The Origin that Darkens the Deep Region of Articular Cartilage in MRI when Loaded at the Magic Angle

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TARGET AUDIENCE

Clinical radiologists and basic science researchers who use MRI to study the degradation of articular cartilage associated with various forms of arthritis.

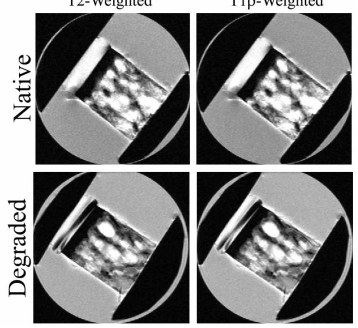
PURPOSE

When the surface of articular cartilage is oriented at 55˚ with respect to the external magnetic field, cartilage usually appears homogeneous and brighter than at other orientations, an effect due to the minimization of the dipolar interaction and known as the "magic-angle effect" in the literature of cartilage MRI [1]. Nearly a decade ago, a study [2] reported the observation of a distinct low-intensity line in the deep region of articular cartilage when the tissue was compressed and oriented at the magic angle. Such unusual appearance of cartilage at the magic angle was attributed to the adaptation of the collagen orientation in the deep region of cartilage when it was compressed [3]. In this project, we investigated the molecular origin that darkens the deep region of compressed cartilage in MRI. The hypothesis of this comprehensive project was that the content of glycosaminoglycans (GAG) in cartilage might play an important role for this unusual observation.

METHODS

A total of thirty canine humeral cartilage-bone blocks were harvested fresh shortly after the sacrifice of mature and healthy animals that were used for an unrelated research, where the institutional review committee approved the animal handling. 18 specimens were divided equally into two groups (native, degraded) for μMRI; 6 were divided equally into two groups (native, degraded) for biochemical analysis; and the remaining 6 (native, degraded) were used for biomechanic measurements. The native specimens were immersed in physiological saline (154 mM NaCl in deionized water) with 1% protease inhibitor (Sigma, Missouri). The specimens were degraded when they were first soaked in 10μg/ml trypsin solution (Sigma, Missouri) for more than 8 hours, then soaked in saline with 1% protease inhibitor to remove excess trypsin. A homemade, unconfined loading device was used for specimen compression, where the specimens were loaded under the 0%, ~15%, and ~45% strains (three blocks at each strain). Quantitative T_1, T_2 and $T_{1\rho}$ measurements were carried out, where the T_1 protocol was used to measure the GAG concentration in the tissue with the soaking of 1 mM $Gd(DTPA)^{2-}$ solution (Magnevist, Berlex, NJ); the T_2 and $T_{1\rho}$ protocols were used to determine the influenced of the tissue anisotropy and macromolecular contents. All μMRI experiments were performed at room temperature on a Bruker AVANCE II 300 NMR spectrometer equipped with a 7 Tesla/89 mm vertical-bore superconducting magnet and micro-imaging accessory (Bruker, Billerica, MA). The MRI experiments were carried out with an acquisition matrix of 256 × 128 (17.6 μm pixel size) and a slice thickness of 1 mm. Other experimental parameters followed the previously established protocols in μMRI [4-5].

Fig 1



RESULTS

Fig 1 shows the intensity images of MRI of cartilage-bone blocks when the specimen was compressed (~ 15% strain) and oriented at the magic angle. It is clear that the native tissue appears mostly homogeneous depth-wise while a low-intensity line can be clearly seen in the deep-region of the degraded tissue when the tissue was compressed. Fig 2 shows the $T_{1\rho}$ profiles when the tissue was oriented at the magic angle and under different compressions. (The T_2 profiles had the similar shapes but lower in values.) When the tissue was healthy (Fig 2a), $T_{1\rho}$ profile with no load at 55˚ was practically uniform, which reduced only in the surface portion under a modest loading but over the whole depth under a heavy loading. When the tissue was degraded (Fig 2b), in comparison, a modest loading caused the profile to have a double bell-curved shape: one near the surface zone and the other in the deep region. At the high compression (~50%), the $T_{1\rho}$ profiles became more uniform, where the double peaks could still be observed. Fig 3 shows the depth-dependent profiles of the mechanical modulus (a) and GAG concentration (b) in the native and degraded tissue as the function of the relative tissue depth. These results are consistent with the MRI relaxation observation.

Fig 2

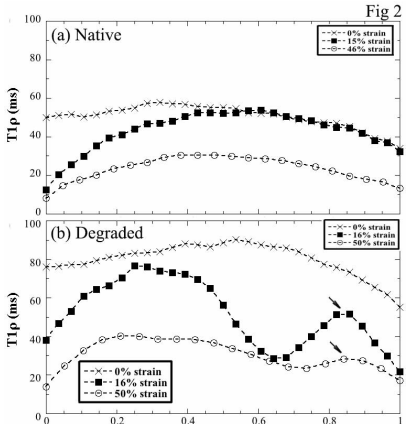
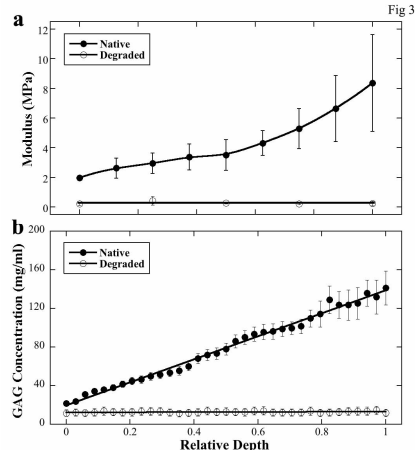


Fig 3



DISCUSSION and CONCLUSION

We have demonstrated that the reduction of the negatively charged glycosaminoglycans, which contributes to the tissue stiffness, plays the key role in the formation of a low-intensity laminar line at the deep-region of articular cartilage when it is loaded and orientated at 55˚. The GAG loss after the trypsin treatment is confirmed in this project by the sodium ICP-OES measurements, MRI GAG quantification, and biomechanical experiments. A schematic model has been formulated to illustrate the fibril differences in the matrix deformations between the native and degraded cartilage. Since the GAG loss is an early sign of osteoarthritis, mechanical loading of cartilage in MRI is a functional study of the tissue. This study demonstrates that this type of MRI of loaded cartilage could, in principle, be developed into a clinical procedure to detect the early degeneration of joint diseases – when the tissue is still intact but has a reduced GAG concentration.

REFERENCES [1] J Magn Reson Img 1997;7(5):887-89; [2] Osteoarthritis and cartilage 2004;12(11):887-894; [3] J Magn Reson Img 2005;22(5):665-673; [4] Magn Reson Med 1998;39(6):941-949; [5] Magn Reson Img 2012;30(3):361-370.

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