorsal atlantoaxial ligament could be seen in 10/10 horses in all planes. The dorsal plane provided the best visualization of the entire length and conformation of this ligament. This ligament connected the cranial aspect of the spinous process of the axis to the dorsal tubercle of the atlas. On the dorsal plane the dorsal atlantoaxial ligament was

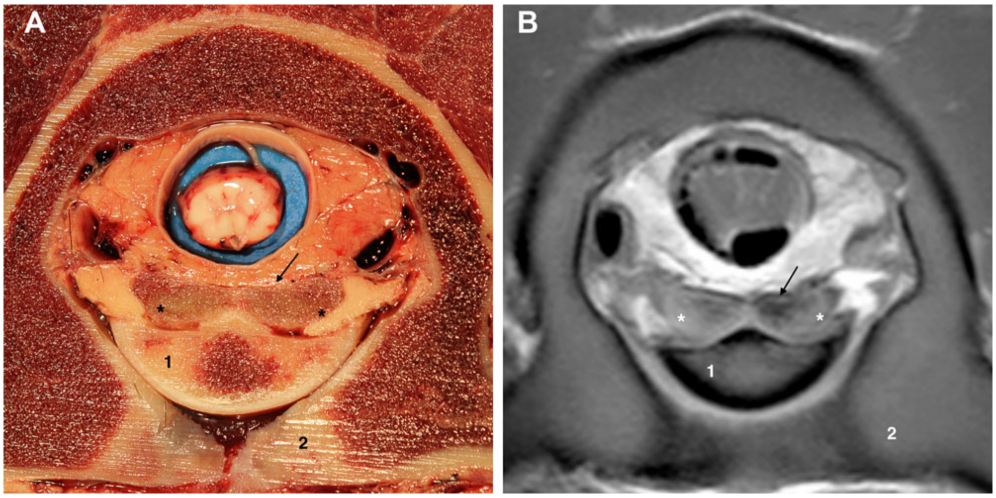

FIG. 2. (A) Transverse prosection image at the level of the dens of the axis. (B) Transverse T1-weighted MR image at the same level as (A). 1: dens of the axis; 2: atlas; asterisks: longitudinal odontoid ligament; arrow: tectorial membrane. The two cords of the longitudinal odontoid ligament (asterisks) are well visualized on prosection (A) and on T1-weighted images (B). The tectorial membrane (arrow) is seen as a thin hypointense line on the T1-weighted image (B). Notice the signal void produced by postmortem gas accumulation within the epidural space.

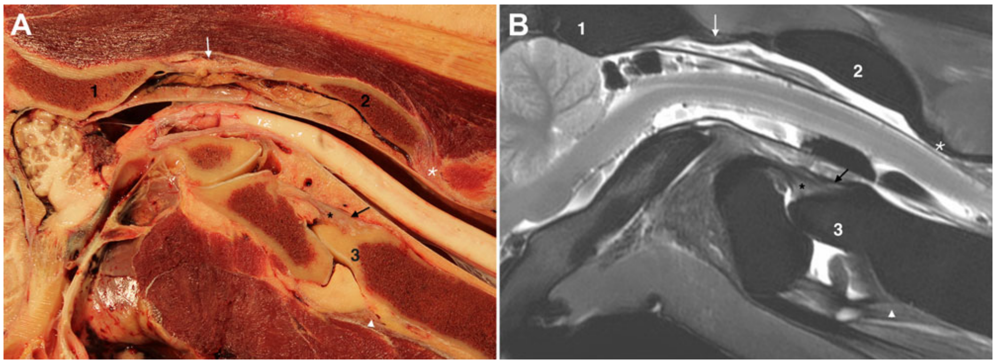

FIG. 3. (A) Sagittal prosection image of the occipitoatlantoaxial region and (B) T2-weighted image at the same level. 1: occipital bone; 2: dorsal arch of the atlas; 3: dens of the axis; black asterisk: longitudinal odontoid ligament; white asterisk: dorsal atlantoaxial ligament; white arrow: dorsal atlantooccipital membrane; black arrow: tectorial membrane; white head arrow: ventral atlantoaxial ligament.

Notice the signal void produced by postmortem gas accumulation within the epidural space.

seen as two symmetric longitudinal cords running parallel and in close proximity to each other (Fig. 4). On the transverse plane these cords appeared as two oval structures. From the sagittal views, a sigmoidal course of the cords was identified in all specimens (Fig. 3). The ligamentous fibers followed a parallel orientation with homogeneous iso-to-mild hypointense signal intensity in comparison to the surrounding musculature in T1W, moderately hypointense

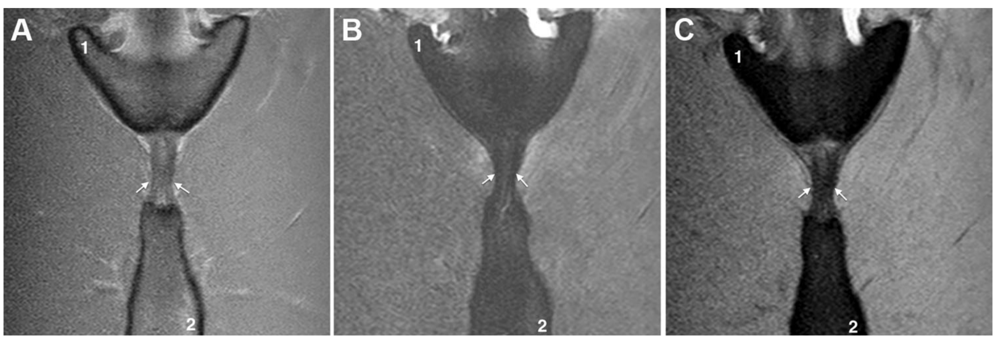

FIG. 4. Dorsal images highlighting the two cords of the dorsal atlantoaxial ligament. (A) T1-weighted, (B) T2-weighted, (C) PD-SPIR. 1: atlas; 2: axis; arrows: dorsal atlantoaxial ligament. The dorsal atlantoaxial ligament is hypointense to muscle in all sequences. In (B) the ligament is isointense to cortical bone, which prevents clear differentiation of its attachments.

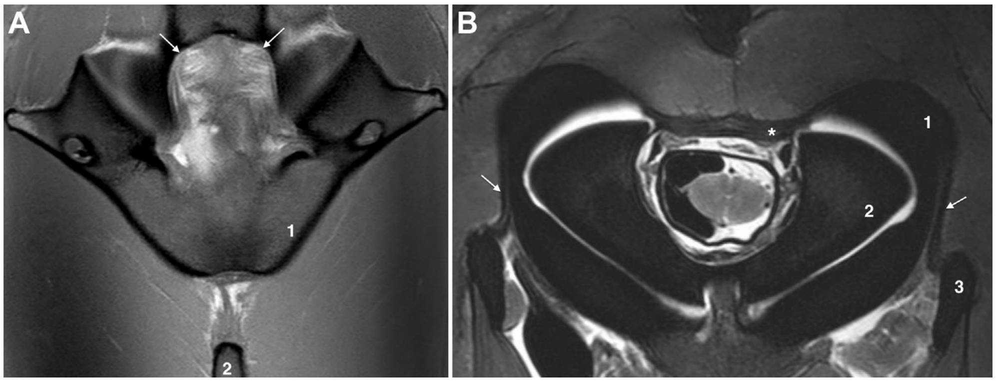

FIG. 5. (A) Dorsal T1-weighted image showing the reinforcement ligaments of the dorsal atlantooccipital membrane (arrows). 1: atlas; 2: axis. Notice the crossed shape and the striped appearance of this ligament. (B) Transverse T2-weighted image at the level of the atlantooccipital joint. The lateral atlantooccipital ligaments (arrows) are clearly visible. The asterisk; indicates the dorsal atlantooccipital membrane. 1: atlas, 2: occipital condyles 3: paracondylar process of the occipital bone. Notice the signal void produced by postmortem gas accumulation within the epidural space.

in PD-SPIR, and markedly hypointense (isointense to cortical bone) in T2W.

Ventral Atlantoaxial Ligament

In 10/10 horses the ventral atlantoaxial ligament appeared as a fibrous band and was completely visualized and better seen in transverse and sagittal planes. The ligament was incompletely visualized in the dorsal plane in 10/10 horses. This ligament had its cranial attachment to the ventral tubercle of the atlas and attached caudally to the ventromedial crest of the body of the axis. On the sagittal plane it was seen as a thick, conical-shaped fibrous band, with the broad base at the level of the atlas getting thinner towards the caudal fixation point at the axis (Fig. 3). The transverse plane showed it with a rounded shape. From the dorsal view, given the position and orientation of the ligament, the entire course could not be delineated. The ventral atlantoaxial ligament showed heterogeneous signal intensity in 6/10 of the horses, with hyper- and hypointense parallel fibers, giving it a striped appearance. In the remaining four horses, this ligament was homogenous. The signal intensity in T1W images was iso-to-mild hypointense to muscle, moderately hypointense in PD-SPIR and markedly hypointense (isointense to cortical bone) in T2W.

The Dorsal Atlantooccipital Membrane

The dorsal atlantooccipital membrane was completely visible in all horses in the sagittal and transverse planes, whereas from the dorsal plane it could not be followed on its entire length in any of the horses. The dorsal atlantooccipital membrane extended from the dorsal border of the foramen magnum and dorsal margins of the occipital condyles to the cranial border of the dorsal arch of the atlas. Reinforcing the dorsal aspect of this membrane, there were two symmetric oblique long bands of fibers that crossed almost describing an X-shape on the sagittal plane. These oblique long bands extended from the mid part of the dorsal margin of the occipital foramen to the opposite side of the dorsal arch of the atlas. The aforementioned reinforcing bands presented a linear parallel pattern in a V-shape converging in oblique direction into the midline from the dorsal plane (Fig. 5A). On the transverse and sagittal planes the reinforcing bands could not be well differentiated from the dorsal atlantooccipital membrane that presented a thick flat appearance (Fig. 3 and 5B). The dorsal atlantooccipital membrane was homogeneous, isointense to muscle in T1W, moderately hypointense in PD-SPIR and markedly hypointense in T2W (isointense to cortical bone). With reference to the reinforcing bands, they showed a heterogeneous striped appearance of hyper and hypointense crossing fibers, being overall isointense to muscle in T1W, moderately hypointense in PD-SPIR and markedly hypointense in T2W.

Lateral Atlantooccipital Ligaments

On the dorsal and transverse planes the lateral atlantooccipital ligaments were visible in 10/10 of the horses; however, on the sagittal views they could not be identified in any sequence. These ligaments were cranially attached to the base of the jugular process and part of the paracondylar process of the occipital bone and they attached caudally to the craniolateral border of the dorsal arch of the atlas. This pair of ligaments was seen as two flat, straight symmetric bands, with a slight oblique cranioventrolateral direction from the transverse and dorsal planes (Fig 5B). In all horses the lateral atlantooccipital ligaments were homogeneous, isointense to muscle in T1W, moderately hypointense in PD-SPIR and markedly hypointense in T2W (isointense in cortical bone).

The MRI findings concerning each ligament are summarized in Table 1.

TABLE 1. Summary of MR Features of the Ligaments of the Occipitoatlantoaxial Region in the Horse. The Signal Intensity of Each Structure was Compared to the Musculature of the Neck

	Planes			Signal Intensity		
Ligaments and mm.	Sagittal	Dorsal	Transverse	T1W	T2W	PD-SPIR
LOL lig	Conic	Fan-shaped	Oval cords	Heterog. striped (10/10) Isointense	Heterog. striped (10/10) Marked hypo	Heterog. striped (10/10) Moderate hypo
Tectorial m.	Flat band	–	Flat band	Homog. (10/10) Moderate hypo	Homog. (10/10) Mark hypo	Homog. (10/10) Moderate hypo
DAA lig	Sigmoidal long cord	Long. parallel cords	Oval cords	Homog. (10/10) Iso-to-mild hypo	Homog. (10/10) Mark hypo	Homog. (10/10) Moderate hypo
VAA lig	Conic	–	Round	Heterog. striped (6/10) Homog. (4/10) Iso-to-mild hypo	Heterog. striped (6/10) Homog. (4/10) Mark hypo	Heterog. striped (6/10) Homog. (4/10) Moderate hypo
DAO m	Flat band	Flat band	Flat band	Homog. (10/10) Isointense	Homog. (10/10) Mark hypo	Homog. (10/10) Moderate hypo
Reinforced bands of DAO m	–	X-shaped	–	Heterog. striped (10/10) Isointense	Heterog. striped (10/10) Mark hypo	Heterog. Striped (10/10) Moderate hypo
LAO lig	–	Flat bands	Flat bands	Homog. (10/10) Isointense	Homog. (10/10) Mark hypo	Homog. (10/10) Moderate hypo

T1W: T1-weighted; T2W: T2-weighted; PD-SPIR: Proton density-spectral presaturation with inversion recovery, lig: ligament, m: membrane, mm: membranes, LOL: longitudinal odontoid ligament, DAA: dorsal atlantoaxial ligament, VAA: ventral atlantoaxial ligament, DAO: dorsal atlantooccipital membrane, LAO: lateral atlantooccipital ligament, —: not differentiated, heterog: heterogeneous, homog: homogeneous, long: longitudinal, iso: isointense, hypo: hypointense.

Discussion

Magnetic resonance imaging of the OAA region was excellent for the identification of all ligamentous structures in all horses, and correlated exactly with the anatomical dissections in this study. Anatomical variations and special features of some of the ligaments in the horse similar to dogs and people were observed, such as the longitudinal odontoid ligament that was perceived as a sole robust fan-shaped ligament. The analogous ligament in dogs and people, can be differentiated into three parts: the median ligament *(lig. apices dentis*) and paired (alar) lateral pillars (*ligg. alaria*.).[13,17,19,20] In the horse, the longitudinal odontoid ligament is the strong continuation of the dorsal longitudinal ligament of the spine.[13] The longitudinal odontoid ligament attaches cranially to the rough surface of the floor of the atlas, cranial to the fossa of the dens[13] in opposition to dogs and people where this ligament extends further cranial to insert at the ventrolateral border of the foramen magnum.[17,19–22] The presence of a pair of ill defined fascia-like structures that flank the odontoid ligament, defined as "pseudoalar" ligaments has been described in horses.[13] However, we could not identify these structures in either MR images or dissection. Another important difference with dogs and people is the fact that the transverse ligament of the atlas in the horse is missing.[13] The longitudinal odontoid ligament is considered a transformed odontoid-transverse ligament.[13]

One more anatomical variation to highlight is the presence of the ventral atlantoaxial ligament, which is a reinforcement of the atlantoaxial joint and it is only present in horses and ruminants.[13] The lateral atlantooccipital ligaments could not be identified in any of the sagittal planes due to their cranioventrolateral course and thin nature of these ligaments. Specific angling of the scan plane and thinner slices would be recommended to assess the entire course of these ligaments.

The signal intensity of the normal ligaments of the occipitoatlantal region in people and dogs have been described, showing a homogeneous low signal intensity in T1W and T2W sequences, being iso- or hypo-intense to muscle tissue.[17,21,22] Histologically the ligaments are composed mainly of collagen.[22–24] The collagen is organized in fibers that restrict the motion of water molecules and enhance the dipolar interactions greatly. Therefore, the normal ligaments have none or very low signal because of shortening of T2 relaxation times.[25,26] In this study, the tectorial membrane, the dorsal atlantoaxial ligament, the dorsal atlantooccipital membrane and the lateral atlantooccipital ligaments showed similar characteristics. However, the longitudinal odontoid ligament, the ventral atlantoaxial ligament and the reinforcing ligaments of the dorsal atlantooccipital membrane presented striped appearance, with a mixture of hyper and hypointense fibers in all sequences. Fat can be hyperintense in T1W and T2W, however, this high signal intensity was also present in the PD sequence with fat suppression; therefore, this possibility is ruled out. Another reason could be magic-angle effect; however, this artifact is minimized or absent in sequences with long TE (T2W).[25–27] In this study, the hyperintense fibers were also clearly visible in T2W images;

thus, magic-angle effect was not present. The presence of connective tissue between the ligament fibrils, like cartilaginous tissue, had been reported and is seen as moderate to high signal intensity in comparison with the low signal intensity of the ligament.[21,22,25] Similar characteristics has been described in the proximal aspect of the oblique distal sesamoidean ligaments in horses[28,29] Fibrocartilage belongs to connective tissue with a regular fiber arrangement consisting of parallel bundles of collagen fibers with chondrocytes distributed among them.[23,28,29] The longitudinal odontoid ligament, the ventral atlantoaxial ligament, and the reinforcing ligaments of the dorsal atlantooccipital membrane may contain a fibrocartilaginous portion, which is thought to be an adaptation caused by the constant compression and support of strong forces upon them.[23,24] This may be specially pronounced in the odontoid ligament, since it substitutes the transverse ligament of the atlas. The longitudinal odontoid ligament may receive vertical forces perpendicular to the ligament resulting from the ventral compression of the dens of the axis, and horizontal forces, working toward the attachments point.[23] This different ligament's composition could be responsible for the characteristic signal intensity of these specific structures described in this study.

All sequences used in this study achieved visualization of the ligaments. However, when comparing them, T1W was judged the less useful, since the signal intensity of the ligaments is rather isointense to the surrounded musculature; while in T2W and PD-SPIR the ligaments were always hypointense to the surrounding muscles. Proton density-spectral presaturation with inversion recovery was considered better than T2W because in this last one, the ligaments were isointense to cortical bone, what does not allow the complete differentiation of the cranial and caudal insertion of the ligaments into the bony structures. However, in PD-SPIR, this is possible since the ligaments are slightly hyperintense to cortical bone. In addition, the fat suppression allows better discrimination by suppressing the surrounded fat. In pathological cases, fat-suppression techniques are very helpful to enhance edematous lesions and highlight injuries.[17,27]

In conclusion, MRI may provide useful information for the assessment of the OAA region in horses. Unique anatomical features in this species such as the fan-shaped longitudinal odontoid ligament, absence of the transverse ligament and presence of the ventral atlantoaxial ligament, and their characteristic signal intensity pattern were well documented. The information in this study will serve as an anatomic reference for MRI studies of the ligaments of the OAA region in those horses where instability of this region due to soft tissue injury and spinal cord damage is suspected.

ACKNOWLEDGMENTS

The authors wish to thank the members of the Institute of Veterinary Anatomy, Institute of Veterinary Pathology, Claudia Di Giovanna, Dr. Florian Willmitzer, from the Vetsuisse Fakültat Zürich, and Dr. Richard Lang for their valuable cooperation in this study.

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