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Is bone density associated with intervertebral disc pressure in healthy and degenerated discs?

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Abstract

The coupling of the intervertebral disc (IVD) and vertebra as a biomechanical unit suggests that changes in the distribution of pressure within the IVD (intradiscal pressure, IDP) as a result of disc degeneration can influence the distribution of bone density within the vertebra, and vice versa. The goal of this study was to assess the correspondence between IDP and bone density in the adjacent vertebrae, with emphasis on how this correspondence differs between healthy and degenerated IVDs. Bone density of the endplates and subchondral bone in regions adjacent to the anterior and posterior annulus fibrosus (aAF and pAF, respectively) and nucleus pulposus (NP) was measured via quantitative computed tomography (QCT) in 61 spine segments (T7-9, T9-11, T10-12; 71±14 years). IDP was measured in the aAF, NP, and pAF regions in 26 of the spine segments (68±16 years) while they were tested in flexed (5°) or erect postures. Disc degeneration was assessed by multiple grading schemes. No correlation was found between bone density and IDP in either posture ($p>0.104$). Regional variations in IDP and, to a greater extent bone density, were found to change with advancing degeneration: both IDP ($p=0.045$) and bone density ($p=0.024$) decreased in the NP region relative to the aAF region. The finding of only a modest correspondence between degeneration-associated changes in IDP and bone density may arise from complexity in how IDP relates to mechanical force transmission through the endplate and from limitations of the available IVD grading schemes in estimating the mechanical behavior of the IVD.

Keywords

disc degeneration; vertebra; endplate; intervertebral disc; nucleus pulposus; annulus fibrosus; glycosaminoglycan; disc space narrowing; computed tomography

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Introduction

The intervertebral disc (IVD) is commonly involved in age-related pathologies in the spine. Disc degeneration afflicts as many as 69% of Americans over age 55 and is associated with back pain, postural changes, and reduced mobility (Burger, et al., 1997; de Schepper, et al., 2010). The role of the IVD in transferring load between vertebrae means that degenerative changes in the IVD can alter how force is distributed over the vertebral endplate (Dai, 1998; Homminga, et al., 2012; Kurowski and Kubo, 1986) and, consequently, affect the likelihood of vertebral fracture (Homminga, et al., 2012; Sornay-Rendu, et al., 2006). Conversely, stresses within the IVD can be impacted by vertebral fracture and other structural and mechanical changes in the vertebra that occur with injury and aging (Dolan, et al., 2013). Thus, for the purposes of managing and preventing IVD-related, deleterious conditions in the spine, it is imperative to determine how disc degeneration is associated with mechanical and structural changes not only in the IVD but also in the adjacent vertebrae.

Current understanding of the biomechanics of disc degeneration regards pressure within the nucleus pulposus (NP) as the lynchpin of proper mechanical function of the IVD. Loss of glycosaminoglycan content and water from the NP, and tears in the annulus fibrosus (AF), lead to changes in the distribution of intradiscal pressure (IDP) among the NP, anterior AF, and posterior AF (Adams, et al., 1996; McNally and Adams, 1992; Zehra, et al., 2015). The abnormal distribution of IDP may cause the clinical symptoms of degenerative disc disease (Inoue and Espinoza Orias, 2011), as well as further structural damage (Stefanakis, et al., 2014). Loss of NP pressure has been qualitatively associated with disc degeneration as assessed by gross observation during dissection (Adams, et al., 1996), and osmotic pressure in the NP has been found to be correlated with two metrics obtained from magnetic resonance imaging (MRI), the Pfirrmann grade and the relaxation time constant T1 ρ (Borthakur, et al., 2011). However, no studies to our knowledge have examined direct quantitative associations between the regional distribution of IDP and degeneration assessed by non-invasive grading schemes such as disc space narrowing (DSN). At present, it is unknown if the spatial variation in IDP—a direct, biomechanical measure of IVD function—can be estimated from clinically feasible evaluations of disc health.

Degenerative changes in IDP have been suggested to cause bone adaptation in the vertebra. Spatial distributions of density and microstructure within the trabecular centrum differ in vertebrae with vs. without degeneration in the adjacent IVDs (Fazzalari, et al., 2001; Keller, et al., 1993; Simpson, et al., 2001). Conceptually, these differences may arise from bone adaptation in response to the altered load distribution (Fazzalari, et al., 2001; Homminga, et al., 2012; Keller, et al., 1993; Pollintine, et al., 2004; Simpson, et al., 2001) and/or effects that altered vertebral mechanical behavior could have on the course of disc degeneration. However, conflicting conclusions have been reported as to whether these differences are consistent with changes in IDP (Adams, et al., 2006; Pollintine, et al., 2004; Wang, et al., 2013). This discrepancy among studies may be due to differences in the regions of the vertebral body that were evaluated, the population sampling (i.e. donor age and sex, and spinal level (Adams and Dolan, 2013)), the measures of bone microstructure, and the methods of scoring disc degeneration. Clarifying the extent of interdependence of disc

degeneration and the internal bony structure of the vertebra would provide much needed insight into the coupling of vertebra and IVD as a biomechanical unit.

The overall objective of our study was to assess the correspondence between IDP and bone density in the adjacent vertebrae, with emphasis on how this correspondence may manifest differently as disc degeneration progresses. The specific tasks were: 1) to define how the IDP and its spatial distribution differ among stages of disc degeneration, as classified both by standard assessments of gross morphology and histological appearance and by noninvasive radiological assessments; 2) to define how the distribution of bone density adjacent to the IVD differs among stages of disc degeneration; and 3) to determine the association between the spatial distributions of IDP and bone density.

Materials and Methods

Study Design

Sixty-one thoracic spine segments (ten T9-T11, 19 T10-T12, and 32 T7-T9) from 42 cadavers (age: 35–91 years; mean±stdev: 71±14 years; 23 males, 19 females) were dissected from fresh-frozen spines (National Disease Research Interchange, Philadelphia, PA; Life Legacy Foundation, Tuscon, AZ). As described below, both IVDs of each spine segment were scored according to two non-invasive, radiological grading methods, DSN (Lane, et al., 1993) and the apparent loss of disc integrity (ALDI) (Hussein, et al., 2013), and the bone mineral density of the endplate region superior and inferior to each IVD was measured via quantitative computed tomography (QCT). A subset of these spine segments (n=26: eight T9-T11 and 18 T10-T12 segments from 26 donors, aged 35–86 years; mean ± standard deviation: 68 ± 16 years; 16 male, 10 female) was then used to measure the IDP in each of the two IVDs per segment. Following the pressure measurements, the IVDs in these 26 spine segments were scored according to two grading methods that require dissection, Thompson (Thompson, et al., 1990) and the histological scoring method of Rutges et al. (Rutges, et al., 2013) Finally, the IVD tissues of these 26 segments were processed to measure glycosaminoglycan (GAG) content and water content. The 35 spine segments not used for IDP measurements were not processed for histology and biochemical evaluation, because they had been subjected to mechanical testing to failure in a prior study (Jackman, et al., 2016); however, Thompson scoring was still performed for the IVDs in these spine segments, and thus Thompson scores were available for the IVDs in all 61 spine segments used in the present study.

Quantitative Computed Tomography (QCT)

Each spine segment underwent a QCT scan (LightSpeed CT, GE Healthcare, Cleveland, OH) at a slice thickness of 0.625 mm and an in-plane resolution of either 0.3125×0.3125 (n=59) or 0.3906×0.3906 (n=2) mm/pixel. Scans were performed in the presence of a calcium hydroxyapatite phantom (Image Analysis, Columbia, KY) to allow conversion of Hounsfield Units to mg/cc. Image stacks were interpolated along the axial direction to produce isotropic voxels and rotated in the sagittal plane to make the endplates approximately horizontal. All interpolations were made in MATLAB (MathWorks, Natick MA) using the bi-cubic method (Lehmann, et al., 1999; Meijering, et al., 2001).

Measurement of IDP

IDP was measured in a manner similar to that used by Adams and colleagues (McNally and Adams, 1992). Briefly, the superior- and inferior-most vertebral bodies were potted in polymethyl methacrylate (PMMA). The posterior elements were left unembedded. The specimens were subjected to a 300N load, in either an erect (0° flexion; n=12) or an anteriorly flexed (5°; n=14) posture, for 30 minutes to reduce effects of super-hydration *post mortem* (Instron 8874, Canton, MA). Specimens were then subjected to 500 N in the same posture. IDP measurements were collected by inserting a pressure transducer (Gaeltec Ltd., Duvegan, Isle of Skye, UK) entirely through the mid-sagittal plane of each disc, upon reaching the 500N load, and then collecting pressure and position data (at a frequency of 1 Hz) as the transducer was retracted at rate of approximately 1 mm/sec (Figure 1). Pressure measurements were not performed in one IVD, because a bridging osteophyte prevented insertion of the transducer.

Evaluation of Disc Degeneration

Four methods of disc grading were used: DSN, ALDI, Thompson, and Rutges (Table 1). Details of these evaluations are included in the Supplemental Material. Not all specimens could be graded by all methods. Three IVDs were damaged during dissection and could not be graded for Thompson (leaving 119 IVDs from 61 spine segments for Thompson grading). The histological sections of three IVDs from the cohort of 26 spine segments used for pressure measurements were not of adequate quality for grading (leaving 49 IVDs for Rutges grading). All 122 IVDs were graded by ALDI and DSN.

Disc degeneration was also assessed by quantifying GAG content and water content (in % of dry weight) of the NP (see the Supplemental Material for details).

Measurement of Bone Density

Changes in load distribution across the endplate alter the distribution of stresses not only within the endplate but also within the subchondral trabecular bone (Homminga, et al., 2012). This phenomenon creates some uncertainty in how much of the subchondral bone to include when examining a potential correspondence between bone density and IVD health. Thus, three measures of bone density, each representing the density of a successively greater portion of the height of the vertebra, extending from the surface of the bony endplate down into the centrum, were collected along a 3mm-wide, mid-sagittal QCT section of each of the four endplates in the spine segment (Figure 2): maximum intensity projection (MIP) of the endplate region (Muller-Gerbl, et al., 1989); the density of the EP to a 2mm depth (EP); and the density of the endplate and subchondral bone down to a total depth of 7 mm (EP+adj). The EP+adj measure was not available in the inferior layer of the superior-most vertebra and the superior layer of the inferior-most vertebra in 14 of the 61 specimens. Osteophytes were excluded from the preceding measures. Integral bone mineral density (in.BMD) was measured for the entire vertebral body (not restricted to the mid-sagittal plane).

Statistical Analysis

To analyze the regional variations in IDP and density, each of the previously described measures of IDP and density were quantified in regions representing the anterior AF (aAF),

the NP, and the posterior AF (pAF) (Figure 2), defined using a modification of the algorithm created by Adams et al. (Adams, et al., 1996) (Supplementary Material). For each grading scheme for disc degeneration, a repeated-measures analysis of variance (ANOVA) was performed with region as the within-subject effect, disc degeneration score as the between-subject effect, and IDP or a density measure (representing the average value within a given region) as the dependent variable. These ANOVAs for density were also run including in.BMD as an additional between-subject effect and, separately, including donor age and sex as additional between-subject effects. The Thompson, DSN, and Rutges grading schemes were compressed to two or three levels (Table 1) in order to distribute the IVDs more evenly among the scores in each grading scheme and thus facilitate analysis by parametric statistics. The ANOVAs were run for each layer of the spine segment (Figure 2) separately. Repeated-measures ANOVAs for bone density as a function of spine level (T7-T12) indicated minimal dependence: the only difference that was found was that MIP in the aAF region was higher in the inferior endplate of T7 compared to T11 ($p=0.038$).

Spearman's rank correlation analyses were performed to test for associations between average IDP in a given region and average bone density (MIP, EP, or EP+adj) in that region, between average IDP in the NP and GAG and water contents of the NP (expressed as % dry weight), between GAG and water contents of the NP, between body weight and regional IDP, and between body weight and bone density (MIP, EP, or EP+adj). We also performed a linear regression analysis of IDP against body weight and density to determine if including body weight as an independent variable changed the correlation between IDP and density. GAG content and water content were each compared among the levels of each IVD grading scheme using one-way ANOVA. Contingency analysis was used to determine the extent to which the disc degeneration scores compared with one another.

All statistical analyses were carried out in JMP (version 11.2, SAS, Cary, NC). Because of the large number of pairwise correlation analyses between IDP and density (nine per layer per loading mode), the significance level was adjusted via the Bonferroni correction to 0.0055. All other analyses used a significance level of 0.05.

Results

IDP as a function of region and disc degeneration

IDP varied among regions in a manner that depended on the non-invasive measures of disc degeneration. Irrespective of degeneration score, IDP was higher in the NP than aAF in the erect posture ($p=0.050$), and higher in the aAF than pAF in the flexed posture ($p=0.028$) (Figure 3A). This regional variation in the erect posture was most pronounced in healthy IVDs, as scored by ALDI ($p=0.012$ for NP vs. aAF for ALDI=0, whereas $p>0.128$ for ALDI=1 or 2), and that in the flexed posture was most pronounced in the degenerated IVDs, as scored by DSN ($p=0.003$) (Figure 3B). Over all three regions, IDP in flexion decreased with increasing Thompson score ($p=0.003$); a trend toward this effect was also noted for DSN score ($p=0.057$). No dependence of IDP ($p=0.151$ and 0.176 for erect and flexed postures, respectively), or of regional variations in IDP ($p=0.608$ and 0.193 for erect and flexed postures, respectively), on Rutges score was found.

NP pressure was positively correlated with GAG and water contents in the flexed (Spearman's $\rho=0.614$ $p<0.001$, Spearman's $\rho=0.516$ $p=0.007$, respectively) but not erect (Spearman's $\rho=-0.059$ $p=0.788$, Spearman's $\rho=0.013$ $p=0.954$, respectively) posture (Figure 4A). GAG and water content were correlated with each other (Spearman's $\rho=0.378$, $p=0.007$) but differed among degeneration scores only for the Thompson ($p<0.001$) and ALDI ($p=0.021$) grading schemes, respectively (Figure 4B, Supplementary Figure 1). The dependence of the GAG and water contents, and of the spatial distribution of IDP (Figure 3), on some but not all grading schemes for disc degeneration raised the question of the extent to which the multiple schemes agree with each other. IVDs scored as healthy or severely degenerated by Thompson and/or Rutges were generally scored as healthy or severely degenerated, respectively, by ALDI and DSN; however, there were also IVDs for which the scores from different schemes did not correspond to one another (Table 2).

Bone density as a function of region and disc degeneration

Bone density varied among aAF, NP, and pAF regions in a manner that was partly independent of disc degeneration scores (Figure 5A). For example, all of the density measures—both at the superior and inferior aspects of the vertebra—were lowest in the NP region ($p<0.001$). MIP was higher in the pAF vs. aAF at the superior endplate ($p<0.001$), but lower in the pAF vs. aAF at the inferior endplate ($p=0.014$).

However, the regional variations in bone density also differed among disc degeneration scores. Whereas the MIP in the pAF region of the superior endplate was higher than that in the aAF region at the lowest ALDI and Thompson scores ($p<0.001$), this difference was not present at the highest ALDI ($p=0.113$) and Thompson ($p=0.870$) scores (Figure 5B). With advancing ALDI and Thompson scores, the differences in MIP between the AF and NP regions became more pronounced ($p=0.024$ and 0.067 , for ALDI and Thompson, respectively). No dependence of regional variations in any of the density measures on Rutges score was found ($p>0.212$).

Including in.BMD, or age and sex, as co-variables in the ANOVAs did not change any of the findings regarding variations in density among NP and AF regions. Yet, these analyses did show that the correlation between the density of the entire EP+adj layer (NP and both AF regions combined) and in.BMD depended on IVD degeneration ($p<0.030$) as scored by ALDI and Thompson: whereas the superior EP+adj density increased with in.BMD ($p<0.001$), this association was least pronounced at the highest ALDI and Thompson scores. All density measures at the superior endplate were higher in male vs. female vertebrae ($p<0.016$). EP+adj of the inferior endplate was also higher in male vs. female vertebrae ($p=0.023$), but MIP and EP only trended higher in males ($p=0.054$ and $p=0.066$, respectively). The difference in EP+adj at the superior endplate between AF and NP regions was larger in male vs. female vertebrae ($p=0.032$); in contrast, this sex dependence of regional variations in bone density was not found MIP or EP at the superior endplate or in any of the density measures at the inferior endplate ($p>0.196$). EP+adj tended to decrease with age in superior ($p=0.062$) and inferior ($p=0.021$) endplates, whereas the other two density measures exhibited less age dependence ($p>0.096$).

Associations between IDP and bone density

IDP was not correlated with any of the measures of bone density in any of the regions (Figure 6, Spearman's $\rho < 0.476$, $p > 0.104$ after Bonferroni correction). GAG content was weakly correlated with NP EP+adj density (Spearman's $\rho = 0.370$; $p = 0.008$) in superior EPs. No other correlations between GAG and density measures, or water content and density measures, were found (Spearman's $\rho < 0.225$, $p > 0.116$). None of the IDP or density measures was correlated with body weight (Spearman's $\rho < 0.324$, $p > 0.191$ after Bonferroni correction), and accounting for body weight did not alter the lack of correlation between IDP and density.

Discussion

Changes that occur in the IVD and adjacent vertebrae with advancing disc degeneration can have profound impact on spine health. The biomechanical coupling of the IVD and vertebra suggests that degenerative changes in the distribution of IDP will influence the distribution of bone density within the vertebra; however, a quantitative correspondence has not been clearly established. As such, our study examined associations between regional variations in IDP and bone density across multiple stages of disc degeneration. We found that regional variations in IDP and, to a greater extent bone density, changed with advancing degeneration. These changes consisted of decreases in IDP and bone density (quantified by MIP) in the NP region relative to the aAF region. These changes suggest a potential correspondence between IDP and bone density in the region directly over- or underlying the nucleus pulposus. However, it is important to note that the sensitivity of the regional variations in IDP and density to degeneration score was only modest, and no direct correlations were found between IDP and any measure of bone density in the NP region.

The lack of strong correspondence between IDP and the density of the immediately under- or overlying bone may reflect the complexity of load transfer between the IVD and vertebral body. Finite-element studies indicate that this load transfer involves more than only axial transmission of force along each sagittal column (*i.e.*, aAF, NP, pAF) of the motion segment (Fields, et al., 2010; Kurowski and Kubo, 1986; Maquer, et al., 2014). Multiaxial stresses occur within the IVD, whereas the pressure transducer recorded only the axial stress. Hence, a region of the vertebra, even near the endplate, may be adapted to loads other than simply the axial stress present in the neighboring region of the IVD. This phenomenon is a possible explanation for why studies have found a decrease in IDP in the anterior half of the IVD in an erect posture as degeneration progresses (Pollintine, et al., 2004) and yet we and others (Wang, et al., 2013) have found a relative increase in bone density (Figure 5) and more robust trabecular architecture (Wang, et al., 2013) anteriorly in vertebrae adjacent to degenerated IVDs.

The lack of strong correspondence between IDP and density may also have resulted from limitations of this study. First, we used a cross-sectional design and cadaveric tissue and so could not investigate longitudinal changes in IDP, density, or disc scores. In some of the IVDs, degenerative changes may have occurred shortly before the donor's death, leaving insufficient time for adaptive changes in bone density to have occurred. Second, this study did not include lumbar levels, despite the higher prevalence of disc degeneration in the

lumbar vs. thoracic spine; however, we note that our cohort of thoracic discs spanned the full range of scores (Table 2). Third, we used non-invasive evaluations of IVD health based on only radiographic methods, rather than Pfirrmann grading (Pfirrmann, et al., 2001) by MRI, which has become more standard. Access to MRI in this study might have produced more accurate stratification of the IDP and density data by the extent of disc degeneration. Additional MRI-based parameters, T2 relaxation time and T1 ρ , are correlated with GAG and water contents (Johannessen, et al., 2006; Marinelli, et al., 2009), suggesting their potential for estimating regional distributions of IDP. However, their use would not change our findings of a general lack of correlation between bone density and each of IDP, GAG, and water content. Fourth, because all spine segments were subjected to 500N compressive force, analyses of correlations between IDP and density may have been confounded by differences in spine size and geometry among donors. Although we repeated the analyses using IDP normalized by IVD cross-sectional area and found no substantive effect on the results, this normalization likely only mitigates the effect of anatomical differences among donors. Fifth, as compared to QCT, higher-resolution CT imaging, such as micro-computed tomography would have allowed us to examine endplate porosity, which has been correlated to IDP within the NP (Zehra, et al., 2015). Lastly, the AF regions included cortical shell, which accentuated the differences in bone density between AF and NP regions. We repeated the analyses by clipping 3 mm from the anterior and posterior aspects. This change eliminated the regional differences in MIP for ALDI scores of 0 and for all Thompson scores (Figure 5B), and regional differences in EP+adj for DSN scores of 0 (Figure 5B), leaving only the differences in MIP between NP and AF regions for ALDI scores of 1 and 2.

By employing multiple invasive (Thompson and Rutges) and non-invasive (ALDI and DSN) schemes for scoring IVD degeneration, this study afforded the opportunity to examine the general but imperfect agreement among them. Some dissimilarity among scores is expected, given that the grading schemes focus on different aspects of the structural appearance and composition. ALDI scores weight heavily toward differences in water content, which appear as differences in QCT attenuation, between the NP vs. AF (Supplementary Figure 1), whereas DSN scores are based on a visual gauge of IVD height. In contrast, Thompson scores and, in particular, Rutges scores also depend on a host of finer-scale features. Although the Thompson and Rutges scores were roughly consistent with each other, only the Thompson scores stratified by NP GAG concentration (Figure 4). The least consistency was found between the two non-invasive grading schemes, DSN and ALDI (Table 2). Loss of disc height has also shown only moderate correspondence to Pfirrmann grades (de Bruin, et al., 2016). These findings emphasize the difficulty of comprehensive, non-invasive assessment of IVD degeneration via a single imaging modality (Benneker, et al., 2005; Zuo, et al., 2012). However, it is also important to note that DSN and ALDI were the only classification schemes for which regional variations in IDP depended on disc score (Figure 3). Thus, despite their limitations, these classifications do yield estimates of degenerative changes in the mechanical function of the IVD.

The results presented here are also relevant to studies of the influence of disc degeneration on vertebral fracture. In the flexed posture, differences in IDP between the aAF and the other two regions were apparent in degenerated but not healthy IVDs (Figure 3B). This result is similar to that of prior investigations (Adams, et al., 1996; Stefanakis, et al., 2014) that used

only a grading scheme similar to Thompson. Consistent with these results, a recent finite-element study estimated that disc degeneration increases the likelihood that anterior flexion will overload the anterior region of the vertebra and cause fracture at lower applied load (Maquer, et al., 2015). Earlier finite-element studies have also concluded that disc degeneration can change the location and force at which failure initiates in the vertebra (Clouthier, et al., 2015; Polikeit, et al., 2004). On the other hand, epidemiological studies have not yielded a consensus regarding associations between disc degeneration and vertebral fracture (Arden, et al., 1996; Roux, et al., 2008; Sornay-Rendu, et al., 2006; Sornay-Rendu, et al., 2004; Verstraeten, et al., 1991). One factor that can contribute to this discrepancy is variability among individuals, and individual vertebrae, in the spatial distribution of bone in the vertebral body. For example, increased bone density and trabecular thickness in the anterior region (Wang, et al., 2013), regardless of whether it occurs in response to or independently of disc degeneration, could reduce the risk of vertebral fracture caused by high anterior forces transferred by a degenerated IVD in flexed postures. As such, we propose that the spatial distribution of bone within the vertebra may be an important mediator of the impact of disc degeneration on fracture risk in the spine. Future investigations that incorporate patient-specific measurements of the spatial distribution of bone density into studies of IVD health and vertebral fracture may shed light on associations between fracture risk and disc degeneration.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(A) Schematic of the erect and flexed testing configurations; (B) spine segment with the pressure transducer partially inserted into the lower IVD; (C) Representative plots of pressure against position within the IVD for four spine segments: 0% and 100% distance are the anterior- and posterior-most aspects of the IVD, respectively.

Figure 2.

(A) The 3mm-wide mid-sagittal section used to quantify bone density; (B) Mid-sagittal QCT slice depicting the three depths used for measurement of bone density: MIP, EP, and EP+adj. These three density measures were calculated for each of the four endplate layers (two inferior and two superior) in each spine segment. A representative IDP profile (yellow) is included, with overlays to show division of the mid-sagittal section into aAF, NP, and pAF regions.

Figure 3.

Regional IDP measurements (A) for all IVDs and (B) stratified by ALDI, Thompson, and DSN scores: The column height is the group mean and the error bar one standard deviation.

*: $p < 0.05$ for comparison between the regions bracketed with arrows or between the marked region and aAF. ^: $p < 0.05$ for comparison between disc grades. #: $0.05 < p < 0.10$ for comparison between disc grades.

Figure 4.

(A) Scatter plot of NP GAG content against NP IDP in erect and flexed postures. A positive correlation was found in flexion ($p<0.001$). (B) Dot plot of NP GAG content in IVDs categorized by ALDI, Thompson, DSN, and Rutges. *: $p<0.05$ for comparison between the regions bracketed with arrows.

Figure 5.

Regional measurements bone density (A) for all endplates and (B) stratified by ALDI, Thompson, and DSN scores in the adjacent IVD: Results are shown for the superior layer (Figure 2 legend) only and are similar to those for the inferior layer. The column height is the group mean and the error bar one standard deviation. *: $p < 0.05$ for comparison between the regions bracketed with arrows. **: $p < 0.05$ for comparison between the NP and both AF regions.

Figure 6. Scatter plots of MIP against IDP, for each of the three regions and in each of the two postures

Table 1

Summary of the grading schemes for semi-quantitative assessment of disc degeneration

Grading Scheme	Modality/Plane	Description	Original Scale	Compressed Scale
Apparent Loss of Disc Integrity (ALDI) ²³	Computed tomography/Mid-transverse cross-section	Scoring is based primarily on the appearance of the NP and AF and secondarily on the presence or absence of osteophytes.	0–3	N/A
Thompson ²⁴	Gross morphology/Mid-sagittal cross-section	Scoring is based on the appearance of the NP, AF, EP, and vertebral body	1–5	1,2 = 1 3 = 2 4,5 = 3
Disc Space Narrowing (DSN) ²²	Radiography/Sagittal view	Scoring is based on the presence and severity of loss of height in the IVD	0–3	0 = 0 1,2,3 = 1
Rutges ²⁵	Histology/Mid-sagittal cross-section	Six categories are scored from 0–2: endplate quality; AF morphology; AF-NP boundary; NP cellularity; NP matrix; and NP matrix staining	0–12	1–4 = 1 5–8 = 2 9–12 = 3

Table 2

Contingency table showing comparison of disc degeneration scores among pairs of grading schemes: Each cell contains the number of IVDs receiving the scores shown in the row and column headers. That number expressed as a percentage of the total number of IVDs scored by both schemes is in parentheses.

		ALDI						DSN ^				
		0	1	2								
Thompson ^	1	17 (14.3)	19 (16.0)	7 (5.9)						Thompson ^		
	2	15 (12.6)	12 (10.1)	20 (16.8)								
	3	5 (4.2)	5 (4.2)	19 (16.0)								
					1	2	3					
DSN ^	0	22 (18.0)	26 (21.3)	27 (22.1)	32 (26.9)	33 (27.7)	9 (7.6)					
	1	15 (12.3)	10 (8.2)	22 (18.0)	11 (9.2)	14 (11.8)	20 (16.8)					
								0	1			
Rutges ^	1	5 (10.2)	9 (18.4)	0 (0.0)	14 (28.6)	0 (0.0)	0 (0.0)	13 (26.5)	1 (2.0)			
	2	7 (14.3)	5 (10.2)	12 (24.5)	9 (18.4)	12 (24.5)	3 (6.1)	15 (30.6)	9 (18.4)			
	3	3 (6.1)	2 (4.1)	6 (12.2)	3 (6.1)	3 (6.1)	5 (10.2)	5 (10.2)	6 (12.2)			

^ Compressed