Quantitative Evaluation of the Exchange Time and T_2 Associated with an Inhomogeneous Component using Inhomogeneous Magnetization Transfer Imaging

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Introduction The presence and composition of white matter (WM) is of interest, particularly for the study of degenerative disease. The proportion of myelin in WM, which is found to degrade in diseases such as multiple sclerosis, has been correlated with the results from quantitative magnetization transfer (MT) [1]. This is based on the macromolecular pool of phospholipids associated with myelin and its interaction with the bulk water pool. The phospholipids in myelin form a bilayer that results in restricted motion and has shown signs of inhomogeneous broadening [2-3]. An inhomogeneous MT (IHMT) sequence showed greater contrast from WM [4], presumably due to myelin selectivity. This work attempts to provide a more quantitative treatise of the IHMT effect and its application to phantoms and in vivo. In particular, the exchange time, τ_{ex} of signal associated with an inhomogeneous component is determined, and consequently the transverse relaxation time T_2 as determined by saturation. In vitro experiments are conducted on hair conditioner, which is also presumed to show inhomogeneous broadening as a result of its lamellar liquid crystal design [5].

Theory The IHMT sequence is based on a saturation scheme at a positive, negative, and combined offset frequency, in which the offset alternates between the two. Using a 2 pool model for exchange in which irradiation at the positive offset is assumed to be disconnected from that at the negative offset, the IHMT effect is modeled based on the assumption of saturation of a single line. The magnetization change following irradiation at the positive offset is given by (1), whilst during periods of negative offset saturation the magnetization (2) recovers on a timescale $R_{ex}=1/\tau_{ex}$, assuming $R_{ex}>>R_1$. In relation to the alternating offset scheme associated with IHMT (Fig.1a), the average magnetization, M_{av} is thus given by the integral of M_{ON} (3) from t=0 to t=w and M_{OFF} (4) from t=w to t=2w, divided by 2w, where $R'_{ex}=R_{ex}+\omega_1^2T_2/(1+\Delta^2T_2^2)$, $M'_0=M_0R_{ex}/R'_{ex}$, M_1 is the steady-state magnetization at t=w, where M_{0N}=M_{OFF}, and w is the saturation period. The IHMT ratio (IHMTR) is calculated as $(M_{ON}+M_{OFF}-2M_{av})/M_0$ (5). Adopting a continuous wave (CW) scheme to investigate saturation the average magnetization, M_{av} is now given by (6) so that IHMT equals $M_0T_2^2\omega_1^4/((R_{ex}+T_2\omega_1^2)(2R_{ex}+T_2\omega_1^2))$ (7).

$$\frac{\partial M_{ON}}{\partial t}=M_0R_{ex}-M\left(R_{ex}+\frac{\omega_1^2T_2}{1+\Delta^2T^2}\right) \quad (1)$$

$$\frac{\partial M_{OFF}}{\partial t}=M_0R_{ex}-MR_{ex} \quad (2)$$

$$M_{ON}=M_1e^{-R'_{ex}t}+M'_0\left(1-e^{-R'_{ex}t}\right) \quad (3)$$

$$M_{OFF}=\left(M_1e^{-R'_{ex}w}+M'_0\left(1-e^{-R'_{ex}w}\right)\right)e^{-(t-w)R_{ex}}+M_0\left(1-e^{-(t-w)R_1}\right) \quad (4)$$

$$M_{av}=\frac{M_0R_{ex}}{\left(R_{ex}+\frac{\frac{\omega_1^2}{2}T_2}{1+\Delta^2T_2^2}\right)} \quad (6)$$

Methods Phantoms consisted of hair conditioner bottles (TRESemme and Suave) and volunteers (V1-5): 4 females and 1 male (ages 21-27) were scanned with 2D single-shot EPI (FOV=25x25cm^2; matrix=128x128; NEX≥8; TE/TR=24/2000ms) on a 3T GE scanner using an 8-channel head coil. A pulsed saturation scheme consisted of a block of 1.2ms with 0.5ms saturation, repeated for 500ms. To elucidate τ_{ex} using (1-5), the following values of w were applied: 1.2, 2.4, 3.6, 4.8, 9.6, 14.4, 24 and 43.2ms and fit to (5). The CW saturation was achieved with a 120ms trapezoid waveform, with sinusoidal modulation for the alternating offset acquisition. The value for ω_1 was varied via $B_{1,peak}$ from 20 to 100 in 20mG steps. A fit of the signal variation to (7) provided an estimate of T_2, using $R_{ex}=1/\tau_{ex}$. A B_1 map was also acquired based on a dual FA acquisition (60 and 120°). Images were masked based on >10% of the maximum signal intensity and maps were further masked based on coefficients of determination, R^2>0.8.

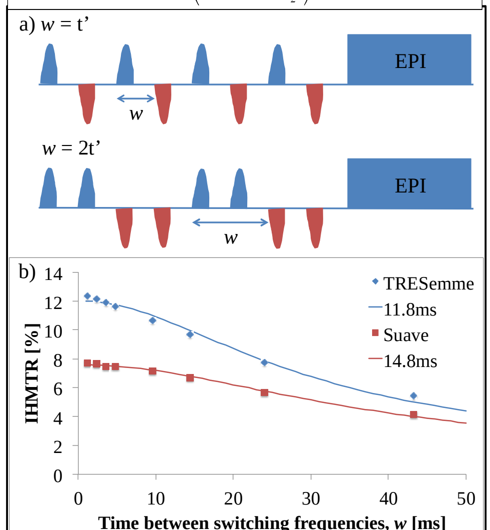

Figure 1 a) Pulsed acquisition scheme (blue=positive; red=negative offset). b) Plot of acquired data fit to (5).

Results In vitro, the data from varied values of w with pulsed saturation experiments show good correspondence using a least squares fit (Fig.1b). Both data and the fit show decay in the IHMTR associated with τ_{ex}. The values for τ_{ex} from the fit are 11.8 and 14.8ms for the TRESemme and Suave respectively, and are used in estimation of the T_2 using (7) and data from the CW experiments (Fig.3d). The IHMTR shows greater contrast from WM than the MTR (Figs.2a-b). A shorter τ_{ex} of ~6ms is seen in vivo, with little sign of spatial variation (Fig.2c). Again, use of this value allows estimate of T_2 from the CW data (Fig.3a). Following correction based on the B_1, a spatial variation is diminished and an estimate for T_2 of 200μs is found (Figs.3c-d).

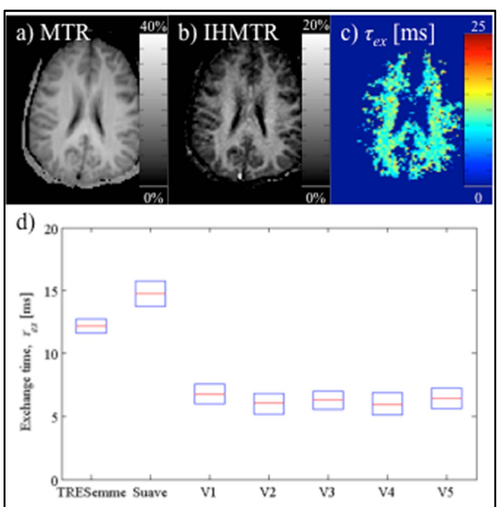

Figure 2 a) MTR image: 1-M_{ON}/M_0. b) IHMTR image. c) Map of τ_{ex}. d) Box plot of τ_{ex} quartile values.

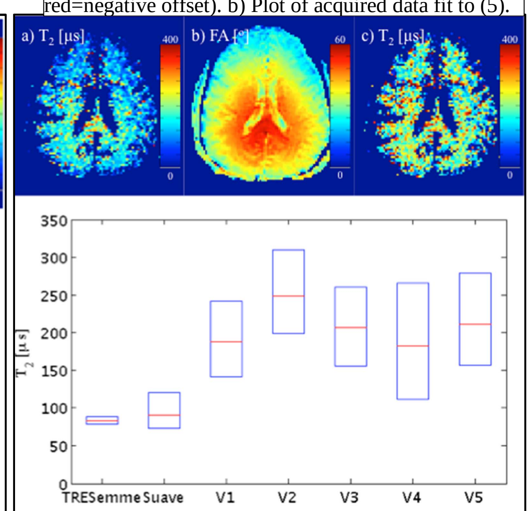

Figure 3 a) Uncorrected T_2, b) B_1, and c) T_2 maps with d) box plot of T_2 quartile values from phantoms/in vivo.

Discussion and Conclusions An inference as to the exchange time, τ_{ex} and T_2 associated with an inhomogeneous component is elucidated using IHMT. Distinct values are found from hair conditioner phantoms and in vivo. Application to pathologies might prove insight into diseases involved with demyelination.

References: [1] Tozer et al. MRM 53(2005)1415-22; [2] Chan et al. Nature 231(1971)110-2; [3] Seiter et al. JACS 95(1973)7541-53; [4] Alsop et al. Proc Intl Soc Mag Reson Med 12(2004)2324; [5] Swanson et al. Proc Intl Soc Mag Reson Med 20(2012)2344