Assessment of the stiffness of intervertebral disk in rat model with Magnetic Resonance Elastography

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Target Audience: MRI physicists and Clinicians who are interested in intervertebral disk (IVD) disease

Background and Introduction: The degeneration of the intervertebral disk (IVD) is one of the most significant causes of low back pain and the etiology of the IVD disease is still vaguely understood. Evaluating the mechanical integrity of the IVD has the potential to quantify early changes in the degeneration [1]. However, most of the current biomechanical measurements are invasive. Magnetic resonance elastography (MRE) is a MRI technique that noninvasively measures stiffness of tissue under harmonic motion [2]. The IVD stiffness has been investigated in human and in a bovine model in recent years [3, 4]. Since rodents have been widely used as models to study disc degeneration [5], in this study, we tested the feasibility of measuring stiffness of IVD in vitro in a rat model with high resolution MRE.

Methods: The MRE experiment was conducted on four dissected L3-L4 lumbar motion segments (vertebra-disc-vertebra) of four Sprague-Dawley type rats (Charles River Laboratories, Wilmington, Mass) weighing 320-350 grams. All lateral and posterior elements were removed. The motion segment was constrained vertically between two 3D printed customized fixtures to avoid free motion. The disc along with the fixtures was inserted into a glass MRI test tube of 8.5 mm inner diameter. Fluorine oil (3M™ Fluorinert™ FC-43) was filled in void spaces in the tube for protection and reduction of susceptibility artifacts. All images were collected on an 11.74 Tesla Bruker vertical bore MR scanner with a 10 mm saddle coil. The test tube was driven by a piezo actuator at 3 kHz in the longitudinal (axial) direction. A gradient echo SLIM MRE pulse sequence [6] was applied to obtain wave images so that motion on three encoding directions could be obtained in one single scan. The wave images were collected in four slices perpendicular to the axial view and parallel to the center line of the disc. Other imaging parameters are as follows: FOV = 1cm, 128x128 matrix made the in plane resolution of 78x78 µm; four slices of 1 mm thickness and no gap between slices; TR/TE = 200/2.94 ms; flip angle = 50°. Five cycles of 3 kHz sinusoidal motion encoding gradient (MEG) with power of 50 Gauss/cm were applied on all three gradient directions. Eight phase offsets over one period of motion were applied to get wave images. Due to the complexity of the sample and experiment setup, a control scan with the actuator turned off was performed as well in order to compare the wave amplitude images with the MRE scan to confirm actuator-driven motion in the disc. The wave images were filtered by a 4th order Butterworth bandpass filter with cutoff value of 1-40 waves/FOV plus an additional 2D directional filter [7] in four directions (with 90° separation). A weighted sum effective shear stiffness map was then estimated by a 2D inversion algorithm [2] from the three motion encoding directions based on the relative energy at each pixel of the displacement amplitude of each encoding direction. All post processing was performed in a customized software written in MATLAB (MathWorks, Natick, MA). For each slice covering the NP, three ROIs were drawn on the stiffness map: 1) the entire disc area; 2) the NP; and 3) the annulus fibrosus. Averaged stiffness in each ROI from four adult rats was estimated.

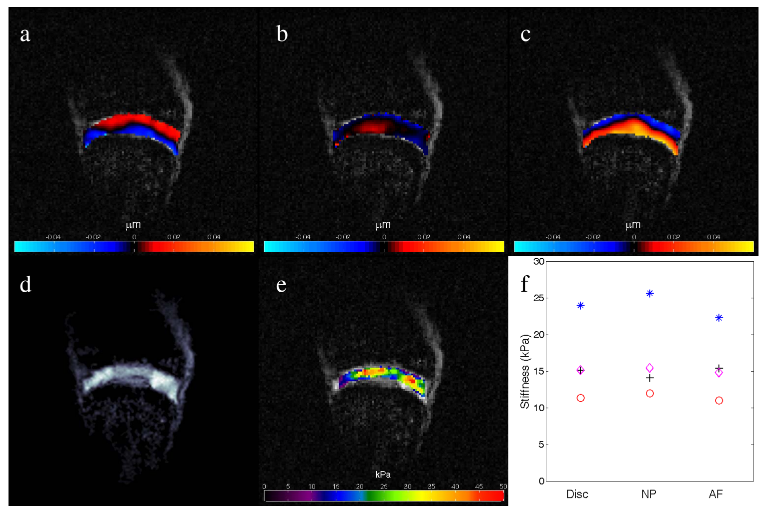

Figure 1. a, b, c: MRE extracted waves in the disc with vibrations on three directions (a) vertical (b) horizontal, and (c) out of plane direction overlaid on the magnitude image; (d) magnitude image of the disc segment; (e) stiffness map of the disc overlap with the magnitude image of the disc segment; (f) measured stiffness results of whole disc, nucleus pulposus (NP) and annulus fibrosus (AF) of the four samples.

Results: Representative wave images are shown in Figure 1 a-c for motion direction of vertical, horizontal and out-of-plane, respectively. The magnitude image shows relatively lower signal intensity in the center of the disc (Figure 1d). The estimated average shear stiffness within each ROI of L3-L4 motion segments based on the algorithm described above are shown in Figure 1f. The stiffness of one sample is notably higher.

Discussion: IVD mechanical properties were reported to be sensitive to both biochemical and structural changes during early degeneration. By measuring vibratory waves in tissue subjected to harmonic mechanical excitation, MRE provides a noninvasive method to investigate the tissue mechanical properties. This study demonstrates the feasibility of performing MRE measurements on the rat lumbar disk, and thus providing the potential for noninvasive biomechanical investigation of the rodent IVDs. However, it is noted that the conventional post processing algorithm applied here to estimate a shear stiffness map based on vibratory wave measurements, has limitations due to the close boundaries of the vertebrae [4]. Nonetheless, despite uncertainty in the absolute quantitative values estimated, we note that, there was a stiffness difference estimated in one case suspected of degeneration, relative to the other cases. Viscoelastic properties of lumbar motion segments at various stages of IVD degeneration need further examination. Additionally, improved postprocessing of wave images to generate shear stiffness estimates is needed, perhaps through image-derived, specimen-specific computational (finite element) simulation in the future.

References:

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