T_2 Relaxation Study of Water in Human Brain using Carr-Purcell Spin-Echoes at 4T and 7T. Frequency shift $\Delta\omega$ at 4T and 7T.

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Synopsis Fully adiabatic Carr-Purcell (*CP*) type sequence *(CP-LASER)* with *SPIRAL* readout was used to investigate the change in $\Delta\omega$ (difference in angular Larmor frequency) with the field (4T vs. 7T). High resolution T_2 – weighted images were acquired to measure the apparent $T_2^\dagger$ in human visual cortex V1 as a function of interpulse time interval in *CP* train. It was found that $\Delta\omega$ increases slightly with the field but significantly less than linearly. This suggest that chemical exchange does not explain the data and that Nuclear Overhauser Effect (NOE) and/or NOE in the rotating frame (ROE) are contributing to MR signal decay.

Introduction

In iron-rich regions of the brain the proton MR transverse relaxation rates measured with a *CP* sequence has been observed to depend significantly on the interpulse time interval (τ_{cp}). It was suggested that this effect is important for in-vivo quantification of brain iron, because of its relevance to several neurodegenerative disorders, including Parkinson's and Alzheimer's diseases as well as for the understanding of the mechanisms of Blood Oxygenation Level Dependent (*BOLD*) contrast. General theory was presented recently[1,2] for weakly magnetized particles and applied to randomly distributed spheres. In this theory, the Luz-Meiboom Chemical Exchange (*CE*) model was compared with the theories of T_2-shortening caused by microscopic magnetic centers, namely: inner- and outer sphere relaxation theories in the long-echo limit and mean gradient diffusion theory for the short-echo limit. It was demonstrated, that at the short – echo limit, when $\tau_{cp} << \tau_d$ (τ_d is the diffusion correlation time), the classical theory of diffusion in magnetic gradients derived originally by Carr and Purcell, may be used. In the long echo limit ($\tau_{cp} >> \tau_d$), the standard relaxation theory applies and no $T_2^\dagger$ dependence on τ_{cp} was predicted. Generally, those theories predict a square dependence of the relaxation rate on the $\Delta\omega$: $[1/T_2]_{CE} \sim F_aF_b(\Delta\omega)^2\tau_{cp}^2 / \tau_d\ (\tau_{ex})$; ($\tau_{cp} << \tau_d\ (\tau_{ex})$). At the long-echo limit: $[1/T_2]_{CE} \sim F_aF_b\tau_{ex}(\Delta\omega)^2$; ($\tau_{cp} >> \tau_{ex}$), where the F_a and F_b = fraction of protons in each site ($F_a+F_b=1$), τ_a and τ_b – residence times in each site, $\Delta\omega$- difference in angular Larmor frequency at site b relative to site a. The relaxation rates are described by equation *(1):*
$1/T_2^\dagger = 1/T_2^{in} + \Delta\omega^2\tau_{cp}\,\alpha\beta x\ \{1\text{-}b \times \tanh[1/(bx)]\}$; $x=\tau_d/\tau_{cp}$; $\tau_d=r^2/D$, where D is apparent diffusion coefficient, τ_d-diffusion time. The intrinsic relaxation rate is defined as: $1/T_2^{in}=1/T_2^{DD}+\sigma$, where the first and second terms spin dipolar interactions and the dipolar cross-relaxation, respectively. The goal of this study was to measure intrinsic transverse relaxation times at 4T and 7T in human brain visual cortex V1 and to investigate $\Delta\omega$ at 7T comparatively to 4T. These results provide important information on the contribution of dynamic dephasing to the MR signal decay and suggest another mechanisms, namely nuclear Overhauser effect (NOE) and/or the rotating-frame-NOE (ROE), that are operative in the sample.

Methods

1D CP-LASER-SPIRAL

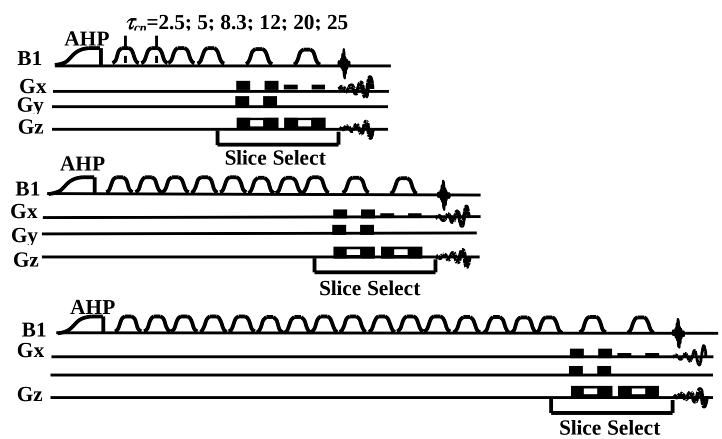

Fig.1 Schematic representation of the *CP-LASER* sequences with *SPIRAL* readout.

Imaging studies were conducted with *4T* and *7T* whole body MRI/MRS systems. A ^1H quadrature surface coils consisting of two geometrically decoupled turns (each 7 cm in diameter) were used for the measurements at 4T and 7T. High resolution T_2 – weighted images (0.7 x 0.7 mm^2 in-plane resolution) were acquired to measure the apparent $T_2^\dagger$ with *CP-LASER*[3] sequence with *SPIRAL* readout.[4] In *CP-LASER*, (Fig. 1) the length of *CP*-train was increased by inserting additional AFP pulses between the excitation pulse and the two AFP pulses used for slice selection. $T_2^\dagger$ values were measured with different interpulse time intervals in the *CP* train: τ_{cp} = 2.5, 5, 8.3, 12,20,25 ms. TR=4s/segment was used to minimize T_1 contribution. For slice selection and in *CP*-train HS1-R10 adiabatic pulses were used. Images were recorded using: FOV = 18 cm, 256-matrix and 8 segments, at = 35 ms, thickness 4 mm. Slice-selection and the *SPIRAL* portions of the sequence were kept constant for all acquisitions, thus the T_2* weighting introduced by this portion was constant.

Results and Discussion

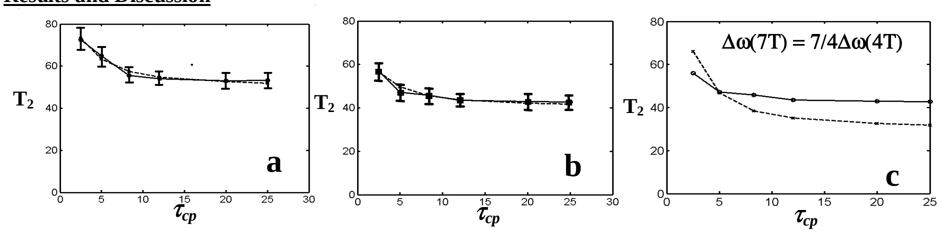

Fig.2 Averaged calculated $T_2^\dagger$ time constants at 4T ((a), 6 individuals) and at 7T ((b), 5 individuals) as a function of τ_{cp} and the theoretical simulations using Eqn. (1) (dashed line). c) theoretical simulation using ratio $\Delta\omega(7T)=7/4\Delta\omega(4T)$, superimposed on 7T experimental results.

Schematic representation of the *CP-LASER* sequence used for the $T_2^\dagger$ measurements is shown on Fig. 1. Fig.2 demonstrates the $T_2^\dagger$ dependence on τ_{cp}. At short τ_{cp} a squared dependence of $T_2^\dagger$ on τ_{cp} was observed, while at long τ_{cp} the $T_2^\dagger$ were independent on τ_{cp}. As expected, the $T_2^\dagger$ measured at 7T were shorter then at 4T (significant difference; $p<0.001$, two-tailed). From the theoretical simulations the best fit to the experimental data was found with τ_d = 11 ms at both 4T and 7T, $\Delta\omega(7T) \sim 1.1\ \Delta\omega(4T)$ and T_2^{in} = 83 ms at 4T and T_2^{in} = 63 ms at 7T. The following features of the simulation results should be pointed out: (i) shortening of T_2^{in} from 4T to 7T; (ii) lack of the linear field dependence of $\Delta\omega$ at 7T comparatively to 4T. A possible explanation of increase of the apparent transverse relaxation rate with the field is the dipolar cross-relaxation of through-space interacting spins. The deviation of the $\Delta\omega$ increase from 4T to 7T from linearity suggests a contribution of a mechanism other than the chemical exchange on τ_{cp} dependence of the transverse relaxation rate, namely: dipole-dipole interaction of the coupled spin packets, that lead to polarization/coherence transfer detected with *CP-LASER* technique.

References

1. R. Brooks, et al., MRM 45, 1014-1029 (2001); 2. J. Jensen et al., MRM 46: 159-165 (2001); 3. Garwood, M. et al., JMR 153: 155-177, 2001; 4. Pfeuffer J. et al., MRM 47: 344-353 (2002).

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