Measurement of Dipolar Oscillations in Articular Cartilage using Spin-LockTechnique

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Introduction

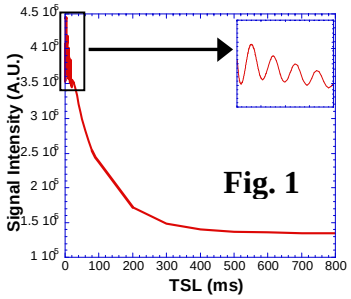
The collagen in articular cartilage is type II and is present in the form of triple helical fibrils. The fibrils are arranged anisotropically and give heterogeneity to the tissue such that water molecules associated with the fibrils experience a residual dipolar interaction. The variation in the measured spin lattice relaxation in the rotating frame ($T_{1\rho}$) of water as a function of spin lock frequency ($\omega_1=2\pi\gamma B_1$ where B_1 is amplitude of the spin locking pulse) is indicative of slow motional processes (1) as well as the presence of residual dipolar interaction. Previously, effects of dipolar coupling in biological systems have been investigated extensively by double quantum filtered spectroscopy and imaging (2). However, these methods inherently have low signal to noise ratio (SNR). Recently, it is shown that in a model of dipolar coupled spin system, the spin locked magnetization is coupled to double quantum, zero quantum and two-spin order. This coupling leads to (i) the formation of residual dipolar oscillations (REDIOS) and (ii) the dependence of the apparent $T_{1\rho}$ on the amplitude of the ω_1 (3). The purpose of this study is to measure the REDIOS, and their $T_{1\rho}$ dispersion in native and PG depleted cartilage using a spin-locking technique.

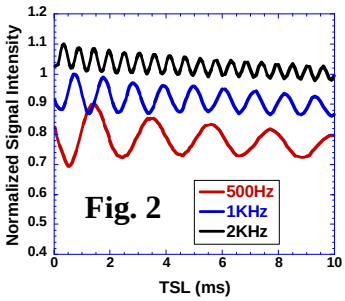
Methods

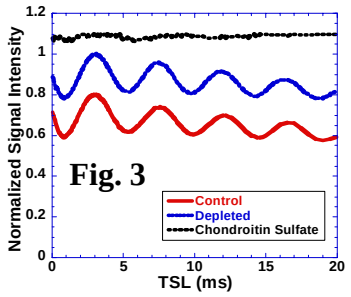
Bovine patellae are obtained from a slaughterhouse within few hours of animal sacrifice. A one centimeter diameter plug was cored from the patellar cartilage for MR measurements. The MR experiments are performed on a 4.7 T UNITY-INOVA NMR spectrometer (Varian, Palo Alto, CA) using a 2.5 cm diameter solenoidal radiofrequency coil. The pulse sequence used for the spectroscopic measurements contains a 90° hard pulse followed by a long, low power, rectangular spin lock pulse with 90° phase shift. The length of the spin lock pulse (TSL) is varied from 50 μs-800 ms. A series of experiments are performed for different ω_1 ranging from 0.2 KHz to 3 KHz. Enzymatic depletion of the cartilage tissue is performed in 200 ug/ml of trypsin to verify the effect of proteoglycan (PG) change on dipolar oscillations. Interactive data language (IDL) is used to process the spectroscopy data.

Results & Discussion

Fig. 1 displays the evolution of magnetization as a function of TSL. The initial rapidly damped oscillations are shown in the inset. These initial oscillations are due to residual dipolar interactions exhibited by water associated with collagen. The smooth decay following the damped oscillations is due to the contribution from other relaxation mechanisms including chemical exchange. Indeed, we recently demonstrated that the $T_{1\rho}$ rate measured from the slow decaying component strongly correlates with the PG content of cartilage (4). The data also shows that the REDIOS increase with increasing ω_1 and are rapidly damped for larger magnitudes of ω_1 (Fig. 2). Data from similar experiments performed on distilled water (data not shown) and 5 % chondroitin sulfate solution, did not show any oscillations (Fig. 3). Proteoglycan depletion of the cartilage with trypsin treatment did not alter the oscillation frequency observed in healthy cartilage (Fig. 3). Absence of REDIOS from chondroitin sulfate phantom and PG depleted cartilage verifies that the observed oscillations are due to oriented collagen in cartilage. REDIOS observed at low spin-locking frequency, are very close to the dipolar splitting frequency measured previously (5). The effect of residual dipolar interaction manifests as a laminar appearance in T_2 weighted image (Fig. 4A). In $T_{1\rho}$ weighted image (Fig. 4B), spin locking reduces the laminar appearance to some extent. The residual dipolar interactions can be eliminated either by orienting the tissue at magic angle to B_0 (6,7) or by applying appropriate ω_1. The above data indicates that the REDIOS can be measured with high SNR and in imaging setting the dipolar interaction can be reduced or eliminated with spin-locking technique.







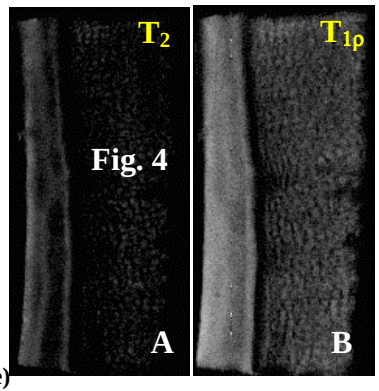


Fig. 3: TSL vs REDIOS for control (bottom trace), PG depleted (middle trace) and chondroitin sulfate (top trace)

Conclusions

Using spin-locking technique, the REDIOS can be measured in articular cartilage. In addition, we have shown that the dipolar oscillations increase with spin-locking frequency and are specific to orientation of collagen fibers. Changes in proteoglycan concentration do not contribute to REDIOS. These results demonstrate that REDIOS observed with spin-locking technique may be used to probe changes in oriented collagen fibrils in cartilage. Quantitation of the dipolar splitting frequency from REDIOS, sensitivity analysis, and extending these studies to an imaging setting are in progress.

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