FULL PAPER

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In Vivo Multifrequency Magnetic Resonance Elastography of the Human Intervertebral Disk

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Purpose: To test in vivo magnetic resonance elastography (MRE) of the human intervertebral disk (IVD).
Methods: The feasibility of MRE in IVD was demonstrated in ex vivo bovine disks. Sixteen asymptomatic volunteers underwent multifrequency MRE of the lumbar spine (IVD L3/4 and L4/5, $n = 32$) using a posterior plate transducer connected to a loudspeaker and operated at five frequencies from 50 to 70 Hz. Full wave field data were acquired in 10 transverse slices of $2 \times 2 \times 2$ mm^3 resolution. High-resolution maps of magnitude $|G^*|$ and phase angle φ of complex shear modulus G^* were generated by multifrequency dual elasto visco (MDEV) inversion. Disk morphology was assessed by the Pfirrmann score (Pf).
Results: Morphological Pf was 1 in 25, 2 in 3, and 3 in 4 disks. $|G^*|$ decreased with Pf by a Pearson's linear correlation coefficient of $R = -0.592$ ($P = 0.0004$), while φ remained unchanged. Group mean mechanical parameters for Pf = 1 to 3 were $|G^*| = 6.51 \pm 1.27$, 5.29 ± 0.95, 4.03 ± 0.99 kPa, and $\varphi = 1.190 \pm 0.181$, 1.170 ± 0.156, 1.088 ± 0.084 rad, respectively (p[Pf1-Pf3] < 0.001). The variability of mechanical parameters in one volunteer including diurnal changes was approximately 11%.
Conclusion: Multifrequency MRE with MDEV inversion allows measurement of in vivo mechanical properties of IVDs and may provide additional information in disc degeneration beyond standard morphological changes. **Magn Reson Med 000:000–000, 2014. © 2014 Wiley Periodicals, Inc.**

Key words: intervertebral disks; magnetic resonance elastography; MRE; multifrequency dual elasto visco inversion; magnitude shear modulus; phase angle; high resolution

INTRODUCTION

Degenerative disk disease is a common cause of chronic back pain without sensory or motor deficits (1–3). Disk degeneration is characterized by progressive cellular senescence (4), aging of the extracellular matrix with loss of tissue hydration (5), and age-related changes in the endplate (6). As a result of these processes, blood vessels and nerves can invade the intervertebral disk (IVD), causing pain and inflammation (7). In addition, the IVD becomes vulnerable to shear-stress-related microtrauma, making degenerative disk diseases a possible precursor of IVD herniation (8).

Various classification systems exist for assessing the grade of disc degeneration. One grading system proposed by Pfirrmann et al. is the most accepted tool due to its high feasibility using T2-weighted magnetic resonance imaging (MRI) and accurate reliability (9). Although the Pfirrmann score is widely used in radiological routine, the morphological MRI appearance of the IVD is not significantly correlated to the extent of symptoms or future herniation events. IVD function is related to its mechanical properties and include bearing heavy loads, absorbing mechanical energy, and providing freedom of motion between adjacent vertebrae. It, therefore, remains challenging to predict disk function based on conventional MRI alone without in vivo assessment of disk mechanics.

For characterizing its mechanical properties, the disk can be subdivided into three gross regions: the anulus fibrosis (AF) made of fibrocartilage tissue, the gelatinous nucleus pulposus (NP), and a transition region with intermediate material properties (10). Being predominantly composed of collagen type-I fibers organized in concentric lamellae, the AF is a stiff solid material with cartilage-like properties characterized by high shear modulus on the order of MPa. In contrast, the NP is soft and viscous due to high water content and a disordered extracellular matrix, which is composed of type-II collagen fibers and proteoglycans, leading to a high water storage capacity. At low dynamics, the NP cannot bear static shear stress, suggesting fluid-like rather than solid material properties, while at higher stimulation frequencies, the NP shows a distinct solid behavior and transmits shear forces (11).

In terms of MRI signal intensities and shear elasticity, NP is in principle accessible by in vivo MR elastography (MRE) (12,13). However, to date no in vivo shear modulus data have been reported for the IVD. Mechanical tests of ex vivo NP specimens, ex situ and in situ, were applied to investigate compression, poroelastic, hyperelastic, and shear elastic properties over a wide dynamic range from static to a few hundreds of Hertz (12–17). The reported NP shear modulus values vary between 10.5 ± 17.4 kPa (11) and nearly 1000 kPa (12) with marked softening (12) or stiffening (13) upon disk degeneration. This variability of data indicates that the outcome of mechanics-based disk assessment is influenced by various factors including mechanical test conditions, tissue viability, or osmotic swelling pressure. Ultimately,

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