Investigating anisotropic elasticity using MR-Elastography combined with Diffusion Tensor Imaging: Validation using anisotropic and viscoelastic phantoms

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Introduction:

Magnetic Resonance Elastography (MRE) is a non-invasive imaging technique which is capable of quantifying soft tissue elasticity in vivo [1]. Most MRE studies have assumed isotropic mechanical properties although many soft tissues possess anisotropic mechanical properties due to their fibrous structure, for instance skeletal muscle or brain white matter. We propose a technique which for the first time combines Diffusion Tensor Imaging (DTI) information with MRE to investigate the anisotropic elasticity of tissue. By calculating the variation of diffusion of water molecules in different spatial directions, DTI can estimate the local fiber direction. Using this information, the shear modulus parallel ($\mu_\parallel$) and perpendicular ($\mu_\perp$) to the fiber can be calculated assuming a transversely isotropic model. Here, we aimed: 1) to design and construct anisotropic viscoelastic phantoms for validating the combined MRE/DTI imaging technique. 2) To quantitatively validate this combined MRE/DTI technique by comparing the anisotropic ratio ($\mu_\parallel/\mu_\perp$) of the MRE results with the "gold standard" rotational rheometry results. Once fully validated, this technique could potentially shed new light on tissue injury mechanisms. Diseases such as multiple sclerosis and atrophy are known to be associated with changes in tissue anisotropy. It could also provide additional physical parameters to help the development of more accurate computer models.

Methods:

Figure 1

Viscoelastic anisotropic phantoms were constructed by embedding elastic spandex fibers (ø = 36μm) in PVA cryogel in polypropylene tubes (ø = 20 mm). Phantoms with three different fiber volume fractions were made: v_f = 0% (isotropic), 15% and 35%, n=4 for each group. All phantoms were scanned using a Philips 3T Achieva MRI scanner with a custom-made MRE transducer. Seven image slices were acquired in the axial plane with fibers positioned in the right-left direction. A excitation frequency of 200 Hz was used with a modified spin-echo pulse sequence [2]. The wave motion was captured at four time points (TR/TE = 385/35 ms, matrix size = 96x96, voxel size = 2x2x2 mm). DTI data were collected from the same slices using the following parameters: 32 gradient directions, 2 mm isotropic voxel size, b-factor = 800 and TE/TR = 71/987ms. Bovine skeletal muscle samples with fibers running mainly in the right-left direction were also scanned using the same protocol. Following scanning, the phantoms were sliced into disc samples (ø = 20mm, thickness = 3 – 4mm, n=4 for each fiber directions per phantom) for rotational rheometry testing (Figure 1). Rheometry experiments were conducted using the Malvern Kinexus rheometer in the linear viscoelastic regime with the following parameters: frequency = 10 Hz, strain = 0.1%, normal preload = 0.2 N. The anisotropic ratio ($\mu_\parallel/\mu_\perp$) of the MRE results was compared to rotational rheometry measurements (two-tail student t-test).
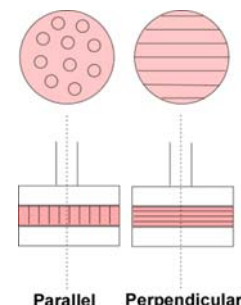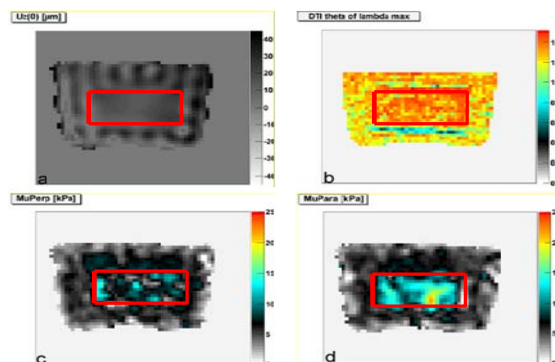

Figure 2

Results:

A typical wave image of the phantom (v_f = 35%) is shown in Figure 2a. The first and second Euler angles were approximately 0° (not shown) and 90° (Figure 2b) respectively, as correctly found by the DTI analysis. Shear moduli parallel and perpendicular to the fiber directions are presented in Figure 2c and 2d, indicating that the fibers are stiffer in their parallel direction. MRE (Figure 3a) revealed that the anisotropic ratio ($\mu_\parallel/\mu_\perp$) of the bovine skeletal samples and the v_f = 35% fiber phantoms were significantly higher than the isotropic phantom (p < 0.05, t-test). Rheometry results (Figure 3b) confirmed these findings. Most importantly, no significant difference was observed between the MRE and corresponding rheometry results.

Discussion:

The combined MRE/DTI technique successfully quantified and visualized for the first time the shear moduli perpendicular and parallel to the fiber direction of mechanically anisotropic materials. The technique was able to correctly detect changes in mechanical anisotropy as demonstrated in phantoms and bovine skeletal muscles. MRE results agreed favorably with the rheometry results in terms of the anisotropic ratio. The phantoms constructed were demonstrated to be suitable for future validations of DTI and MRE scanning protocols. Results of this study suggest that the technique can accurately estimate the mechanical anisotropy of soft tissues using a combined MRE-DTI approach. Currently preliminary in-vivo human brain and skeletal muscle studies in vivo are also being conducted.

References:

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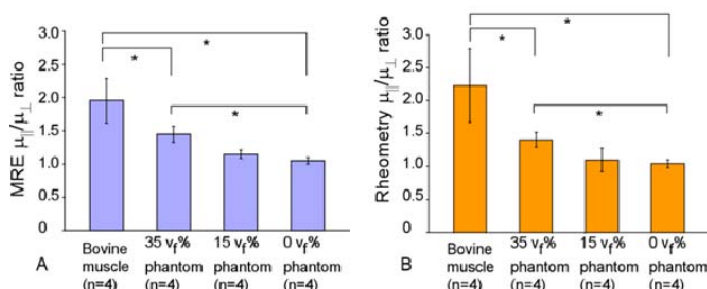
Figure 3