

Feasibility of Using MR Elastography in the Intervertebral Disc and Comparison to Finite Element Model

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Introduction: Low back pain (LBP) is a very costly and prevalent health disorder in the U.S., resulting in total costs exceeding \$100 billion per year.[1] In fact, it is reported that up to 85% of people will experience LBP in their lives.[2] One of the most common causes of LBP is degenerative disc disease (DDD), which has been shown to precede LBP and several other disorders in the spine associated with LBP.[3] DDD is a complex cascade of biological and structural changes in the intervertebral disc (IVD) caused by altered mechanics and load distribution of the disc. There are many techniques that have been developed to characterize disc degeneration such as x-ray, T2-weighted MRI [4], axial T2 mapping [5], T_{1ρ}-weighted MRI [6], T2 relaxation times [7], and sodium MRI [8]. However, there is no way to directly assess the material properties of the IVD within the intact spine. It has been shown that the nucleus pulposus within the disc undergoes significant changes in shear modulus, even with early stage disc degeneration.[9] Magnetic resonance elastography (MRE) is a sensitive, phase contrast-based imaging technique for non-invasively mapping the mechanical properties of tissues.[10] The *purpose* of this study is to determine if MRE is capable of detecting shear wave propagation in the IVD, and compare the experimental results with a finite element model of intervertebral disc MRE. The target audience of this research is MRI scientists involved in developing spinal imaging methods, radiologists involved in spinal imaging, clinicians involved in managing patients with low-back pain and disc-related spinal disorders, and basic scientists investigating DDD.

Methods and Materials: (1) Intervertebral Disc. The L3-L4 motion segment of a baboon lumbar spine was removed with musculature and entire IVD intact. All posterior elements of the motion segment were removed to increase flexibility of the specimen. (2) Mechanical vibration. A piezoelectric mechanical driver was used to apply mechanical vibrations at frequencies in the 1-10 kHz range. The driver was positioned such that shear vibration was applied to the upper vertebral body of the motion segment while the lower vertebral body was fixed using a custom-built testing fixture. The specimen was put into a single-channel, 5-in diameter receive coil with the transverse, or axial, cross-section of the IVD parallel to the B₀ direction. The vibration direction was parallel to the B₀ direction and perpendicular to the spinal motion segment (fig. 1a). (3) Wave imaging sequence. The disc specimen was imaged with a spin echo-based MRE sequence with the following parameters: 30 total cycles of 1000Hz motion-encoding gradients (2.4 Gauss/cm), motion sensitivity = 12.9μm/π, offsets = 4, 290/50-ms TR/TE, 8-cm FOV, one 8-mm slice, 256x96 matrix, 1 NEX. A standard 1.5T full-body MRI scanner (Signa, GE, Milwaukee, Wisconsin, USA) was used in the experiment. (4) Finite element model. A dynamic, linear finite element model was created to simulate the experimental disc MRE with shear vibration applied at 1000Hz. The model includes the partial vertebral bodies (white), end plates (red), disc annulus (green), and disc nucleus pulposus (blue) (fig. 1b and 1c) with the appropriate reported material properties from previous lumbar spine finite element models [11]. Commercially available software was used for the finite element analysis (ABAQUS, Dassault Systèmes Simulia Corp., Providence, Rhode Island, USA). (5) Inversion algorithms. The resulting wave images were then phase unwrapped, bandpass filtered (1-20 waves per FOV), directionally filtered (8 directions) [12], and processed using a local frequency estimation (LFE) inversion algorithm [13] to provide maps of shear stiffness. The average shear stiffness of the nucleus pulposus region within the IVD was measured with a circular ROI placed in the center of the disc.

Results and Discussion: As shown in Figure 2a, propagating waves were seen in the transverse cross-section of the IVD in all three motion-encoding directions. There are very distinct wave patterns differentiating the annulus and nucleus pulposus regions of the disc, with the nucleus showing a much shorter wavelength. Interestingly, the finite element model of disc MRE showed very similar shear wave displacement patterns in all three motion encoding directions when compared to the experimental baboon disc MRE results (fig. 2b). The principle wave data (S/I) was inverted using the LFE inversion algorithm to give a shear stiffness map for the transverse cross-section of the disc (fig. 3). Although the wavelength was too long in the annular region to reliably approximate stiffness, the nucleus showed an average stiffness of 79 ± 15 kPa, which is very near the range reported in literature for the human IVD nucleus stiffness[11,14].

Conclusions: These initial results suggest MRE is capable of detecting shear wave propagation in intervertebral disc specimens *in vitro*, and experimental results appear to correlate well with FE-predicted results. Additionally, the data suggests MRE can differentiate the nucleus and annulus regions of the intervertebral disc. The ability to perform disc MRE *in vivo* could provide a valuable tool to study the progression of DDD, improve the clinical evaluation of LBP patients and investigate potential therapies for DDD. Further work is needed to demonstrate the ability to detect mechanical property changes in the disc using MRE and determine the clinical viability of this application.

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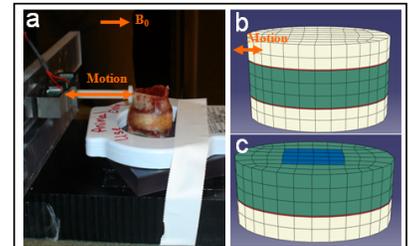


Figure 1: (a) Experimental setup for baboon intervertebral disc MRE with motion applied using piezoelectric driver. (b) Intervertebral disc model with motion applied to the upper vertebral body as shown to simulate disc MRE. (c) Cross section of intervertebral disc finite element model to show the annulus (green) and nucleus (blue) regions included in the disc model.

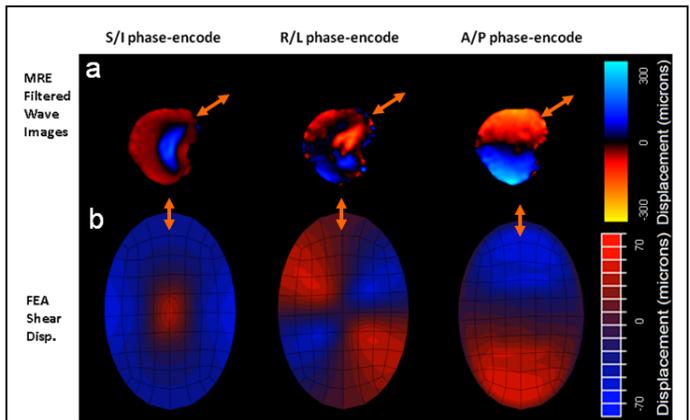


Figure 2: Top row (a): MRE wave images of intervertebral disc in all three motion encoding directions after filtering with a Gaussian bandpass filter with cut-offs of 1 and 20 waves/FOV. Color bar indicates the motion amplitude measured with MRE. Bottom row (b): shear displacement patterns in all three motion directions from simulated intervertebral disc using Finite Element Analysis (FEA). Color bar indicates motion amplitude as predicted by FE model of disc MRE. Applied motion directions are shown with arrows.

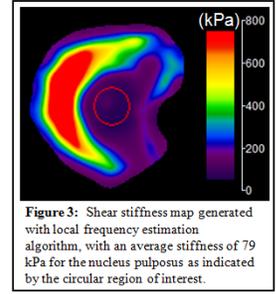


Figure 3: Shear stiffness map generated with local frequency estimation algorithm, with an average stiffness of 79 kPa for the nucleus pulposus as indicated by the circular region of interest.