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Original Research

Prevalence of Age-Related Changes in Ovine Lumbar Intervertebral Discs during Computed Tomography and Magnetic Resonance Imaging

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Ovine models are used to study intervertebral disc (IVD) degeneration. The objective of the current study was to assess the naturally occurring age-related changes of the IVD that can be diagnosed by CT and MRI in the lumbar spine of sheep. We used CT and T2-weighted MR images to score the IVD (L6S1 to L1L2) in 41 sheep (age, 6 mo to 11 y) that were euthanized for reasons not related to musculoskeletal disease. T2 mapping and measurement of T2 time of L6S1 to L2L3 were performed in 22 of the sheep. Degenerative changes manifested as early as 2 y of age and occurred at every IVD level. Discs were more severely damaged in older sheep. The age effect of the L6S1 IVD was larger than the average age effect for the other IVD. The current study provides evidence that lesions similar to those encountered in humans can be identified by CT and MRI in lumbar spine of sheep. Ideally, research animals should be assessed at the initiation of preclinical trials to determine the extent of prevalent degenerative changes. The ovine lumbosacral disc seems particularly prone to degeneration and might be a favorable anatomic site for studying IVD degeneration.

Abbreviation: IVDD, intervertebral disc degeneration

Low back pain is one of the most common musculoskeletal diseases in humans, with a point prevalence of 12% to 30%.[10] The presence of intervertebral disc degeneration (IVDD) in the lumbar region shows a significant positive association with low back pain.[24] Preclinical research studies are commonly conducted on the lumbar spines of animal models.[1] In these models, IVDD can be induced by different methods, either mechanically or chemically, but several models of spontaneous IVDD have been described as well.[1]

Studies in animal species with spontaneously occurring lesions are important to investigate the natural process of IVDD, especially in the early phase of the disease.[1] In addition, it is important to know the prevalence of age-related naturally occurring IVDD in a population of research animals, to better select the subjects for preclinical trials.

Radiologic and morphologic studies provided evidence of age-related progressive disc degenerative changes in the lumbar spine of rabbits.[12,23] Furthermore, spontaneous IVDD of the thoracolumbar spine of both chondrodystrophic and nonchondrodystrophic dogs induces similar gross anatomic, histologic, and biochemical changes as those in humans.[3] Natural lumbar discal pathology occurs in large-animal species, too. However, in a series of 670 horses with back pain, only 3 had radiographic evidence of lumbar spondylosis.[13] Gross anatomic changes of IVD were identified frequently in slaughtered pigs and cattle.[6-8] In sheep, a species known as a favorable model in which to study IVDD given its anatomic, histologic, and biomechanical similarities with the human lumbar spine,[18,20,27] the prevalence of spontaneous IVDD is not well documented. Spondylosis was assessed in a series of 51 culled rams of unknown age, whereas age-related calcifications in the lumbar IVD has been investigated in a series of 18 sheep.[14,16]

The objective of the current study was to describe the age-related degenerative changes of the lumbar IVD that can be diagnosed by using CT and MRI in a population of sheep of differing ages. We hypothesized that (1) degenerative changes occur at every IVD level; (2) IVD damage increases in severity with increasing age; and (3) the age effect is larger for the lumbosacral disc than for other IVD.

Materials and Methods

Animals. The study population comprised 41 Texel-cross ewes (age, 6 mo to 11 y; weight, 50 to 75 kg) which were euthanized for reasons not related to musculoskeletal or neurologic disease and dedicated to the teaching of anatomy (dissection). These animals came from the pedigree flock of the breeding farm of the University of Namur: when ewes are no longer suitable for breeding due to loss of fertility or mastitis, they are retired and used for

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research or teaching. The experimental protocol (10/150/MU) was approved by the local ethics committee for animal welfare. All procedures complied with the Royal Decree on the Protection of Experimental Animals in concordance with European Directive 2010/73.

CT and conventional MRI. After euthanasia (intravenous injection of 150 mg/kg pentobarbital), sheep underwent CT scanning (model ICT256, Philips Healthcare, Best, Netherlands) in sternal recumbency. Acquisition parameters were 140 kV; 871 mA; slice thickness, 0.67 mm; matrix, 768 × 768; and pixel size, 0.3 × 0.3 mm. The field of view included 6 IVD starting from the lumbosacral disc. Sheep were also scanned in sternal recumbency by using a 1.5 T MRI unit (Magneton Symphony, Siemens, Erlangen, Germany) with 2 body coils. The field of view included 5 IVD starting from the lumbosacral disc. MRI acquisition parameters are listed in Table 1.

Conventional CT and T2-weighted MR images were used to generate a combined imaging score (CIS) for each of the 41 sheep (Figure 1), on the basis of the MRI signal and morphologic changes that are associated with IVDD:[2] loss of disc height (width loss in quadrupeds), osteophytes at the margins of the vertebral body, calcifications in the annulus or the nucleus, extension of the nucleus within and beyond the annulus, and Modic changes (a formal classification of signal intensity changes in vertebral body marrow adjacent to the endplates of degenerative discs).[15] Each parameter was scored on a scale of 0 to 3 according to the criteria defined in Figure 1; individual scores were summed to obtain an overall score.

Compositional MRI. In recent years, compositional imaging techniques using MRI have been developed to assess the biochemical composition of cartilage.[9]

MRI (or nuclear magnetic resonance, NMR) aims to identify the electromagnetic signal of the protons of the nuclei of specific atoms, typically the hydrogen atoms, within a magnetic field, after they have acquired additional energy from a proton-adapted radiofrequency pulse, which causes them to resonate. After the radiofrequency pulse ceases, the protons can return to their native energy state by 2 processes. In one process, they interact with magnetic fields in their environment and transfer their energy. This transfer of energy is called longitudinal (T1) relaxation (or T1 recovery). Alternatively, protons stop precessing in phase under the influence of other adjacent protons. This entropic process causes a decrease in phase coherence and an increase in global chaos or entropy; this phenomenon is called transverse (T2) relaxation (or T2 decay). These processes have specific durations, and the recovery of the protons' initial energy state is therefore specified by 2 relaxation times (time constants), T1 and T2, that are characteristic of the composition of the tissue.

The mobility of water protons varies with the tissue (that is, high mobility when they are in free water, low when they are immobilized in extracellular matrix), and this mobility influences especially the T2 relaxation time, due to interactions with neighboring protons. In MRI sequences highlighting T2 (referred to as T2-weighted sequences), mobile water protons (such as those in synovial fluid or in tissue with increased free-water content) give a hypersignal (long T2), whereas water protons immobilized in extracellular matrix (short T2) give a hyposignal. Because T2 reflects the water content and integrity of the extracellular matrix, specialized T2 sequences have been created to identify early stages of degeneration of cartilage. Overall, T2 sequences are preferred to T1 sequences to help identify pathology where changes in water content exist.

The term 'T2 time' or 'T2 relaxation time' refers to the measure of the time constant for the decay of transverse magnetization, T2. With T2 mapping, T2 relaxation times are transformed into a 2-dimensional, color map. For example, in the current study, blue indicates areas of short T2 time (less water), whereas red indicates regions of long T2 time (more water), reflecting variations in the compositional characteristics of the tissue. A validated color scale was used.[25] Criteria for T2 mapping are described in Figure 2. In the current study, compositional imaging was performed in 22 animals. Each parameter was scored on a scale of 1 to 4 according to the criteria defined in Figure 2; individual scores were summed to obtain an overall score.

Statistical analysis. Data included 246 discs from 41 sheep: 6 IVD levels were assessed and labeled L6S1 (lumbosacral), L5L6, L4L5, L4L3, L2L3, and L1L2. Even when 7 lumbar vertebrae were present, the last disc was labeled as L6S1. The effects of age and IVD level were assessed on 3 variables: CIS, T2 time, and T2 mapping. Three of the 41 sheep were excluded from analysis because of partial fusion between the last lumbar vertebra and the sacrum (transitional vertebra). Four categories of age were considered, respectively 0 to 1 y ($n = 5$), 2 to 4 ($n = 8$), 5 to 7 ($n = 14$) and 8 to 11 ($n = 11$), corresponding to young nulliparous female sheep, young breeding ewes, elderly breeding ewes, and older sheep that had not yet been retired because they retained reproductive potential despite their age.

For each analysis, a linear mixed-effects model was used with age, IVD level, and the interaction between age and IVD level as fixed effects and the sheep as a random effect. F-tests were computed to assess the statistical significance of fixed effects. To test the a priori hypothesis that the age-dependent modification of the scores was higher for the L6S1 level than for the other IVD levels, a linear contrast was used to compare the age effect (slope) in L6S1 level against the average age effect in the other IVD levels. A P value of 0.05 was considered to indicate statistical significance. The statistical software used was R 3.0.2 (R Foundation for Statistical Computing, Vienna, Austria), with ggplot2 for graphical presentation (Elegant graphics for data analysis, Springer, NY)[26].

Results

T2 mapping scores, CIS, and T2 times are reported in Table 2 for each IVD level and age category, and the slopes of changes in these parameters as a function of age are illustrated in Figure 3. Because several observations were superimposed when using raw data, slight noise ('jittering') was added to the age variable to avoid overplotting. However, statistical analyses were computed by using the raw data.

Whereas T2 time decreased with increasing age, CIS and T2 mapping scores increased (Table 2), thus indicating that IVDD was more prevalent in older animals. The effect of age was statistically significant at every IVD level for CIS ($F = 32.0$, $P < 0.0001$), T2 mapping score ($F = 21.1$, $P = 0.0003$), and T2 time ($F = 27.4$, $P = 0.0001$). In addition, the age effect at the L6S1 IVD was greater than the average age effect at all other IVD for all 3 experimental outcomes, that is, CIS score ($Z = -10.11$, $P < 0.0001$), T2 mapping score ($Z = -3.05$, $P = 0.001$), and T2 time ($Z = 2.05$, $P = 0.02$). The slopes of changes in CIS, T2 mapping, and T2 time as a function of age (Figure 3) were greater for the L6S1 level, illustrating a faster degenerative process at that level compared with others.

Table 1. MRI parameters

	Sagittal T2-weighted Fast SE	Sagittal T1-weighted Fast SE	Sagittal T2 Mapping
Field strength (T)	1.5	1.5	1.5
Repetition time (ms)	3770	400	1110
Echo time (ms)	88	11	13.8 / 27.6 / 41.4 / 55.2 / 69 / 82.8
Flip angle (degrees)	180	150	180
Matrix	512 × 304	512 × 304	320 × 320
Pixel size (mm)	0.7 × 0.7	0.7 × 0.7	0.7 × 0.7
Section thickness (mm)	3	3	6
No. of signals acquired	10	4	3
Bandwith	150	181	226

	CT			MRI		
Score	Loss in height	Osteophytes	Intradiscal calcification	T2 signal intensity	Shape of nucleus	Modic change
0	0%–10%	Margins rounded	None	Normal	Oval	None
1	10%–20%	Margins pointed	Rim calcification	Moderate loss	Extension into inner annulus	Type I
2	20%–30%	< 2 mm	Intranuclear calcification	Marked loss	Extension into outer annulus	Type II
3	>30%	≥ 2 mm	Intranuclear calcification	Signal absent	Extension beyond outer annulus	Type III

Figure 1. Using CT and conventional MRI, 6 different parameters were scored in sheep: (1) loss of disc thickness (height); (2) new bone formation at the margins of the vertebral body (osteophytes); (3) calcifications in the annulus or nucleus; (4) penetration of the nucleus within and beyond the annulus; (5) reduction of T2 signal (indicating loss of water from the disc or loss of integrity of the extracellular matrix); and (6) Modic changes (Modic type 1, vascular development in the vertebral body, without trabecular damage or marrow changes; Modic type 2, changes in the bone marrow, with fatty replacement of the red, cellular marrow; and Modic type 3, visible fractures of the trabecular bone). A score from 0 to 3 is assigned to each of the 6 parameters according to defined characteristics. For example, a score of 2 is given for the parameter 'osteophytes' when pointed articular margins are identified. The 6 scores are summed to generate a combined imaging score (CIS), which is interpreted as no, moderate, intermediate, and severe intervertebral disc disease when it is less than 1, 2 to 4, 5 to 7, and greater than 7, respectively.

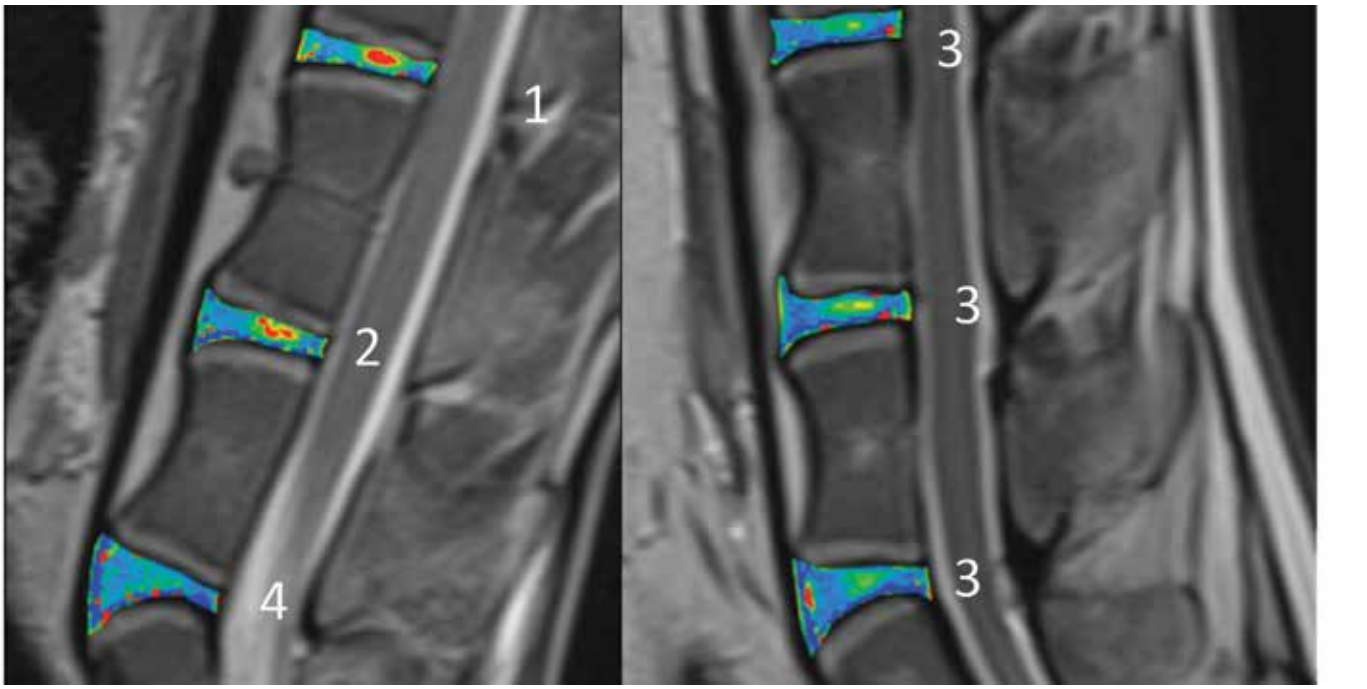

Figure 2. Scores at T2 mapping. With T2 mapping, T2 relaxation times are transformed into a color map. Regions of interest were placed around the nucleus pulposus. As degeneration advances, color repartition in the annulus fibrosus (AF) and nucleus pulposus (NP) changes and, at the last stage, the distinction between the AF and NP is lost. Blue (high score) indicated areas of short T2 time and red (low score) depicted regions of long T2 time. Scores ranged from 1 to 4: 1, healthy intervertebral disc (IVD) with high and homogeneous T2 signal and a clear distinction between NP and AF; 2, mildly decreased and inhomogeneous T2 signal and less regular borders; 3, the T2 signal of the IVD is moderately reduced and inhomogeneous, and the distinction between the NP and the AF is not clear; and 4, the T2 signal of the IVD is severely decreased and inhomogeneous, and the distinction between the NP and the AF is lost.

Table 2. Combined imaging score, T2 mapping score, and T2 time by intervertebral disc level and age category

	Age (number) of sheep			
Combined imaging score	0–1 y (*n* = 5)	2–4 y (*n* = 8)	5–7 y (*n* = 14)	8–11 y (*n* = 11)
L1L2	0 ± 0	0.9 ± 0.4	0.7 ± 0.5	2.0 ± 1.7
L2L3	0 ± 0	0.9 ± 0.4	0.9 ± 0.8	1.8 ± 1.7
L3L4	0 ± 0	0.9 ± 0.4	0.9 ± 0.8	1.9 ± 1.6
L4L5	0 ± 0	0.9 ± 0.4	0.8 ± 0.6	1.9 ± 1.6
L5L6	0 ± 0	1.0 ± 0.5	1.1 ± 0.5	1.8 ± 1.5
L6S1	0 ± 0	4.4 ± 2.0	4.9 ± 1.6	7.7 ± 2.4
T2 mapping score	0–1 y (*n* = 5)	2–4 y (*n* = 4)	5–7 y (*n* = 5)	8–11 y (*n* = 5)
L2L3	1.0 ± 0.0	2.5 ± 0.6	2.8 ± 0.4	3.2 ± 0.8
L3L4	1.0 ± 0.0	2.5 ± 0.6	2.9 ± 0.5	3.1 ± 0.7
L4L5	1.2 ± 0.4	2.6 ± 0.8	2.9 ± 0.5	3.0 ± 0.8
L5L6	1.2 ± 0.4	2.8 ± 1.0	2.8 ± 0.6	3.1 ± 0.8
L6S1	1.0 ± 0.0	3.6 ± 0.5	3.8 ± 0.3	4.0 ± 0.0
T2 time	0–1 y (*n* = 5)	2–4 y (*n* = 4)	5–7 y (*n* = 5)	8–11 y (*n* = 5)
L2L3	72.0 ± 13.4	55.8 ± 10.2	41.6 ± 1.8	34.2 ± 12.5
L3L4	77.0 ± 11.2	48.2 ± 5.0	42.0 ± 9.5	36.0 ± 15.7
L4L5	74.4 ± 13.3	54.0 ± 9.9	43.2 ± 14.2	38.2 ± 16.1
L5L6	73.2 ± 16.0	55.0 ± 16.1	44.8 ± 9.3	38.8 ± 16
L6S1	75.8 ± 11.7	34.5 ± 7.0	27.4 ± 6.8	21.8 ± 3.4

The data show that CIS and T2 mapping scores increased with age, whereas T2 time decreased.

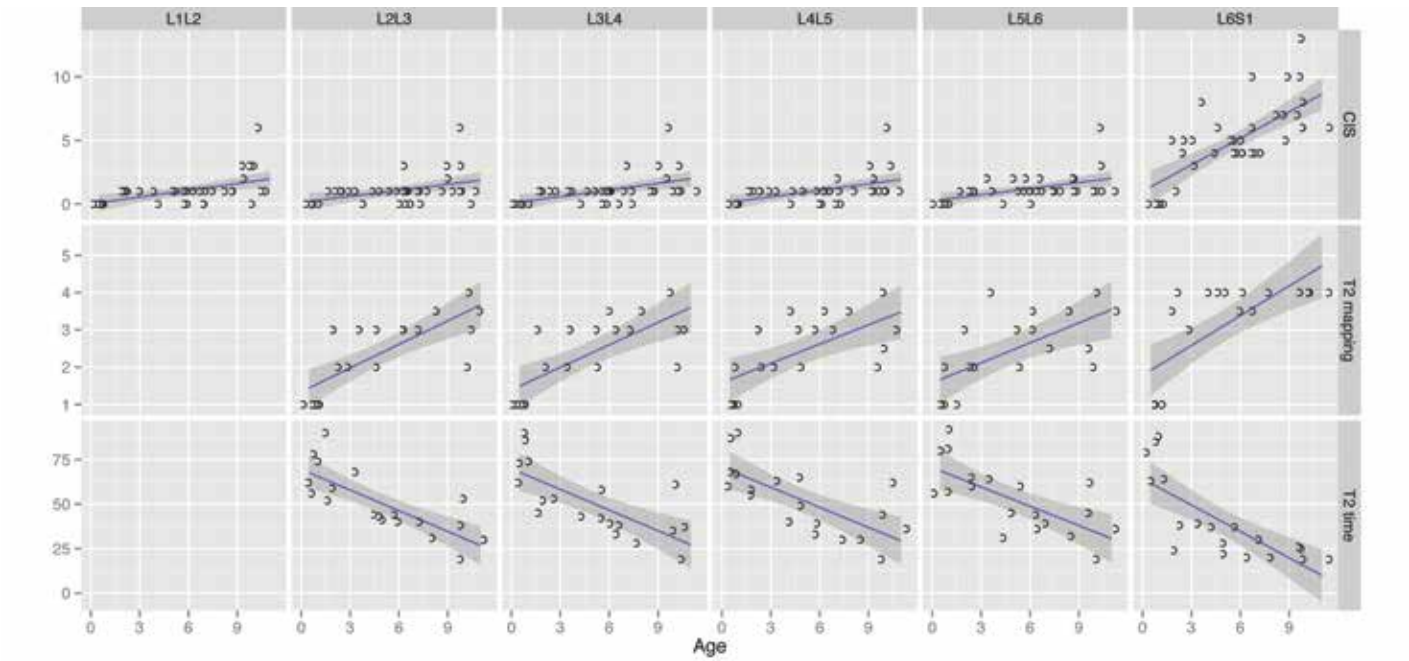

Figure 3. Changes in combined imaging score (CIS), T2 mapping score, and T2 time as a function of age (in years) according to intervertebral disc level. Blue, linear regression line; shaded area, 95% confidence interval for the mean. Slopes are larger for L6S1, illustrating more rapid degeneration at that level.

The prevalence of intradiscal calcifications and osteophytes is reported in Table 3. When present in the lumbosacral disc, calcifications were present at the ventral border of the annulus, whereas they were always found at the transition region between the nucleus and the annulus when they were identified at other levels (Figure 4). Loss of endplate integrity was seen in one sheep (at the L6S1 level). In addition, 3 sheep had lumbosacral transitional vertebrae (Figure 5); this condition is an anatomic variation of

Table 3. Prevalence of osteophytes and intradiscal calcifications

	% of intervertebral discs affected			
	0–1 y (n = 5)	2–4 y (n = 8)	5–7 y (n = 14)	8–11 y (n = 11)
Calcifications				
at L6–S1	0	0	1	27
at other levels	0	0	20	27
Osteophytes				
at L6–S1	0	12	35	90
at other levels	0	0	0	0

the last lumbar vertebra in which an enlarged transverse process forms a joint or fusion with the sacrum or ilium. In those sheep with partial fusion of L6 and S1, the highest CIS score (indicating disease) was at the L5L6 level. In these sheep, the absence of osteophytes and lesions (such as thinning) of the disc indicated that the fusion was congenital and not due to a degenerative process.

Discussion

The current study identified age-related changes of the IVD that can be diagnosed by CT and MRI in a population of ewes of various ages. Our findings demonstrate that changes in IVD can occur naturally and manifest in young adult sheep, even as early as 2 y of age. Changes were found at every IVD level, and their extent increased with age. The age effect was particularly marked at the L6S1 level.

Naturally occurring IVDD occurs in several large-animal species. The lumbar columns of 60 adult breeding sows of unknown age and collected from a slaughter house were assessed macrocopically.[6] IVDD-associated changes, such as narrowing of the intervertebral space; conversion of the nucleus pulposus to a dark, friable, sometimes granular mass; fraying and discoloration of the annulus fibrosus; osteosclerosis of the epiphyses and bodies of adjacent vertebrae were present in 40% of the samples. Although there was no evidence of ventral or dorsal herniation of disc material, 38% of the sows had vertebral osteophytes mostly localized between L1 and L3.[6] A series of 30 young (age, 5 to 7 mo) slaughter pigs demonstrated only asymmetry of lumbar articular facets and minor periarticular osteophytes.[6] Similarly, in a study population of 78 boars, pathologic changes were not noted in 6-mo-old animals, but lumbar disc degeneration was identified in 38% of boars older than 18 mo.[7]

Another study assessed the lumbar spines of 200 slaughtered female Swedish red-and-white cattle in different age groups.[8] Calves and heifers had no macroscopic signs of lumbar disc degeneration. However, 27.5% of the 3- to 5-y-old animals and 93.7% of those 9 y of age and older showed macroscopic signs of degeneration of the lumbar vertebral discs. In addition, lesions were 9 times more frequent at the lumbosacral junction than elsewhere. Lumbosacral lesions consistently showed a characteristic dorsal rupture of the nucleus pulposus, which typically was combined with rupture of the annulus fibrosus.[8]

Limited information is available regarding the prevalence of spinal disc degeneration in sheep. A cross-sectional study radiographically and histologically assessed the vertebral columns from 51 cull rams and identified evidence of spondylosis, defined as boney proliferation from the margin of vertebral end-plates, in at least one intervertebral space in 40 (78%) of the animals;[16] 11 of these had ankylosis (spondylosis resulting in osteophytes that fuse between adjacent vertebrae) involving one or more intervertebral spaces. The frequency of lesions was greater in the thoracic than lumbar region and was greatest at T10T11. However the study did not attempt to assess the effect of age.[16] Another study of 18 sheep documented age-related calcification of IVD by using scanning and transmission electron microscopy, energy-dispersive X-ray spectroscopy, X-ray powder diffraction, and histology.[14] The authors concluded that 50% of the discs in 6-y-old sheep, 84% of those in 8-y-olds, and 86% of those in 10-y-olds presented calcifications due to hydroxyapatite deposition, with maximal incidence in lower-level discs (L4L5, L6L7) and no occurrence in the lumbosacral disc.

The low frequency of advanced macroscopic changes is a major difference between the current study involving sheep and those investigating structural changes in cattle. End-plate integrity was lost in only one case in the current study, and no osteolysis was identified. In cattle, radiographic assessment showed that lumbosacral changes affected not only the disc but also the cartilage end-plate and adjacent bone and included sclerosis, osteolytic processes with the creation of subchondral bone cysts, and avulsion fractures of the dorsocranial border of the sacrum.[8] Differences in the manner in which cases were selected for inclusion might account for the differences between the current and previous study: questionnaires sent to the owners of slaughtered cattle revealed that 25% of the animals presented with hindquarter problems.[8] In contrast, all sheep in the current study were free of clinical signs of musculoskeletal disease.

Because details of the age or reason for culling are unavailable regarding the study that assessed spondylosis in rams,[16] it is difficult to explain the lower frequency of lesions in our current population. It is unlikely that discrepancies are due to a more protected environment in the current study, which involved sheep belonging to pedigreed breeding flock. In general, sheep are used for teaching or research when they are retired for a reason not associated with a musculoskeletal disease (mastitis, loss of fertility). As such, they have spent a normal life. Differences between the previous[16] and current study are more likely due to breed, sex, or activity level. For example, rams extend their lumbosacral spine during sexual mounting. Among nonchondrodystrophic dogs, German Shepherds, especially male working dogs, are at the highest risk of developing IVDD, particularly at the lumbosacral level.[22]

In the current study, calcifications were identified by CT less frequently than in the study using microscopic imaging.[14] Differences in resolution account for this difference between studies. Another discrepancy was that we identified calcifications at the ventral border of the annulus of the L6S1 disc whereas this abnormality was not identified at all at the L6S1 level in the previous study. However, calcifications at the transitional zone were found at other levels in both studies.

As noted in cattle, the L6S1 disc of sheep was the site most often affected by degeneration. This portion of the vertebral column is subjected to strong mechanical stresses.[8] In nonchondrodystrophic dogs, the L7S1 junction is very mobile in flexion, extension, and axial rotations. In addition, this joint is very prone to ventrodorsal subluxation and instability due to low ventrodorsal shear stiffness.[20] These biomechanical factors predispose the L6S1 disc to increased wear and tear and IVDD. Interestingly, in the current study, partial ossification (transitional vertebra) was identified in

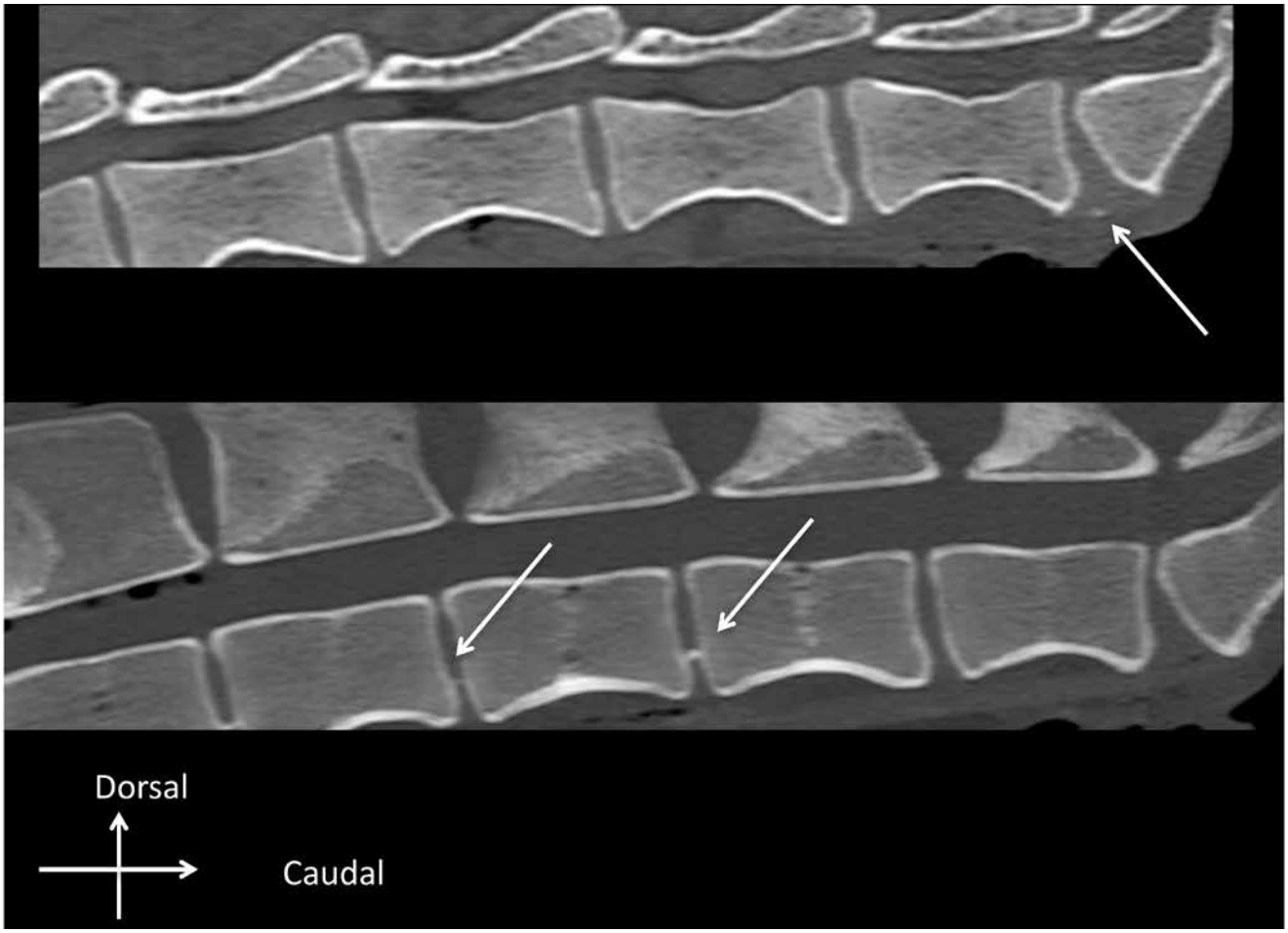

Figure 4. Intradiscal calcifications were present at the ventral border of the annulus fibrosus (AF) when they were identified at the L6S1 level (white arrow, top). At other levels, they were always seen at the transitional zone between the AF and nucleus pulposus (NP; white arrows, bottom).

3 sheep, in which the highest CIS (indicating disease) occurred at L5L6. This finding may strengthen the hypothesis of a biomechanical etiology of the disease and that IVDD occurs where mobility is the highest, in this case being transferred to the L5L6 level in the presence of a congenital transitional vertebra at L6S1.

The appropriateness of using ovine IVD as models of IVDD for examining the suitability and practicality of therapeutic procedures has been questioned.[1] Comparative biomechanical and anatomic studies have demonstrated that vertebral columns are comparable between humans and sheep.[27] In addition, the vertebral discs have similar histologic and biochemical characteristics in both species.[18] Despite the conjecture that, due to the horizontal position of the vertebral column, intradiscal loads may be less in sheep than in bipeds, the intervertebral ovine disc is consistently subjected to higher pressures than is the human disc.[19,27] Because spinal segments cannot withstand substantial bending moments, additional tensile forces from muscles and ligaments are necessary to control the posture of a quadruped spine; as a consequence, the spine is mainly loaded by axial compression.[21] The current study provided additional evidence that lesions similar to those encountered in humans can be identified by CT and MRI in ovine spines.

In addition, the current study suggested that CT and MRI scores used for man could be useful to assess IVDD in sheep in future longitudinal preclinical studies.[2,25] The Pfirrmann MRI score has been used in dogs and was moderately correlated with the histologic grade.[11,17] In rabbits, an early age-dependent increase in the Pfirrmann grading perfectly corroborated histologic scoring.[4] The classification reported by Pfirrmann focuses on signal intensity and structural morphology of the nucleus pulposus on sagittal T2-weighted MR images.[17] In the current study, a CIS score was used. This CIS score includes CT criteria and has therefore the advantage of identifying calcifications and small osteophytes, which are not always visible with MRI.[2] Our study provided useful reference values for the CIS, T2 mapping score, and T2 time in a population of research sheep. This information is useful because of evidence indicating that compositional imaging, such as T2* relaxation time, has relatively good correlation with the histologic structure and proteoglycan content of the IVD in small ruminants, such as goats.[5]

In conclusion, the current study showed that IVDD in the ovine lumbar spine can occur very early. Therefore, in longitudinal clinical studies, research animals should ideally be assessed at baseline—even if they are young adults—to determine the extent of

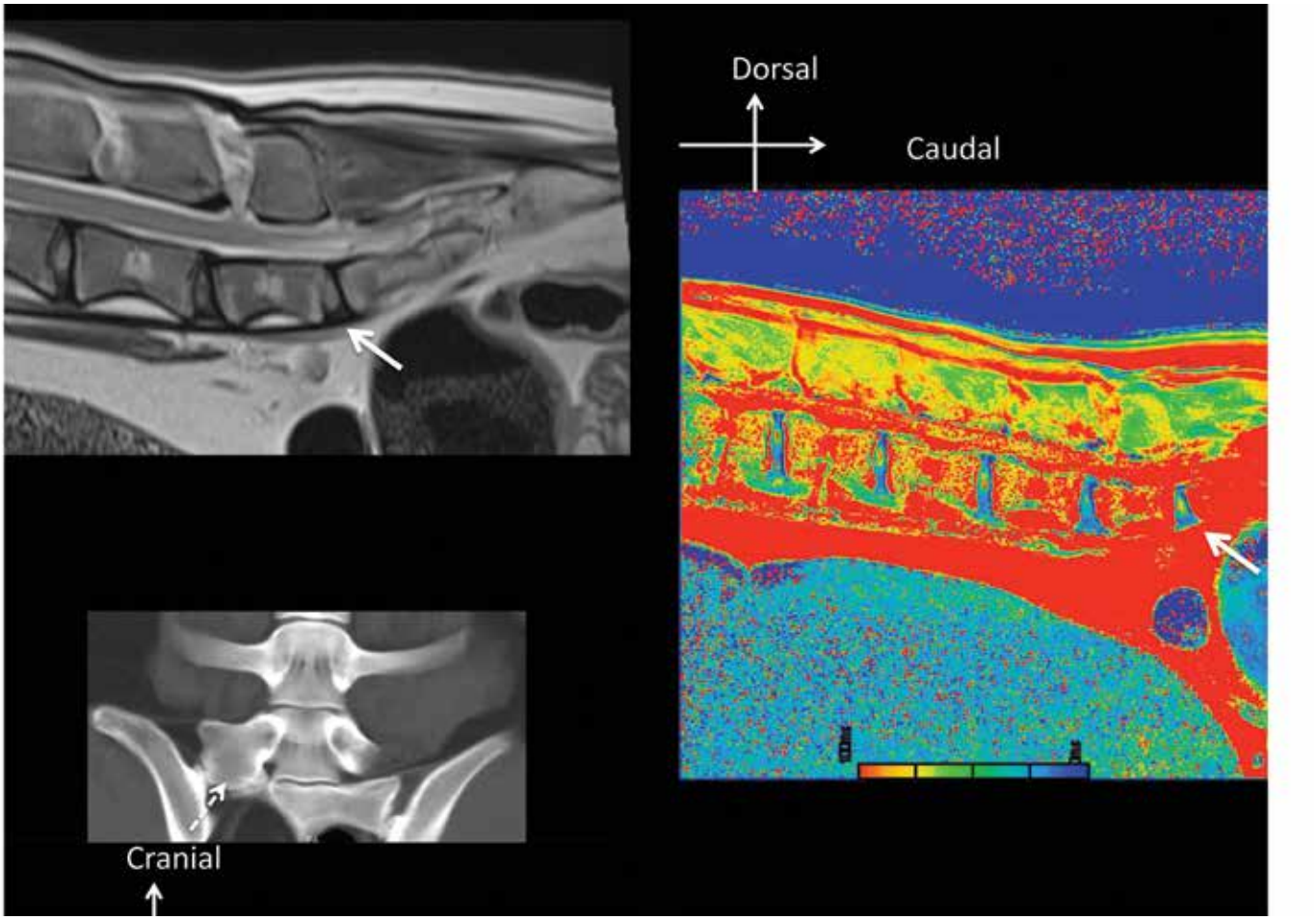

Figure 5. Transitional vertebrae were found in 3 sheep. Transitional vertebrae are an anatomic variation of the last lumbar vertebra (L6) in which an enlarged transverse process (dotted white arrow) can form a joint or fusion with the sacrum (S1). In those 3 animals, the lumbosacral disc (white arrow) had a lower CIS score and higher T2 time than the L5L6 disc (white arrow). With T2 mapping, T2 relaxation times are transformed into a color map. Blue (high score) indicates areas of short T2 time, and red (low score) depicts regions of long T2 time.

degenerative changes. CT and MRI appear to be useful modalities to detect prevalent degenerative changes in IVD and to help select animal subjects for research. The lumbosacral disc seems particularly prone to degeneration and might be an especially helpful anatomic site to study IVDD. The reference data we provide here will increase our ability to evaluate the pathogenesis, progression, and treatment of IVDD.

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