q-Space imaging correlates with mechanical strain

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Abstract

q-Space imaging can be used to measure the diffusion properties of water molecules in a variety of mediums. By applying a series of diffusion gradients in multiple directions a 3-dimensional description of water diffusion can be constructed. These data can be used to measure diffusion anisotropy. Mechanical strain has been shown to be sensitive to anisotropic properties of tissue. This mechanical anisotropy could be due to an underlying tissue structure that should demonstrate a diffusion anisotropy as well. In this paper we report the combined mechanical anisotropy and diffusion anisotropy of a meat phantom embedded in an isotropic hydrogel substrate.

Introduction

Diffusion properties of water in tissue can be elucidated with q-space imaging. This method utilizes a pair of strong magnetic pulsed field gradients to encode diffusion, and in the limit of short gradient pulses with respect to gradient pair separation, q-space imaging is essentially the Fourier transform of the water displacement probability, $P(r|r',\Delta)$, at a fixed time Δ, as illustrated in equation 1.

$$E_{\Delta}(g) = \int \rho(r) \int P_S(r,r',\Delta) e^{i\gamma\delta g\cdot(r'-r)} dr' dr \quad [1]$$

The elegance of q-space imaging is the ability to fully describe the diffusion properties of water in an arbitrary constraining geometry unlike diffusion tensor imaging that assumes an ellipsoid geometry of the microscopic structures. q-Space imaging has been used to image the crossing of white matter fibers in human brain[1]. Additionally, diffusion anisotropy in human calf muscle has been measured [2] using only 2 directions with a single b-value. Mechanical strain measures have shown that highly structured tissue such as muscle has an anisotropy. We hypothesize that the macroscopic measure of mechanical stain anisotropy and diffusion anisotropy should correlate.

Methods

In this work q-space data and mechanical strain data were collected using a single meat phantom. An approximately cubic (25mm x 23mm x 20 mm) piece of ***eye of round*** was prepared from a larger piece purchased at a local market. The sample was raw and unfixed. The deformation tests were performed using tissue holder with two parallel vertical walls. The sample was snugly fit between vertical plates while deformations were applied over the entire top horizontal surface of the sample constrained at the bottom. When the sample is vertically deformed in the tissue holder, the resulted free strain is limited to the remaining direction only. By varying the direction of the applied and free strains (or orientation of the sample in the holder, which is equivalent), the mechanical behavior of the anisotropic sample was measured. The tissue holder was attached to an electronic scale (1 sample/second, 10^{-4} N resolution), and 5 cycles of static deformations (up to 20%) were applied using computer-controlled stepper motor system until the pre-set force/stress threshold was reached. The initial test served as sample pre-conditioning, and remaining sets were used to analyze the mechanical properties of the sample. After the mechanical strain measurements were made the sample was embedded in a hydrogel (56mm x 56mm x 95mm) substrate for magnetic resonance imaging. q-Space images were acquired along a direction parallel and perpendicular to the grain direction using a stimulated echo sequence. Gradient strengths g varied from -6 gauss cm^{-1} to 6 gauss cm^{-1} in steps of 0.5 gauss cm^{-1} (25 diffusion weight images per direction). The pulse gradients (g) were on for 14 ms (δ) with a leading edge separation (Δ) of 100 ms. Spatial encoding was done with a 10cm square field of view and a resolution of 128^2. The resulting q-images have a 28 micron resolution and a 335 micron field of view. This corresponds to a maximum b value of 4813 s mm^{-2}. A single plane was imaged through the middle of the sample. The fibers were oriented along the y direction of the imaging system (Bruker/Varian CSI 2T).

Results

In Fig. 1, the stress-strain relationships are contrasted for each orientation of the sample. Clearly, when the muscle fibers are oriented along the free strain direction, the sample appears hardest (solid line). In opposite, for the other two orientations where the fibers are oriented either vertically (i.e., along the direction of applied deformation), the sample appears near identical and softer. This is expected from the transversely isotropic material such as muscle and consistent with other literature data. q-Space results are shown in Figure 2. Regions of interest were drawn in the hydrogel substrate as well as the meat sample. The displacement probabilities were calculated from an inverse Fourier transform of the q-space data for each ROI. The vertical scale is in arbitrary MR units with the relevant quantity being the widths of the Gaussians. Each displacement distribution $P(r'|r,\Delta)$ was fit to a Gaussian distribution using χ^2 minimization. The top two plots are the $P(r'|r,\Delta)$ distributions for the hydrogel along the Y and X axes of the phantom (Z is slice select). The widths of the diffusion distributions are σ_y=35.9+/-0.1 microns and σ_x=35.7+/-0.2 microns. Clearly indicating no preferred direction in the isotropic hydrogel substrate. The bottom two plots are for the meat (meat fiber orientation was along Y) phantom where clearly the $P(r'|r,\Delta)$ is wider (σ_y=27.2+/-0.2 microns vs. σ_x=24.9+/-0.2 microns) along the direction of the fiber orientation, indicating a preferred direction for diffusion. The ratio of the widths of the Gaussians distributions is used as a metric for anisotropy. The hydrogel has a resulting anisotropy of 0.0% +/- 0.8% while the ***eye of round*** has an anisotropy of 9.0% +/- 1.3%.

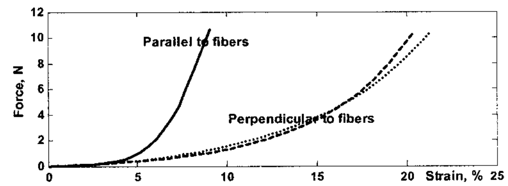

Figure 1: Mechanical strain measure of meat phantom.

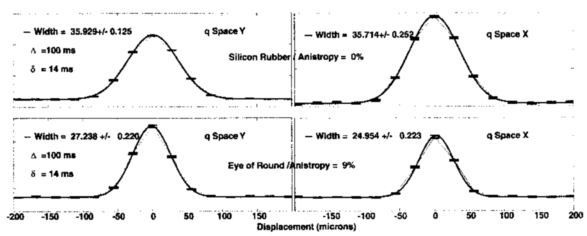

Figure 2: q-Space measures of diffusion anisotropy.

Conclusions

We have demonstrated that anisotropy observed mechanically has the same direction as that of diffusion anisotropy. Furthermore our results of q-space imaging and mechanical strain measurements are consistent with recent magnetic resonance strain imaging done on the same phantom. These data along with recent results [3] in magnetic resonance elastography (MRE) indicating that elastic anisotropy is an indicator for the detection of breast cancer suggest that a q-space imaging approach, possible even the subset of diffusion tensor imaging, might be a method to detect breast cancer. Through numerical simulations we have also investigated the use of a full q-space image to measure multiple diffusion compartments (e.g. crossing fibers, different inter-cell spaces) and arbitrary fiber orientation.

References

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