Ultra-short TE-enhanced T_2* mapping of cartilage

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Background This work explores the utility of ultra-short echo time (UTE) enhanced T_2* mapping to non-destructively probe articular cartilage structure, particularly the integrity of the collagen extra-cellular matrix. T_2* measurement built on UTE sequences (e.g., UTE-enhanced T_2* mapping) is sensitive to changes in short-T_2 signal (T_2 <10ms) and may provide improved sensitivity to subtle matrix alterations that are not well-captured by standard T_2 sequences[1,2]. Optical coherence tomography (OCT) is capable of non-destructively imaging articular cartilage at microscopic resolutions to detect structural changes within grossly normal appearing articular cartilage[3,4]. We hypothesize that high-resolution UTE-enhanced T_2* maps will discriminate between normal and abnormal collagen architecture as observed by OCT and polarized light microscopy (PLM).

Methods Ten osteochondral specimens from human tibial plateaus were collected post-mortem and from total knee replacement surgery, and were stored at -20ºC before use. Explants were mounted on an acrylic plate with MRI lucent fiducial markers to allow precise spatial registration of study locations across imaging modalities. Quantitative T_2 and UTE-enhanced T_2* images were acquired on a clinical 3T MRI scanner (MAGNETOM Trio TIM 3T, Siemens Medical Solutions, Erlangen, Germany) using standard extremity coils (Invivo Inc., Gainesville, Florida, USA). A multislice coronal 2-D T_2 FSE sequence was acquired with seven echo images (TEs) ranging from 10-80 ms, repetition time (TR) 1800 ms, BW 326 Hz/pix, and 4 averages. The 20 2-D slices were collected with 417 x 417 µm in-plane resolution and 2 mm section thickness. Total T_2 scan time was 12 minutes. UTE-enhanced T_2* mapping images were acquired using a home-developed fast 3D UTE sequence named as AWSOS (acquisition-weighted stack of spirals)[5]. Eleven echo images, TE ranging 0.5 – 40 ms, were collected with resolution 391 x 391 µm in-plane, and 2 mm section thickness; FA/TR = 30º/100 ms. Scan time was 4.27 minutes per TE-image. T_2 and T_2* maps were generated with a mono-exponential fitting routine using MRIMapper software (© Beth Israel Deaconess and MIT 2006). Following MRI imaging, several 6.5 – 8.5 mm diameter osteochondral cores from each plateau were removed and imaged by OCT with ≤50 µm resolution (Niris Imaging System, Imalux, Cleveland, OH). Cores were then sectioned and stained with picrosirius red for collagen organization as evaluated by PLM.

Results Osteochondral cores from human tibial plateaus were evaluated by microscopic OCT and histology and compared to corresponding regions of interest (ROIs) from T_2 and UTE-enhanced T_2* maps. Lower values were seen by T_2* compared to standard T_2 in the same section of tissue, and the two metrics exhibited different laminar patterns. UTE-enhanced imaging permitted T_2* mapping in the deep radial zone, a zone not detected by standard T_2. Zonal stratifications observed on T_2* maps were similar to those observed within the collagen matrix arrangement seen by PLM. Focal T_2* lesions within the transitional zone corresponded to matrix derangement observed with PLM. OCT detected surface disruptions that could not be resolved by MRI and provided evidence for structural integrity and/or deficiency consistent with collagen organization seen by PLM. Example images from two ROIs on the same tibial plateau are shown in Figures 1-3.

Figure 1

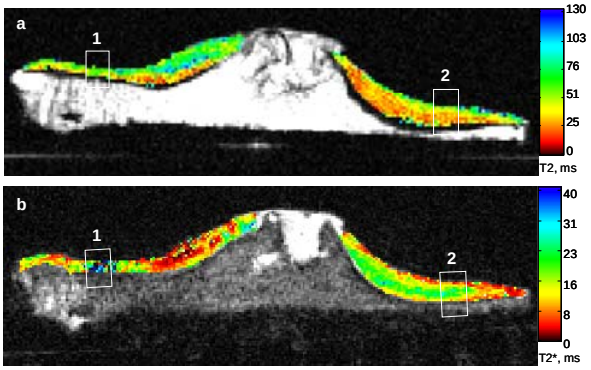

Fig 1 – (a) T_2 and (b) UTE-enhanced T_2* maps of a human tibial plateau. White boxes depict sites of osteochondral cores assessed with OCT and histology. T_2* values are lower and show a different pattern of laminae than standard T_2, however, the zonal stratification exhibited by T_2* is similar to the collagen matrix arrangement depicted by PLM (Fig 4). At site 2, the pattern of low T_2* in a thin superficial zone above higher, more homogeneous T_2* in a thick transitional zone resembles the collagen structure seen by PLM. Likewise, a focal high T_2* lesion seen at site 1 corresponds to collagen matrix derangement by PLM but is not obvious by standard T_2.

Figure 2

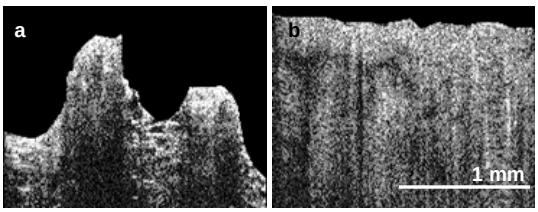

Fig 2 – Non-destructive OCT images of cores taken from sites 1 (a) and 2 (b) from Figure 1. Site 1 shows an irregular articular surface and no obvious laminar pattern below the surface. Site 2 has a smoother surface and a dim birefrigent form OCT. Previous work has shown loss of birefrigent form OCT to predictive of metabolic incompetence and correlated to greater degree of cartilage degeneration[6].

Figure 3

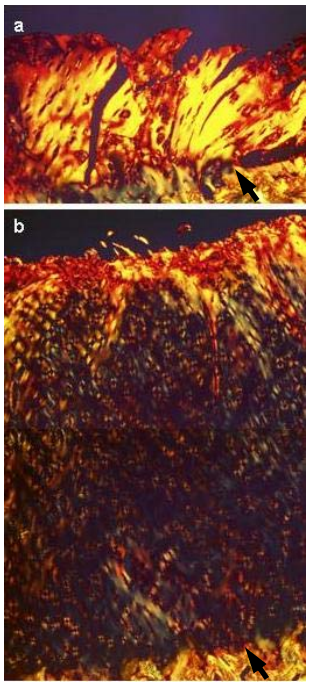

Fig 3 – PLM from sites 1 (a) and 2 (b), shown at the same magnification. Cartilage at site 1 is much thinner than site 2. Arrows indicate bone/cartilage interface. Site 1 exhibits an amorphous, deeply fibrillated collagen matrix with a weakly stained deep radial zone suggesting low collagen density adjacent to bone. Site 2 shows disorganization in the thin superficial zone and a more uniformly organized collagen arrangement in the thick transitional zone. The deep radial zone at site 2 is strongly stained and demonstrates a highly ordered matrix with the prevailing orientation appearing tangential to the bone surface.

Discussion

Although standard T_2 is sensitive to water content and fragmentation of the collagen fibers occurring in cartilage degeneration[7], long echo times (usually>10ms) used in standard T_2 prevent detection of short T_2 components, resulting in decreased overall sensitivity to subtle matrix alterations. UTE-enhanced T_2* mapping permits detection of short T_2 components such as those found in the deep radial zone. Results of this work suggest that T_2* mapping is also sensitive to focal derangements of the collagen matrix that are not obvious by standard T_2 mapping. Microscopic OCT and histology examinations of tissue sections with grossly different T_2* appearances demonstrate that UTE-enhanced T_2* mapping differentiates between normal and abnormal collagen architectures.

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