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T1 ρ MRI and Discography Pressure as Novel Biomarkers for Disc Degeneration and Low Back Pain

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Abstract

Study Design—Prospective MRI study of LBP patients requiring discography as part of their routine clinical diagnoses and asymptomatic age-matched volunteers.

Objective—To determine whether T1 ρ MRI and discography opening pressure are quantitative biomarkers of disc degeneration in LBP patients and in asymptomatic volunteers.

Summary of Background Data—Disc degenerative disease (DDD), a common cause of low back pain (LBP), is related to the patient's prognosis and serves as a target for therapeutic interventions. However, there are few quantitative measures in the clinical setting. Discography opening pressure (OP) and T1 ρ MRI are potential biomarkers of DDD related to biochemical composition the intervertebral disc (IVD).

Methods—The Institutional Review Board approved all experiments and informed consent was provided by each subject. Patients being treated for LBP (n=17, 68 levels, mean age 44 $\pm$ 6 years, range 30–53) and control (CTL) subjects (n=11, 44 levels, mean age 43 $\pm$ 17, range 22–76) underwent T1 ρ and T2 MRI on a Siemens 3T Tim Trio clinical scanner. The LBP patients also received multi-level provocative discography before their MRI. Opening Pressure (OP) was recorded as the pressure when fluid first enters the nucleus of the IVD.

Results—T1 ρ was significantly lower in the painful discs (55.3ms $\pm$ 3.0 ms, mean $\pm$ std. error) from control (92.0 $\pm$ 4.9 ms, p<0.001) and non-painful discs (83.6 $\pm$ 3.2 ms, p<0.001). Mean OP for the painful discs (11.8 $\pm$ 1.0 psi, mean $\pm$ std. error) was significantly lower than non-painful discs (19.1 $\pm$ 0.7 psi, p<0.001). Both T1 ρ and OP correlated moderately with Pfirrmann degenerative grade. ROC area under the curve was 0.91 for T1 ρ MRI and 0.84 for OP for predicting painful discs.

Conclusions—T1p and OP are quantitative measures of degeneration that are consistent across both control subjects and LBP patients. A significant and strong correlation exists between T1p values and *in vivo* OP measurements obtained by discography in LBP patients.

INTRODUCTION

Low Back Pain (LBP) is a common cause of disability and has enormous medical and economic consequences¹. Disc degenerative disease (DDD) is a common cause of LBP, and while the etiology of the disease can be confounded with physiological changes due to normal aging, there are features of degeneration that are potentially related to the patient's prognosis and serve as targets for therapeutic interventions². The quantitative assessment of disc health and the identification of specific biomarkers are therefore essential for the selection of treatment options and to the future of biomedical research in the development of new spine technologies. While many clinical diagnostic modalities exist for identifying the multi-factorial etiologies of LBP, there are few quantitative measurements of DDD³.

The intervertebral disc (IVD) consists of a gel-like nucleus pulposus (NP) containing proteoglycan (PG) and water surrounded by a lamellar architecture of collagen type I known as the annulus fibrosus (AF). Hydrostatic pressure in the young healthy NP helps to resist load in the spine, while normal aging causes a loss of hydration that transfers some of the load-bearing capacity directly to the compressive stiffness of the fibrous AF. The early stage of DDD is marked by the breakdown of PG^{4,5} resulting in a loss of tissue hydration and decreased hydrostatic pressure⁶⁻⁹, which leads to morphological delaminating changes in the AF, such as annular fissures, rim lesions, loss of disc height, hypertrophy of the posterior elements, and the formation of osteophytes¹⁰⁻¹². Clinical manifestations that result are common and include low back pain, disc herniations, spinal stenosis, and spinal deformities¹³.

Provocative discography is an invasive test frequently used to determine if degenerative disc pathology observed using standard imaging is responsible for LBP symptoms¹⁴. While somewhat controversial due to the subjective nature requiring the patient's pain response¹⁵, there are several quantitative pressure measurements obtained as part of a manometric-controlled study. Opening Pressure (OP), the pressure where an injected contrast dye first overcomes the internal osmotic pressure and is visualized using continuous x-ray imaging to enter the disc¹⁴, is a potential indicator of disc degeneration. The invasive nature of discography, however, reserves its use to patients diagnosed with LBP in whom conservative treatments have failed to improve symptoms and potential surgical solutions are being contemplated.

Initially, standard work-up of spine pathologies punitively responsible for LBP incorporates noninvasive imaging methods, such as plain film radiographs and MRI, which are used as the first line of diagnosis to determine the presence of infection, tumor, fractures, and to characterize disc degeneration¹³. However, as it pertains to DDD, these conventional techniques, based on T1- and T2-weighted imaging, which can readily detect later stage morphological changes in disc height and hydration^{16,17}, are insensitive to early disc biochemical changes¹⁸. The Pfirrmann grade determined using a T2 weighted MR image is

currently the gold standard to determine disc degeneration¹⁹. This method has been widely applied, yet is quite limited, as it is not a continuous quantitative measure.

An alternative technique that is sensitive to PG content in cartilage is the T1 ρ time constant obtained by spin-lock MRI. T1 ρ MRI uses low power RF pulses applied on-resonance to lock the magnetization in the transverse plane. The relaxation that occurs during the application of the spin-lock pulse is referred to as spin-lattice relaxation in the rotating frame, or T1 ρ relaxation. The T1 ρ time constant is related to slow motional interactions between macromolecules and bulk water and has been exploited to probe early biochemical changes in cartilage and may potentially be used as a biomarker of disc degeneration. In articular cartilage, T1 ρ is strongly correlated with PG content and has been shown to detect early osteoarthritic changes^{20–22}. T1 ρ -weighting provides T2-like images with the advantage of increased dynamic range compared to conventional T2-weighting²³. T1 ρ MRI assessment of PG content in the human IVD ex vivo^{24,25} and the quantification of degeneration in vivo²⁶ have been demonstrated.

The objectives of the current study were to determine whether T1 ρ MRI and disc opening pressure are quantitative biomarkers of disc degeneration in patients being treated for LBP and in asymptomatic volunteers.

MATERIALS AND METHODS

Patient Selection

The Institutional Review Board approved all experiments and each subject provided informed consent. Patients being treated for LBP (n=17, 68 levels, mean age 44 $\pm$ 6 years, range 30–53) and control (CTL) subjects (n=11, 44 levels, mean age 43 $\pm$ 17, range 22–76) underwent T1 ρ and T2 MRI. The LBP patients also received multi-level provocative discography before their MRI. These patients also underwent a routine non-investigational MRI as part of their selection.

Measurement of Disc Opening Pressure

Discography data was obtained, following the placement of 22 gauge needles into the center of the L2/L3 through L5/S1 discs, using the IntelliSystem (Merit Medical, South Jordan, UT) with digital pressure display. Iohexol-Omnipaque 300 (GE Healthcare, Princeton, NJ), a low osmolar, nonionic, iodinated contrast agent was injected into each disc under continuous fluoroscopic imaging. Opening Pressure (OP) was recorded as the pressure when fluid first enters the NP. All discography was performed by the same physician.

Quantification of T1 ρ in the NP

MRI was performed on a Siemens Tim Trio 3Tesla MRI scanner with a vendor supplied 8-channel spine array coil. A series of T1 ρ -weighted images were acquired with five spin-lock times (TSL) from 5–40ms using a 3D T1 ρ pulse sequence²⁷. Other parameters were: TE/TR/flip angle = 3ms/6ms/20°, FOV=20x20cm, acquisition matrix = 256x128x16, interpolated to 256x256x16, slab thickness = 80mm, in-plane resolution = 0.8x0.8mm², BW = 130Hz/pixel, centric k-space encoding and the spin-locking frequency was fixed at 500Hz.

Total imaging time was under 20 minutes. T2 MRI was performed for Pfirrmann grading of the same slice locations as T1 ρ MRI by with a turbo spin-echo (TSE) pulse sequence with the following parameters: FOV=20x20cm; slice thickness=4mm; acquisition matrix=256x256; and TE/TR=127/4320ms.

Data Analysis

The images were processed using custom-written software in the IDL programming language (RSI Corp., Boulder, CO). T1 ρ images were used to generate T1 ρ “maps” by fitting signal intensities as a function of TSL by linear regression²⁷. In the fitting routine, pixels whose intensities correlated poorly (i.e. $R^2 < 0.95$) with the theoretical signal expression were set to zero. Average ($\pm$ standard deviation) of T1 ρ values were recorded in middle 1/3 of each disc to reflect the NP manually selected by a single user (A.B.). The same user performed Pfirrmann grading on the T2 MRI from the mid-sagittal slice based on the 5-point scoring system¹⁹.

Statistical Analysis

Statistical analysis was performed in PASW Statistics 18.0 (SPSS Inc., Chicago, IL). One Way Analysis of Variance (ANOVA) were performed to determine differences between painful and non-painful discs' T1 ρ values. Pearson correlation was performed between T1 ρ , OP and Pfirrmann grade. ROC curves were generated for T1 ρ and OP as continuous rating scale of disc pain and areas under the curve were calculated. A p-value of less than 0.01 was considered to be statistically significant in all analyses.

RESULTS

Figure 1 shows T1 ρ color-coded maps of a mid-sagittal slice from a 3D data set of 12 slices of the lumbar spine. Painful discs possess lower T1 ρ (42–51ms) compared to non-painful discs (62–95ms) in the LBP patients and are indicative of loss of PG and hydration in the NP. Some painful discs also demonstrate low OP (<10psi). As a comparison, an asymptomatic 38-year old male (C) exhibited bright discs on T2 as well as T1 ρ values >80ms. Although qualitatively similar appearing to T2 MRIs, T1 ρ values possess a greater dynamic range and hence are more sensitive to small changes in tissue hydration and PG content as described before^{20,23,24}. The non-painful disc with low T1 ρ (52ms) but relatively high OP (23psi) in the L4-L5 disc in the LBP patient (A) signifies low PG and hydration yet mechanically competent IVD, and a likely candidate for adjacent level disease. She has since undergone a lumbar AP fusion of the L5-S1 disc and will be assessed again in our ongoing study during a two-year follow-up MRI.

Average T1 ρ (Figure 2A) in the painful discs was significantly lower from control ($p < 0.001$) as well as from non-painful discs ($p < 0.001$). Mean OP (Figure 2B) for the non-painful discs and significantly higher than the painful discs ($p < 0.001$). A plot of T1 ρ versus Pfirrmann grade is shown in Figure 3A. Note that the T1 ρ is a continuous scale whereas Pfirrmann grade is not and hence the correlation coefficient of the combined data ($r = -0.55$) while significant ($p < 0.001$) does not provide much more information. Some interesting observations were noted e.g. the control cohort's discs possessed both higher T1 ρ as well as

lower degenerative grade compared to the LBP cohort's discs. Figure 3B shows a correlation between OP in the LBP cohort and Pfirrmann grade as well ($r=-0.52$, $p<0.001$). The majority of the discs of the LBP patient cohort have some degree of degeneration (grade 2 or more on the Pfirrmann scale). This is due to the selection criteria used by the treating authors (P.M. and R.B.) for discography candidacy in the population of LBP patients routinely evaluated in their clinical practice. Non-painful discs exhibit higher OP and lower degenerative grade with OP being a strong discriminator of the two pools of discs ($p<0.001$). This indicates that disc pain is related to biomechanical failure of the IVD resulting from a loss of hydrostatic pressure in the NP of these patients. Consistent with these observations, T1 ρ and OP are positively correlated (Figure 4). The moderate correlation ($r=0.54$) suggests that the two metrics are not redundant and are indeed providing complementary information and predict painful discs at different rates in an ROC analysis (Figure 5). The area under the curve (AUC) was 0.91 for T1 ρ MRI and 0.84 for OP indicating high sensitivity and specificity of both methods for predicting painful discs (Table 1).

DISCUSSION

There are two primary findings of this study. First, both T1 ρ and OP are quantitative measures of degeneration that are consistent across both control subjects and LBP patients. Second, we demonstrated a significant and strong correlation between the T1 ρ values and OP in LBP patients. This is not surprising since T1 ρ is related to NP GAG²⁴, which drives the disc osmotic pressure²⁸. Thus, T1 ρ appears to be quantifying disc health via the NP osmotic pressure. Since T1 ρ and OP are both quantitative continuous measures, it would be expected that they would correlate better than either would correlate with Pfirrmann grade.

A limitation of the study is that T1 ρ and OP measurements were performed with the patient in the supine and prone positions, respectively, and so reflects the NP pressure without axial loading. Moreover, moderate correlations observed with Pfirrmann grade for both T1 ρ and OP are a result of the integer nature of the Pfirrmann grading scale; it is unlikely that better correlation could be achieved since this scale is not continuous. Regardless, the results suggest a biomechanical basis for LBP. From previous studies on the sensitivity of T1 ρ MRI, we conclude that the primary cause of its decrease in the IVD is due to lower PG and hydration. Since PG content in the disc is responsible for maintaining disc osmotic pressure, decrease in its value implies compromised mechanical function, a finding that is further corroborated by the low OP measured in painful discs.

Measurements of T1 ρ were only performed in the NP region by manually recording T1 ρ in the middle third of each disc. However, more sophisticated analyses is possible since the entire lumbar spine is captured in the MRI permitting T1 ρ to be mapped across an entire IVD. In addition, multi-slice T1 and T2 images were also acquired so that the data can be combined for multi-parametric and 3D spatial analyses. These analyses could account for T1 ρ variations from the presence of disc pathologies such as fissures and herniations. Moreover, such studies can evaluate T1 ρ to elucidate the mechanisms of disc degeneration in the AF as well.

While discography OP is a minimally invasive measure, T1 ρ MRI has the advantage of being a non-invasive technique to determine NP GAG. T1 ρ MRI is currently limited to research studies but it has certain advantages over other MRI-based methods for measuring PG content in the discs that justify a wider application to clinical diagnostic imaging. Contrast-enhanced proton MRI, in which a contrast agent is permitted to diffuse into the cartilage, has been used to measure PG content^{29,30}. However, due to variations in Gd-DTPA2- diffusion and relaxivity with changes in macromolecular content, quantitation of PG in pathologic tissues with this method will be problematic³¹. These methods have found limited applications in imaging IVD, where the negative fixed charged density of the NP hinders diffusion of ionic contrast agents^{32,33}. Another promising method for measuring PG is sodium MRI. It has been shown that sodium MRI provides direct spatial maps of PG content in cartilage^{34–36}. However, the need for hardware modification on a typical scanner and its inherently low signal has limited its use in the clinical setting.

The LBP patients in this study were a combination of pre-operative surgical (lumbar AP fusion or disc arthroplasty) and non-surgical patients. These patients, and others still being recruited to the study, will be followed over the next several years to determine the change in NP T1 ρ of discs in non-operative conservatively managed patients and in adjacent non-operative levels in the surgical cohort and thus investigate the potential for further development of disc disease in these separately managed LBP groups. These studies will also shed light on controversies regarding the efficacy of treatment options for disc degeneration, provide potential further understanding of adjacent level disease, and the influence of rigid fixation vs. motion sparing surgery on adjacent discs. The results could possibly justify the development of new minimally-invasive technologies based on targeting specific biomarkers for DDD to prevent or reverse the level of progression of disease to both non-operated adjacent levels and in non-surgically treated symptomatic disc disease. In this context, the goal of developing noninvasive biomarkers is to help determine not just how to treat a patient but who to select for the best outcome from the treatment.

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References

1. Wipf J, Deyo R. Low back pain. *Med Clin North Am.* 1995; 79(2):231–46. [PubMed: 7877388]
2. Adams M, Roughley P. What is intervertebral disc degeneration, and what causes it? *SPINE.* 2006;2151–61. [PubMed: 16915105]
3. Carragee EJ, Hannibal M. Diagnostic evaluation of low back pain. *Orthopedic Clinics of North America.* 2004; 35(1):7–16. [PubMed: 15062713]
4. Buckwalter JA. Aging and degeneration of the human intervertebral disc. *Spine.* 1995; 20(11): 1307–14. [PubMed: 7660243]
5. Pearce RH, Grimmer BJ, Adams ME. Degeneration and the chemical composition of the human lumbar intervertebral disc. *J Orthop Res.* 1987; 5(2):198–205. [PubMed: 3572589]
6. Antoniou J, Goudsouzian NM, Heathfield TF, Winterbottom N, Steffen T, Poole AR, Aebi M, Alini M. The human lumbar endplate. Evidence of changes in biosynthesis and denaturation of the

- extracellular matrix with growth, maturation, aging, and degeneration. *Spine*. 1996; 21(10):1153–61. [PubMed: 8727189]
7. Urban JP, McMullin JF. Swelling pressure of the lumbar intervertebral discs: influence of age, spinal level, composition, and degeneration. *Spine*. 1988; 13(2):179–87. [PubMed: 3406838]
 8. Johannessen W, Elliott DM. Effects of degeneration on the biphasic material properties of human nucleus pulposus in confined compression. *Spine*. 2005; 30(24):E724–E9. [PubMed: 16371889]
 9. Cloyd J, Malhotra N, Weng L, Chen W, Mauck R, Elliott D. Material properties in unconfined compression of human nucleus pulposus, injectable hyaluronic acid-based hydrogels and tissue engineering scaffolds. *Eur Spine J*. 2007; 16(11):1892–8. [PubMed: 17661094]
 10. Marchand F, Ahmed AM. Investigation of the laminate structure of lumbar disc anulus fibrosus. *Spine*. 1990; 15(5):402–10. [PubMed: 2363068]
 11. Andersson GB. What are the age-related changes in the spine? *Baillieres Clin Rheumatol*. 1998; 12(1):161–73. [PubMed: 9668961]
 12. Kirkaldy-Willis WH, Wedge JH, Yong-Hing K, Reilly J. Pathology and pathogenesis of lumbar spondylosis and stenosis. *Spine*. 1978; 3(4):319–28. [PubMed: 741238]
 13. Modic MT. Degenerative disc disease and back pain. *Magn Reson Imaging Clin N Am*. 1999; 7(3):481–91. [PubMed: 10494530]
 14. Tehranzadeh J. Discography 2000. *Radiologic Clinics of North America*. 1998; 36(3):463–95. [PubMed: 9597067]
 15. Carragee EJ, Alamin TF, Carragee JM. Low-pressure positive Discography in subjects asymptomatic of significant low back pain illness. *Spine*. 2006; 31(5):505–9. [PubMed: 16508542]
 16. Morgan S, Saifuddin A. MRI of the lumbar intervertebral disc. *Clin Radiol*. 1999; 54(11):703–23. [PubMed: 10580761]
 17. Gunzburg R, Fraser RD, Moore R, Vernon-Roberts B. An experimental study comparing percutaneous discectomy with chemonucleolysis. *Spine*. 1993; 18(2):218–26. [PubMed: 8441937]
 18. Urban JP, Winlove CP. Pathophysiology of the intervertebral disc and the challenges for MRI. *J Magn Reson Imaging*. 2007; 25(2):419–32. [PubMed: 17260404]
 19. Pfirrmann CW, Metzdorf A, Zanetti M, Hodler J, Boos N. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine*. 2001; 26(17):1873–8. [PubMed: 11568697]
 20. Li X, Han ET, Ma CB, Link TM, Newitt DC, Majumdar S. In vivo 3T spiral imaging based multi-slice T(1rho) mapping of knee cartilage in osteoarthritis. *Magn Reson Med*. 2005; 54(4):929–36. [PubMed: 16155867]
 21. Lozano J, Li X, Link TM, Safran M, Majumdar S, Ma CB. Detection of posttraumatic cartilage injury using quantitative T1rho magnetic resonance imaging. A report of two cases with arthroscopic findings. *J Bone Joint Surg Am*. 2006; 88(6):1349–52. [PubMed: 16757771]
 22. Borthakur A, Mellon E, Niyogi S, Witschey W, Kneeland JB, Reddy R. Sodium and T(1rho) MRI for molecular and diagnostic imaging of articular cartilage. *NMR Biomed*. 2006; 19(7):781–821. [PubMed: 17075961]
 23. Regatte RR, Akella SV, Borthakur A, Kneeland JB, Reddy R. Proteoglycan depletion-induced changes in transverse relaxation maps of cartilage: comparison of T2 and T1rho. *Acad Radiol*. 2002; 9(12):1388–94. [PubMed: 12553350]
 24. Johannessen W, Auerbach JD, Wheaton AJ, Kurji A, Borthakur A, Reddy R, Elliott DM. Assessment of human disc degeneration and proteoglycan content using T1rho-weighted magnetic resonance imaging. *Spine*. 2006; 31(11):1253–7. [PubMed: 16688040]
 25. Nguyen AM, Johannessen W, Yoder JH, Wheaton AJ, Vresilovic EJ, Borthakur A, Elliott DM. Noninvasive Quantification of Human Nucleus Pulposus Pressure with Use of T1{rho}-Weighted Magnetic Resonance Imaging. *J Bone Joint Surg Am*. 2008; 90(4):796–802. [PubMed: 18381318]
 26. Auerbach JD, Johannessen W, Borthakur A, Wheaton AJ, Dolinskas CA, Balderston RA, Reddy R, Elliott DM. In vivo quantification of human lumbar disc degeneration using T1rho-weighted magnetic resonance imaging. *Eur Spine J*. 2006; 15:338–44.
 27. Witschey W, Borthakur A, Elliott M, Fenty M, Sochor M, Wang C, Reddy R. T1rho-prepared balanced gradient echo for rapid 3D T1rho MRI. *J Magn Reson Imaging*. 2008; 28(3):744–54. [PubMed: 18777535]

28. Ishihara H, Warensjo K, Roberts S, Urban J. Proteoglycan synthesis in the intervertebral disk nucleus: the role of extracellular osmolality. *Am J Physiol.* 1997; 272(5)(Pt 1):C1499–506. [PubMed: 9176140]
29. Bashir A, Gray ML, Burstein D. Gd-DTPA2- as a measure of cartilage degradation. *Magnetic Resonance in Medicine.* 1996; 36:665–73. [PubMed: 8916016]
30. Bashir A, Gray ML, Hartke J, Burstein D. Nondestructive imaging of human cartilage glycosaminoglycan concentration by MRI. *Magnetic Resonance in Medicine.* 1999; 41(5):857–65. [PubMed: 10332865]
31. Burstein D, Velyvis J, Scott KT, Stock KW, Kim YJ, Jaramillo D, Boutin RD, Gray ML. Protocol issues for delayed Gd(DTPA)2--enhanced MRI (dGEMRIC) for clinical evaluation of articular cartilage. *Magn Reson Med.* 2001; 45(1):36–41. [PubMed: 11146483]
32. Ibrahim MA, Jesmanowicz A, Hyde JS, Estkowski L, Haughton VM. Contrast enhancement of normal intervertebral disks: time and dose dependence. *AJNR Am J Neuroradiol.* 1994; 15(3): 419–23. [PubMed: 8197936]
33. Rajasekaran S, Babu JN, Arun R, Armstrong BR, Shetty AP, Murugan S. ISSLS prize winner: A study of diffusion in human lumbar discs: a serial magnetic resonance imaging study documenting the influence of the endplate on diffusion in normal and degenerate discs. *Spine.* 2004; 29(23): 2654–67. [PubMed: 15564914]
34. Reddy R, Insko EK, Noyszewski EA, Dandora R, Kneeland JB, Leigh JS. Sodium MRI of human articular cartilage in vivo. *Magn Reson Med.* 1998; 39(5):697–701. [PubMed: 9581599]
35. Shapiro EM, Borthakur A, Gougoutas A, Reddy R. ²³Na MRI accurately measures FCD in articular cartilage. *Magn Reson Med.* 2002; 47(2):284–91. [PubMed: 11810671]
36. Wheaton AJ, Borthakur A, Dodge GR, Kneeland JB, Schumacher HR, Reddy R. Sodium magnetic resonance imaging of proteoglycan depletion in an in vivo model of osteoarthritis. *Acad Radiol.* 2004; 11(1):21–8. [PubMed: 14746398]

Figure 1.

Representative proton T_2 MRI (grayscale) and corresponding $T_{1\rho}$ maps (in color overlaid on grayscale $T_{1\rho}$ -weighted image) of the lumbar discs from a 52-year old female (A) and a 35-year old male (B) patients diagnosed with LBP and from an asymptomatic 38-year old male (C). Average $T_{1\rho}$ (in ms) was measured in the NP and is displayed below the discs, followed by the OP (in psi) and whether discs were painful (P) or non-painful (N), both determined by discography are indicated in the LBP patients. The asymptomatic subject only displays $T_{1\rho}$ values since discography was not performed on the control cohort. Color bar on the right indicates a $T_{1\rho}$ scale from 0–250ms.

Figure 2.

Plot of mean $T_{1\rho}$ (in ms) for the control (c), LBP non-painful (n) and painful (p) disc cohorts along with 95% confidence intervals (A). $T_{1\rho}$ was 92.0 ± 4.9 ms (mean $\pm$ std. error) for the control group and in the LBP cohorts' discs without pain was 83.6 ± 3.2 ms and with pain was $55.3 \text{ ms} \pm 3.0$ ms. Mean OP in the painful discs along with the respective 95% confidence intervals (B) was 19.1 ± 0.7 psi (mean $\pm$ std. error) and 11.8 ± 1.0 psi, in the non-painful and painful cohorts respectively. The percent decrease between cohorts and the significance of this difference (p-value) are shown.

Figure 3.

T1ρ in the NP correlates significantly with Pfirrmann degenerative grade (A) with $r=0.59$ ($p<0.001$) from painful discs (**x**, $n=25$) discs with no pain (**○**, $n=43$) in the LBP cohort and in control discs (**Δ**, $n=44$). Disc OP and Pfirrmann grade (B) are correlated significantly with $r=-0.52$ ($p<0.001$) in LBP patients with painful discs (**x**) discs with no pain (**○**).

Figure 4.

$T_{1\rho}$ was correlated with disc OP ($r=0.54$, $p<0.001$) with painful discs ($\times$) exhibiting both lower pressure and $T_{1\rho}$ values compared to discs with no pain ($\circ$). The horizontal lines indicate significantly ($p<0.001$) different mean $T_{1\rho}$ of the painful (55.3 ms, solid line) and non-painful (83.6 ms, dashed line). Also shown are the 95% confidence limits for both means as corresponding curved lines.

Figure 5.

ROC curve of $T_{1\rho}$ and OP as predictors of painful discs. The results are summarized in Table 1.

Table 1
Results of ROC analyses of T_{1p} and OP as continuous rating scale predictors of disc pain.

<i>Variables</i>	ROC Area Under Curve			<i>95% Confidence Interval</i>	
	<i>Area</i>	<i>Std. Error^a</i>	<i>Significance^b</i>	<i>Lower Bound</i>	<i>Upper Bound</i>
T _{1p}	.91	.04	.0001	.84	.98
Opening Pressure	.84	.06	.0001	.73	.95

^aUnder the nonparametric assumption

^bNull hypothesis: true area = 0.5