Orientational dependence of compressed cartilage by µMRI T2 anisotropy

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Introduction

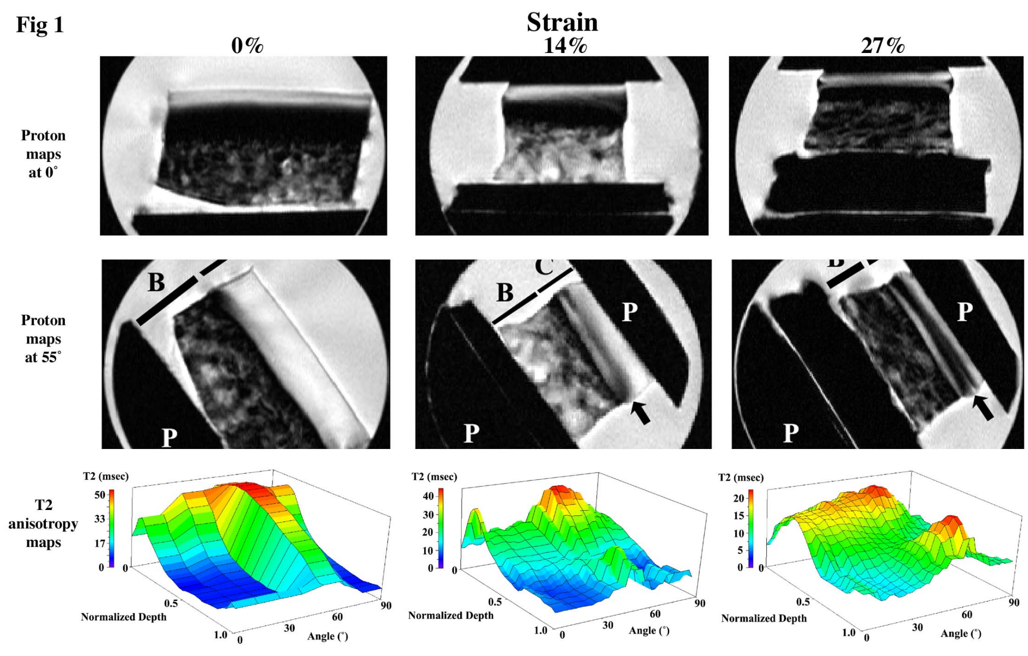
Although articular cartilage is thin, it is known to have depth-dependent anisotropic characteristics due to its histological zonal structure, which is defined by the collagen fibril orientation. The close interactions between the water protons and the collagen fibrils impose an anisotropy to T_2 relaxation in articular cartilage, which becomes the physical origin of the laminar appearance of cartilage in clinical MRI (also known as the magic angle effect in MRI of cartilage). A number of subtle changes in matrix ultrastructure in healthy and diseased cartilage have been reported by the method of µMRI T_2 anisotropy. Because T_2 anisotropy is sensitive to organizational changes in cartilage matrix, external loading will inevitably have profound effects on the characteristics of T_2 anisotropy in cartilage.

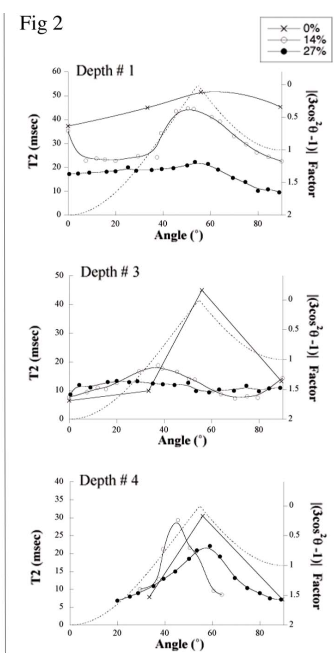
Methods

Six specimens were excised from the central load-bearing region of a healthy humeral head, each with a full thickness of cartilage still attached to the underlying bone. The specimens were T_2 imaged in a Bruker AMX NMR micro-imager with 7T magnet. Out of the six specimens: one specimen served as an uncompressed control (0% strain level) and was imaged at four orientations: (0˚, 36˚, 55˚, and 90˚); three specimens were subjected to compression at approximately three strain levels (10%, 16%, and 23%) respectively and at two orientations (0˚ and 55˚); and two specimens were subjected to compression at two strain levels (14% and 27%) and at nineteen different orientations (every five-degree increment in the first quadrant of the angular space). The total number of independent 2D T_2 weighted intensity images from all specimens at all orientations was 192. A total of 48 2D T_2 maps was constructed using these T_2 weighted intensity images. The echo time of the imaging segment was 8.7 ms and the repetition time of the imaging experiment was 2 s. The in-plane resolution across the depth of the cartilage tissue was 19.8 µm and the slice thickness was 1 mm.

Results

Contrary to the homogeneous appearance of unloaded cartilage at the magic angle (55˚), the loaded tissue exhibits a distinct laminar appearance for the proton images at 55˚ (Fig 1). In addition, the load-induced laminar appearance in cartilage becomes more profound at high strain levels (the arrows in Fig 1). To investigate the changes in the orientational dependence of T_2 anisotropy in cartilage during compression, three 3D T_2 anisotropy maps for the rotation of specimen were constructed within the first quadrant of the angular space (Fig 1), where each row is one quantitative T_2 profile as a function of the tissue depth at a fixed orientation and each column is a plot of T_2 versus the sample orientations at a fixed tissue depth. These 3D maps of T_2 anisotropy show that a second T_2 peak starts to emerge in the deep tissue toward the bone at 14% strain and becomes more distinct at 27% strain (the normalized depth has the articular surface at Depth 0 and the cartilage/bone interface at Depth 1). Close examination of these 3D T_2 anisotropy maps reveals different strain-dependent sinusoidal variations at different tissue depths (Fig 2). At Depth #1 that marks the center of the transitional zone, the tissue had the highest average T_2 values and the smallest angular anisotropy at the zero strain. However, sinusoidal variations in the T_2 anisotropy profiles became weaker as the applied strain increased. At Depth #3 that is located deep in the radial zone of the tissue, the tissue became almost isotropic toward the sample rotation at a strain of 27%. At Depth #4 that is close to the tide-mark region in tissue, the tissue has the smallest strain-induced T_2 reduction and maintains the largest anisotropic variation centered around the magic angle even at a strain of 27%.





Discussions

This work studied the depth-dependent T_2 anisotropy in cartilage during compression under different strain levels at high spatial resolution. Static compression in our study becomes an active mechanism to induce new image contrast in MRI. The use of T_2 anisotropy maps enable the examination of fibril orientation and reorientation under loading. Because T_2 anisotropy is the physical basis for the magic angle phenomenon in clinical MRI, incorporating adjustable external loading in clinical MRI could provide additional manner in the diagnosis and management of various joint diseases.