The Effect of Discectomy and the Dependence on Degeneration of Human Intervertebral Disc Strain in Axial Compression

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Discectomy may accelerate the progression of disc degeneration by damaging the annulus fibrosus (AF) and decreasing nucleus pulposus (NP) pressure. We recently presented a technique to quantify internal disc strains using magnetic resonance imaging. The objectives of this study were to noninvasively quantify the effect of discectomy on internal strains under axial compression and to determine whether the effect of discectomy depended on degeneration. $T_{1\rho}$ relaxation times were calculated as a quantitative measure of degeneration. Samples were prepared from the lower lumbar levels, and a 1000N compressive load was applied while in the MR scanner. Discectomy was performed by removing 2g of NP through the posterior-lateral AF. The discs were rehydrated, reimaged and retested. The analyzed parameters include the initial disc height, the axial deformation, the inner and outer radial bulge and strain. The axial deformation was more compressive following discectomy. The axial deformation following discectomy correlated with degeneration, with minimal alteration in nondegenerated discs. Discectomy altered the radial displacements and strains such that the inner AF radial bulge decreased and the radial strains were more tensile in the lateral AF and less tensile in the posterior AF. Discectomy alters the internal radial and axial AF strains in compression, which may leave the AF vulnerable to damage and microfractures. Some of the discectomy effects are modulated by degeneration, where the mechanical effect of discectomy was magnified in degenerated discs and may further induce mechanical damage and degeneration.

Discectomy, a surgical procedure to remove nucleus pulposus (NP) fragments following herniation, has increased steadily over the past decade[1]. Short-term benefits of discectomy have been shown, but long-term benefits and reherniation rates remain controversial[2-4]. Furthermore, discectomy may accelerate the progression of disc degeneration by damaging the annulus fibrosus (AF), decreasing the NP pressure, decreasing the disc height, impairing the disc's ability to rehydrate, and increasing the AF stresses and strains[1,5-10]. Many cadaveric studies have shown altered mechanics of the bone-disc-bone segment following discectomy, including in a decrease in the internal pressure and endplate strain and an increase in the neutral zone[11-19]. The radial bulging of the inner AF changes from outward in intact discs to inward following discectomy[16,17,20]. In spite of these observations, the internal AF strains following discectomy remain unknown because the internal tissue deformation could not be quantified without altering the tissue by placing markers[16,17]. Furthermore, it is unknown whether the effect of discectomy depends on degenerative state of the disc.

We recently presented a technique to quantify internal disc strains under load by using magnetic resonance imaging (MRI) and image correlation[21,22]. This technique was applied to quantify the effect of degeneration on the internal disc deformations and strains under axial compression[22]. The AF of degenerated discs had higher tensile radial and compressive axial strains, which was likely due to decreased NP pressure placing more of the applied load directly onto the AF. This analysis was made possible by using MRI-based $T_{1\rho}$ relaxation time as a quantitative measure of degeneration to perform statistical correlations with measured parameters[22,23]. The $T_{1\rho}$ relaxation time has a strong positive correlation to the NP proteoglycan content (r = 0.70) and pressure, and a strong negative correlation to the MRI-based Pfirrmann grade (r = −0.75)[23-26].

We hypothesize that removal of some NP tissue via discectomy will increase internal strains and that the effect of discectomy will be greater in degenerated discs. The objectives of this study were to noninvasively quantify the effect of discectomy on human disc strains under axial compression and to determine whether the effect of discectomy depended on the state of degeneration.

Materials and Methods

Thirteen human spine sections were obtained from an IRB approved tissue source (NDRI, Philadelphia, Pennsylvania). A series of $T_{1\rho}$-weighted images were acquired to determine the $T_{1\rho}$ relaxation time as a quantitative measure of degeneration[22,23,25]. Bone-disc-bone segments were prepared by removing the muscles and facet joints from L3-L4 and/or L4-L5 levels (n = 19; 22-76 years old) and potted in polymethylmethacrylate bone cement. The

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samples were wrapped in gauze, hydrated in a refrigerated phosphate buffered saline (PBS) bath, and allowed to equilibrate to room temperature prior to testing. The PBS-soaked gauze was kept wrapped around the disc during imaging to prevent dehydration.

A loading device was constructed of non-magnetic materials to apply axial compressive loads to the disc while in a 3T MR scanner (Trio, Siemens Medical Solutions), as previously described[21]. Each disc was tested under axial compression before and after discectomy. (Note that the data for the intact condition have been previously published[22].) The disc recovered unloaded for at least 8 hours in a refrigerated PBS bath between tests. A high-resolution T_2-weighted turbo spin-echo sequence was used to acquire mid-sagittal MR images with a custom-built 80 mm square surface coil (512×512 matrix size, TR = 3000 ms, TE = 113 ms, slice thickness = 3 mm, 10 averages, total scan time 12.5 min, SNR $\approx$ 13; resolution = 0.234 mm/pixel). A mid-coronal image was also acquired.

The disc was preconditioned with 5 cycles from 0 to 20N and a nominal 20N preload applied for 5 minutes to ensure contact with the loading plate. A reference (undeformed) image was acquired while the disc was under the nominal 20N compressive load. A 1000N compressive load was applied rapidly (~3 sec) and maintained for 20 minutes, to allow for creep deformation, before repeating the imaging sequence to acquire a deformed image.

Following imaging and mechanical loading of the intact disc, each disc was rehydrated for 8 hours. A discectomy was performed by making a cruciform incision with a #11 scalpel blade through the posterior-lateral AF consistent with clinical procedures[27]. Two grams of NP material (approximately 20% of NP volume)[21] was removed with pituitary ronguers, based on the amount of removed NP material reported by Fountas et al[2]. The disc was rehydrated and loaded as described above.

A custom program was used to calculate the average disc height of the reference and deformed images (MATLAB version 7.0.1, MathWorks, Inc., Natick, MA)[21,22,28]. The axial deformation was calculated as the change in disc height between the reference and deformed image normalized by the undeformed height. The reference and deformed MR images were used to calculate the internal tissue displacements and 2D Lagrangian strains using a commercial texture correlation algorithm (resolution = 1/20th of a pixel = 0.01 mm, Vic 2D, Correlated Solutions, Inc.). Two-dimensional strain analysis was performed in three disc regions: the anterior AF, posterior AF, and lateral AF. The Cartesian coordinate system was defined by the spine geometry such that the x-direction corresponded to radial strains oriented across lamellae, and the y-direction corresponded to axial strains along the spinal axis (Figure 1A). Strains were reported as a percent, and the shear strains were reported as an absolute value. The radial bulge for the inner and outer AF was calculated as the average radial displacement of the node at the mid-disc height, and an outward radial bulge from the NP was defined as positive[22].

Since the data did not follow a Gaussian distribution, nonparametric statistical analyses were used, and the data are presented as median (interquartile range). To evaluate the effect of discectomy, a Wilcoxon matched pairs test was performed comparing parameters from intact and following discectomy. The analyzed parameters include the initial disc height, the axial deformation (actual and normalized to initial disc height), the inner and outer radial bulge, and the average strains (radial, axial, and shear components) in each AF region. Evaluation was undertaken to determine if the impact of discectomy was correlated with degeneration. A change in the parameter before and after discectomy was calculated ($\Delta x = x_{discectomy} - x_{intact}$, where 'x' represents the parameter), and a Spearman's correlation was performed with the $T_{1\rho}$ relaxation time. Significance was set at $p \leq 0.05$.

Results

The wet weight of the removed NP material was 1.96 grams (interquartile range = 1.79 to 2.01g). In 15 of 19 samples, the remaining NP material is presumed to have swelled and redistributed to fill the void from the discectomy (Figure 1A). However, a void was observed in the NP of four degenerated discs ($T_{1\rho}$ relaxation times = 46 − 64 msec; Figure 1B).

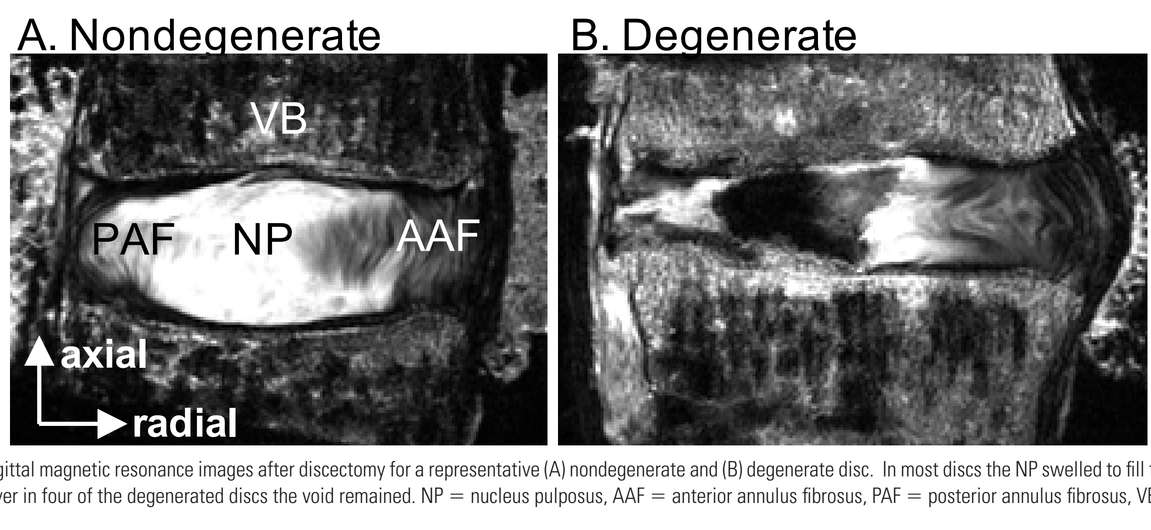

Figure 1. Midsagittal magnetic resonance images after discectomy for a representative (A) nondegenerate and (B) degenerate disc. In most discs the NP swelled to fill the void craused by discectomy, however in four of the degenerated discs the void remained. NP = nucleus pulposus, AAF = anterior annulus fibrosus, PAF = posterior annulus fibrosus, VB =vertebral body.

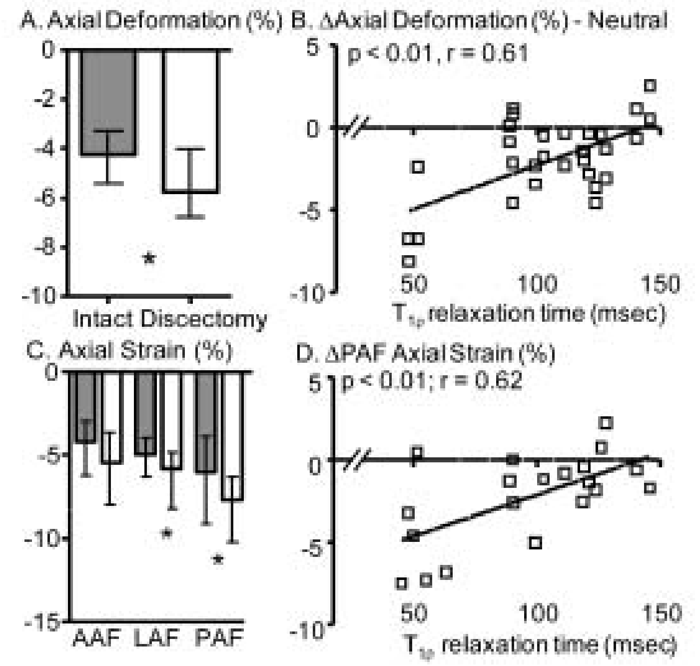

Figure 2. (A) The axial deformation was more compressive following discectomy compared to intact. (B) The effect of discectomy correlated with degeneration for axial strain. Note that a larger $T_{1\rho}$ relaxation time (e.g., at 150 ms) represents a less degenerated disc and a smaller $T_{1\rho}$ (at 50 ms) represents a more degenerated disc. (C) Average axial strain was more compressive following discectomy for LAF and PAF locations. (D) The effect of discectomy correlated with degeneration for axial strain in the posterior AF. *p < 0.05. Grey bars = intact, White bars = discectomy, AAF = anterior AF, LAF = lateral AF, PAF = posterior AF.

Therefore, NP strain analysis was not performed in this study. The initial disc height (under the nominal 20 N load) was 11.8 mm (9.9 to 12.5 mm) and was not affected by discectomy ($p > 0.7$). The qualitative strain pattern following discectomy was similar to the intact case: axial strains had horizontal bands of tension and compression, radial strains had vertical bands, and shear strains were highest at the endplates.

The axial deformation under compression increased from 0.63 mm (0.46 to 0.84 mm) for intact to 0.78 mm (0.63 to 1.11 mm) following discectomy ($p < 0.01$), and when normalized by the initial disc height, the axial deformation was more compressive following discectomy ($p < 0.01$; Figure 2A). The effect of discectomy on the axial deformation correlated with degeneration ($p = 0.04$, $r = 0.61$, Figure 2B), where the effect of discectomy was minimal in nondegenerated discs (e.g., at $T_{1\rho} = 150$ msec).

As one might expect, the effect of discectomy on the AF axial strain was similar to the axial deformation, where the axial strain was more compressive with discectomy reaching significance in the lateral and posterior AF (Figure 2C). The anterior AF axial strain followed a similar pattern, but did not reach significance ($p = 0.06$; Figure 2C). Similar to the axial deformation, the effect of discectomy on the AF axial strain was dependent on degeneration in the lateral and posterior AF, where nondegenerate discs ($T_{1\rho} \sim 150$ msec) were relatively unaltered (Figure 2D).

Following discectomy, the inner AF radial bulge in the mid-coronal plane remained outward, but was 65% smaller ($p < 0.01$; Figure 3A). The inner AF radial bulge in the mid-sagittal plane also remained outward with a reduced amplitude after discectomy; however, the effect was not significant ($p = 0.09$; Figure 3A). The decrease in the inner AF radial bulge followed discectomy was not dependent on degeneration in either the mid-coronal or mid-sagittal plane ($p > 0.4$). Therefore, the inner AF radial bulge decreased for both nondegenerate and degenerate discs. The outer AF radial bulge was 0.50 (0.41 to 0.60) mm (pooled for mid-coronal and mid-sagittal) and was not affected by discectomy ($p > 0.6$).

The radial strain increased in the lateral AF ($p < 0.01$), decreased in the posterior AF ($p < 0.01$), and was not significantly altered in the anterior AF following discectomy ($p = 0.6$; Figure 3B). The effect of discectomy on the radial strain was not correlated with degeneration in any AF region ($p > 0.1$). Therefore, the observed change in the lateral AF and posterior AF radial strains were similar across all states of degeneration (Figure 3C – shown for posterior AF).

The shear strain was 3.0% (2.1 to 4.1%) and was not altered by discectomy in the anterior AF or lateral AF ($p \geq 0.2$). The posterior AF shear strain decreased from 3.5% in intact discs to 2.6% with discectomy ($p = 0.03$).

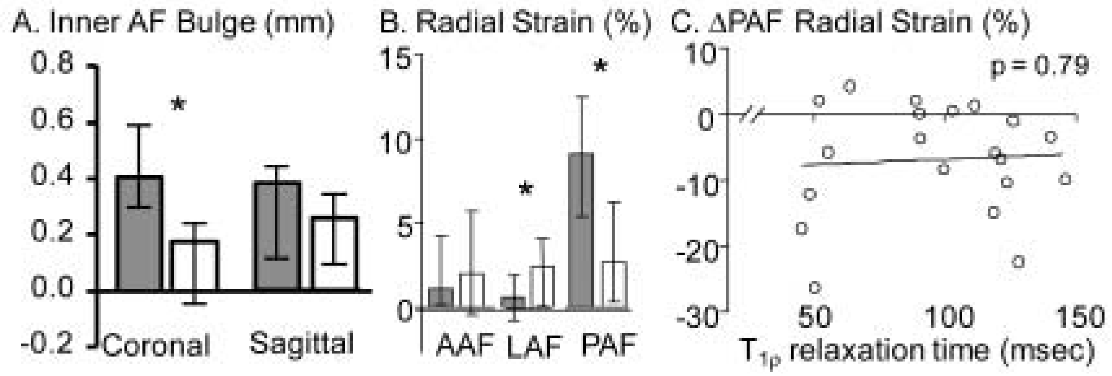

Figure 3. (A) Inner AF radial bulge decreased in the mid-coronal and mid-sagittal plane following discectomy compared to intact. (B) Radial strain following discectomy increased in the LAF and decreased in the PAF. (C) The effect of discectomy on the radial strain in the posterior AF did not correlate with degeneration. *p < 0.05. Grey bars = intact, White bars = discectomy, AAF = anterior AF, LAF = lateral AF, PAF = posterior AF.

Discussion

In this study, the effect of discectomy on internal disc displacement and strain in axial compression was investigated, as was the dependence of these parameters on the degree of degeneration. While several studies have measured deformation and NP pressure in response to axial compression in models of discectomy[10,13,29], internal strains were neither measured nor correlated with degeneration. The use of $T_{1\rho}$ relaxation time, which has a strong correlation to the NP proteoglycan content and the MRI-based Pfirrmann grade[22,23,25], as a quantitative measure of disc degeneration represents a significant advancement in the analysis of the role of degeneration on disc mechanics. The axial deformation prior to discectomy was between 4 and 6% and increased to a range of 6 to 7% after discectomy (Figure 2), which is consistent with previous studies that reported a 10-20% increase in deformation following discectomy[12,15,17]. The axial strains also significantly increased with discectomy (Figures 2) and had similar values to the normalized axial deformation (which were measured independently). The consistency of the average axial strains derived by texture correlation with the dimensionally derived axial deformation results supports the validity of the MRI technique as previously reported[21].

Some of the discectomy effects are modulated by the state of degeneration, and when that was true the mechanical effect of discectomy was minimized in nondegenerated discs (examples Figure 2B and 2D). This is likely due to the observed ability of the NP in nondegenerated and moderately degenerated discs to swell and redistribute to fill the void left from the discectomy. Of the 19 discectomies, only four had voids after re-hydration, and those four had $T_{1\rho}$ values consistent with advanced degeneration. The results suggest that as long as the amount of NP removed is not too large and the post discectomy disc is allowed to re-hydrate, the residual NP tissue may fill the void and may improve mechanical function in inverse proportion to its state of degeneration[15,18,30]. Conversely, changes observed in this study induced by discectomy have the greatest effect on degenerated discs.

Inhomogeneity between the anterior, lateral, and posterior AF strains occurred. Anterior AF radial strain was not affected by discectomy while the posterior AF radial strain became less tensile (Figure 3B). This inhomogenity in strain has previously been observed[31,32] and is not surprising given the spatial variability in AF geometry, fiber structure, biochemistry, and material properties. The decreased radial strain in the posterior AF with discectomy was surprising and may be due to shifting of the NP towards the posterior region under load[16,31-33]. It is possible that the remaining NP moved towards the posterior under load, placing more radial compression loading on that region. While such shift of the NP would have the positive effect of decreased radial tensile strains, posterior NP shift may also make it more susceptible to re-herniation.

Study limitations include the long imaging time, which permits study of the steady-state response but not the dynamic response, and the two-dimensional imaging sequence, which permits calculation of deformation and strain only for cases in which the tissue remains in the same imaging plane during loading (e.g., mid-sagittal and mid-coronal)[21]. Future studies will expand this method to three-dimensional imaging and strain analysis. This advance will permit measurement of strain at the posterior-lateral annulotomy site; it is likely that the annulotomy site experiences high strains due to disruption in AF structural integrity[34]. It is currently unknown how the incision site responds to applied load and knowledge of this response will be helpful to design and evaluate new AF closures to potentially decrease the risk for re-herniation. Finally, the acute mechanical effects of discectomy presented here do not reflect the potential biological remodeling and progressive degeneration that may occur over time following herniation and discectomy.

In conclusion, discectomy alters the radial and axial AF strains. Increased strains may make the AF vulnerable to fatigue damage and microfractures that develop into circumferential or radial tears following herniation and/or discectomy. Some of the discectomy effects are modulated by the state of degeneration, where nondegenerated discs had minimal changes for some strain components following discectomy. In these cases the NP swelled and redistributed to support the AF. The combined mechanical effect of discectomy is magnified in degenerated discs, and may induce further mechanical damage and progressive degeneration. The initial state of degeneration should be evaluated, and the amount of NP removed should be minimized during discectomy. In future work these techniques can be applied to evaluate the mechanical efficacy of NP replacements and other interventions[35-39]. While it can be hypothesized that mechanical damage and progressive degeneration may occur as a consequence of alterations in deformation and strain following discectomy, the mechanical and clinical significance of these alterations is yet to be understood.

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