The Effect of Refocusing the Dipolar Interaction on the Measured T_2 of Articular Cartilage.

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Abstract: T_2 of the water in cartilage, and the appearance of the MR images, are orientation dependent due to the intramolecular dipolar interaction which stems from the interaction of water with the oriented collagen fibers. Two dipolar refocusing schemes, solid (dipolar) echo and spin lock, were introduced in order to refocus this interaction. Our results show that the T_2 becomes independent of the orientation of the plug relative to the field for echo times smaller than 300μs and for spin lock powers of 6-10kHz. Application of these techniques to clinical imagers will greatly facilitate clinical interpretation

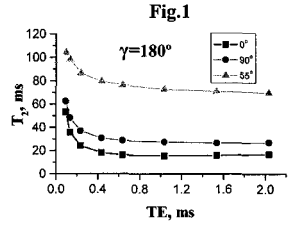
Introduction: The T_2 weighted images of articular cartilage exhibit several laminae (1-4). The number and the relative intensity of these laminae varies form sample to sample and depends strongly on the orientation of the cartilage relative to the magnetic field and thus hinders the clinical interpretation of the images. The origin of these laminae is the variations of T_2. In articular cartilage, the major contribution to the transverse relaxation time is the non-vanishing intramolecular dipolar interaction, which stems from the interaction of water molecules with the oriented collagen fibers. We introduce here dipolar refocusing schemes that eliminate the dependence of the relaxation times, and thus of the images of articular cartilage, on the orientation.

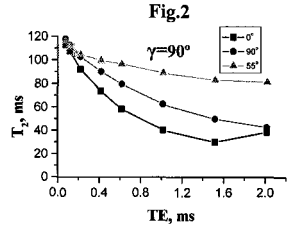
Methods: Plugs composed of bovine articular cartilage, detached from the bone above the calcified zone, 8 mm in diameter, were harvested from fresh femoral medial condyles and equilibrated in PBS. The cartilage plugs were blotted dry and immersed in Fluorinert for NMR measurements. Teflon holders were used in order to orient the plug with the normal to the surface at 0^0, 90^0,and 55^0 to the external magnetic field. T_2 was measured by $90^0 - (\tau - \gamma - \tau)_n$ – Acq (1) sequence where γ was either 180^0 for the conventional CPMG and 90^0 in the dipolar echo refocusing sequence (5,6). For the measurements of $T_{1\rho}$, the spin lattice relaxation time in the rotating frame, a 90^0 – spinlock- Acq. sequence was employed (7,8).

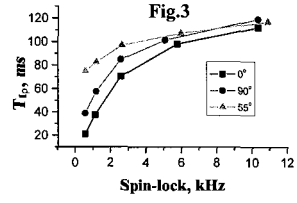
Results: T_2 was measured for echo intervals ($2\tau+\gamma$ in Eq. 1) ranging from 0.96 – 2.036 ms for $\gamma=180^0$ (Fig. 1) and from 0.78-2.018 ms $\gamma=90^0$ (Fig. 2) for three orientations of the plug in the magnetic field. The T_2 values plotted were obtained obtained from an average mono-exponential fit of the magnetization decay curve as a function of the number of echoes in each experiment. For $\gamma=180^0$ the results fit much better to a bi-exponential function but are given here in this way so that the $\gamma=180^0$ and the $\gamma=90^0$ experiments could be directly compared. For both methods, the longest relaxation times are obtained when the normal to the surface of the plug is at 55^0 to B_o while the shortest relaxation times are obtained at 0^0 to B_0. For the $\gamma=180^0$ sequence there are larger differences in T_2 between the different plug orientations, throughout the range of echo times. For the $\gamma=90°$ sequence, for $2\tau+\gamma$ of up to 300 μs, the difference in T_2 at the different plug orientations is very small. Also, T_2 obtained with the dipolar refocusing sequence ($\gamma=90°$) is in all cases longer than that obtained with CPMG.

The results of $T_{1\rho}$ are plotted in Fig. 3. At low spin-lock powers, $T_{1\rho}$ is shortest when the normal to the surface is at 0^0 to B_0 and longest when is positioned at 55^0 . For spin-lock powers of 6-10 kHz, no significant difference is found for $T_{1\rho}$ at the different orientations.

Our recent ^2H double quantum filtered (DQF) measurements of articular cartilage have shown that there are at least 2 distinct







pairs of quadrupolar split satellites (9). For ^1H, the dipolar splitting is modulated by proton exchange and is not resolved at room temperature (10). We have found that below the freezing point of the non-bound water in the tissue the dipolar splitting is detected. We have performed a ^1H one-dimensional DQF spectroscopic imaging of articular cartilage at -21^0C. One pair of very broad satellites is observed with a frequency difference of 1800 Hz at the cartilage bone interface and 1200 Hz at the surface. The frequency difference between the satellites depends on the creation time of the DQ coherences, indicating heterogeneity.

Discussion: The observed dipolar splitting at -21^0C is related to the unfreezeable water molecules that are in close association with the collagen. The residual dipolar interaction at body temperature is a weighted average between the bulk and the "unfreezeable" water is expected to be smaller by an order of magnitude. Thus it is much smaller than the water proton exchange rate and cannot be resolved.

The spin lock technique was recently used (7,8) for articular cartilage. It was concluded that proton exchange from protein NH or OH groups is responsible for the $T_{1\rho}$ dispersion profile. Our results, showing the angular dependence of the $T_{1\rho}$ dispersion, as well as the similarity with the dipolar echo results, indicate that the averaging of the intramolecular dipolar interaction by the water proton exchange, is responsible for the major part of the dispersion profile.

From the present results it can be concluded that methods based either on high power spin-lock or dipolar echo ($90^0 - (\tau - 90^0 - \tau)_n$) sequences, with 2τ smaller than 300μs, can give images that are invariant to the sample orientation, allowing for better detection of pathologies.

References: 1. Rubenstein J. D. et al. Radiol. 188:219, 1993. 2. Freeman D. M. et al., MRM 38:72, 1997. 3. Xia Y., MRM 39:941, 1998. 4. Grunder W. et al. MRM 43:884, 2000. 5. M. Mehring in High. Res. NMR Spect. Solids, Springer-Verlag, 1976. 6. Eliav U. et al., ISMRM 6th Mtg P. 602, 1998. 7. Duvvuri U. et al., MRM 38:863, 1998. 8. Duvvuri U. et al., PNAS 98:12479, 2001. 9. Eliav U. et al., JMR 137:295, 1999. 10. Navon G. et al., NMR Biomed.14:112, 2000.