Microscopic MRI Assessment of Human Articular Cartilage Degeneration Using q-Space Analysis

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INTRODUCTION

Articular cartilage, which coats all skeletal joint surfaces, is a thin heterogeneous tissue that consists of three distinct zones: deep, middle, and superficial zones; each zone consisting of chondrocytes in a unique extracellular matrix of connective tissue, complex carbohydrates, and water. The physical and chemical integrity of articular cartilage is essential for maintaining normal joint movement. Conventional MRI, commonly used to evaluate joint disease and injury, is not capable of visualizing structural changes or damage within the articular cartilage. New MRI techniques are being developed to visualize articular cartilage for the purpose of assessing the structural changes that occur with the onset of joint disease. For example, the diffusion tensor analysis using MRI was recently shown feasibility in characterizing the articular cartilage (1). Another new approach for the analysis of the diffusion experiment involves *q*-Space, which like ADC can be correlated with the structural information of complex systems (2, 3). *q*-Space analysis produces the displacement distribution function of water molecules at a given diffusion time. The displacement distribution function is characterized by the mean displacement measured in microns and the probability for zero displacement measured in arbitrary units. *q*-Space analysis has been successfully used in several applications. For example, *q*-Space analysis was found to be sensitive to the pathophysiological states of white matter in multiple sclerosis (3, 4). In this study, we report the feasibility of *q*-space analysis for studying the structural changes accompanying cartilage degeneration. Three stages of articular cartilage degeneration have been investigated, each with *q*-Space analysis in seven diffusion directions from which the displacement distribution function is calculated. From the seven displacement distribution functions, two newly defined parameters, the fractional mean displacement ($F_{\overline{D}}$) and the fractional probability for zero displacement (F_{P_0}), are calculated to account for tissue anisotropy.

METHODS

Human tali were obtained through the Gift of Hope Organ and Tissue Donor Network with institutional approval, and frozen at -20 ^{0}C until experimentation. Prior to experimentation, 10 mm^3 cubes_containing full thickness cartilage with subchondral bone were harvested from the talar dome using a band saw with a diamond tip blade. To eliminate any saw blade artifacts, the samples were then trimmed, with a sharp scalpel blade, to 3 mm width cubes. The cartilage/bone cubes were fitted in a 5 mm NMR sample tubes filled with physiologic saline. There were three grades of cartilage degeneration: un-degenerated, G0 = normal,; superficial fibrillation, G1 = shallow, and excessive degenrationn, G2 = fissuring. MR experiments were conducted using a 56-mm vertical bore 11.74 T (500 MHz for proton) magnet equipped with Bruker DRX Avance spectrometer. Human cartilage samples were loaded into a 5-mm diameter RF saddle coil and inserted into the Bruker Micro5 imaging probe equipped with a tri-axial gradient set with a maximum strength of 200 G/cm. Diffusion-weighted images were obtained using a standard spin-echo diffusion-weighted pulse sequence with the following parameters: TR = 1000 ms, TE = 30 ms, Δ = 18 ms, δ = 3 ms, NEX = 4. The diffusion-weighting gradient was varied to produce 16 distinct q-space samples corresponding to a gradient strength ranging from 0 to 30 G/cm. At each of the 16 q-space values, a set of diffusion weighted images were acquired with diffusion gradient along seven directions (*x, y , z, xy, xz, yz, xyz*). The q-space analysis was performed on a pixel by pixel basis for each of the seven diffusion gradient directions. Displacement profiles were obtained by performing a FFT on the normalized signal decay along the *q* axis after zero padding of the signal decay curve to 128 points (3). For each pixel, two parameters were measured, the apparent mean displacement, and the apparent probability for zero displacement. These parameters were calculated from, respectively, the full width at half height of the normalized Gaussian displacement distribution profile, and the peak height of the normalized displacement distribution profile.

The fractional displacement $F_{\overline{D}}$ and fractional probability F_{P_0} were subsequently evaluated according to Eqs. [1, 2]

$$F_{\overline{D}} = \sigma(\sum_i D_i) \quad ,i = x, y, z, xy, xz, yz, xyz \qquad [1]$$

$$F_{P_0} = \sigma(\sum_i P_{0,i}) \quad ,i = x, y, z, xy, xz, yz, xyz \qquad [2]$$

where $\sigma(\sum_i D_i)$ is the standard deviation of all the measured mean displacements, and $\sigma(\sum_i P_{0,i})$ is the standard deviation for the measured probability for zero displacement.

RESULTS

Fig.1 shows the normalized Gaussian displacement distribution profile in the tangential, transitional, and radial zones of a normal articular cartilage calculated using the *x*-diffusion gradient. From this profile, the mean displacements in the radial, transitional, and tangential zones were found to be 13, 13, and 15 microns, respectively. While the probability for zero displacement showed a monotonic decrease for the tangential (12.3), transitional (11.4), and radial (10.1) zones. For the same pixel, different distribution functions were obtained when changing the diffusion direction for the three stages of cartilage degeneration. The probability for zero displacement for all seven diffusion gradient direction for the three stages of cartilage degeneration is shown in Fig. 2. The fractional probability and fractional mean displacement maps are illustrated in Fig. 3.

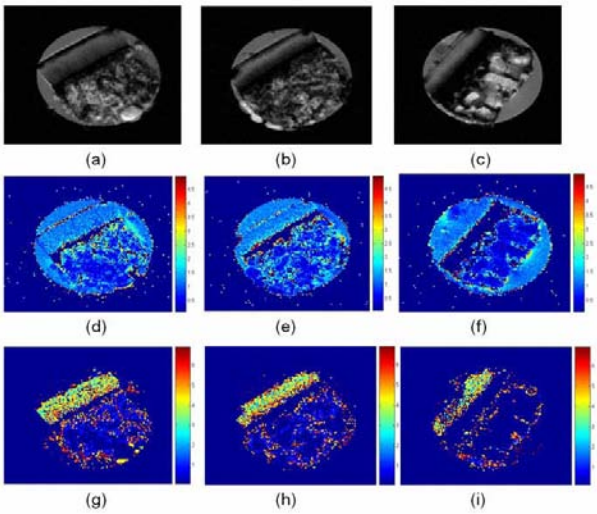

Fig. 3 MR magnitude image for grade 0 (a), grade 1(b), and grade 2 (c) and their corresponding fractional probability for zero displacement (d-f) and the fractional mean displacement (g-i)

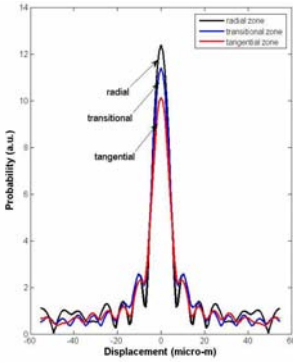

Fig. 1 The normalized displacement distribution profile in the tangential, transitional, and radial zones.

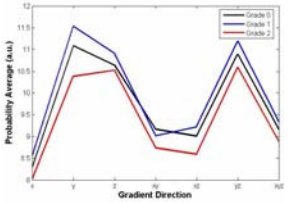

Fig. 2 The probability for zero displacement for all seven diffusion gradient directions for the three stages of cartilage degeneration

DISCUSSION AND CONCLUSION

q-Space analysis was capable of differentiating different cartilage regions and disease states. Compared to the mean displacement, the probability for zero displacement was more sensitive and showed a monotonic change when analyzing different regions of the cartilage or disease states consistent with the known cartilage structure. Significant anisotropy was observed when performing the experiments with seven diffusion gradient directions, suggesting that one diffusion direction might bring bias to the results. While this anisotropy can be approximately described using $F_{\overline{D}}$ and F_{P_0}, a sample-orientation independent metric needs to be developed to better characterize the anisotropy of the tissue.

REFERENCES: [1] Deng et al., ISMRM 13th scientific meeting 2005, Miami, FL. [2] Cory and Garroway, MRM 1990;14:435-444. [3] Callaghan et al., Nature 1991:351:467-469. [4] Assaf et al., MRM 2002;47:115-126.

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