Correlation time diffusion coefficient brain mapping: combined effects of magnetization transfer and water micro-kinetics on T1 relaxation

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Purpose: To develop a T1 relaxation theory incorporating the combined effects of magnetization transfer (MT) (**Ref.** 1) and water micro-kinetics –*i.e.* translational diffusion and molecular rotations (**Ref.** 3-5)-- for the purpose of computing accurate ***correlation time diffusion coefficient*** ($D_{(CT)}$) maps of multi-pool biological tissues exhibiting magnetization transfer phenomena, such as white matter. Additionally, to test the theory's accuracy in the human brain by comparing *in vivo* and in the same subject the whole-brain distributions of the correlation time diffusion coefficient maps relative to those obtained with a standard ***pulsed-field-gradient*** (PFG) diffusion MRI technique: i.e. by comparing the same-subject whole-brain histograms of ($D_{(CT)}$) *vs.* ($D_{(PFG)}$).

Theory: Two contributions to the observed T1 relaxation rate of ^{1}H-proton magnetization in structurally complex aqueous biological tissue are identified. First a micro-kinetics contribution stems from translational and rotational motions of the solvent water molecules and second, a T1 contribution stems from exchange of ^{1}H-protons between the mobile solvent water pool and the restricted pool, specifically:

$$\left[\frac{1}{T_1}\right]_{(obs)} = \left[\frac{1}{T_1}\right]_{(solvent)} + \left[\frac{1}{T_1}\right]_{(exchange)} \qquad \text{[Eq. 1]}$$

A $D_{(CT)}$ theory and associated image processing technique for the solvent water was reported earlier (**Ref.** 5), showing excellent quantitative accuracy for tissues devoid of magnetization transfer effects. We propose here the following model for T1 relaxation caused by MT effects:

$$\left[\frac{1}{T_1}\right]_{(MT)} = c\left(\frac{PD^{(H_2O)} - PD^{(obs)}}{PD^{(obs)}}\right)\left(\left[\frac{1}{T_1}\right]_{(obs)} - \left[\frac{1}{T_1}\right]_{(rest\ pool)}\right) \qquad \text{[Eq. 2]}$$

Accordingly, the magnitude of MT-caused T1 relaxation rate is proportional to the difference in T1 relaxation rate of the restricted pool (**Ref.** 1) relative to the observed T1 relaxation rate. Furthermore, MT effects are also modulated by the tissue proton density relative to that of pure water at the same temperature.

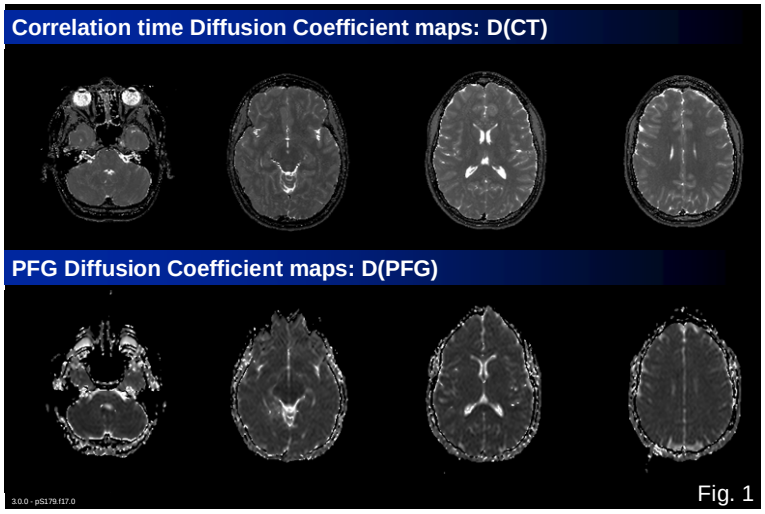

Fig. 1

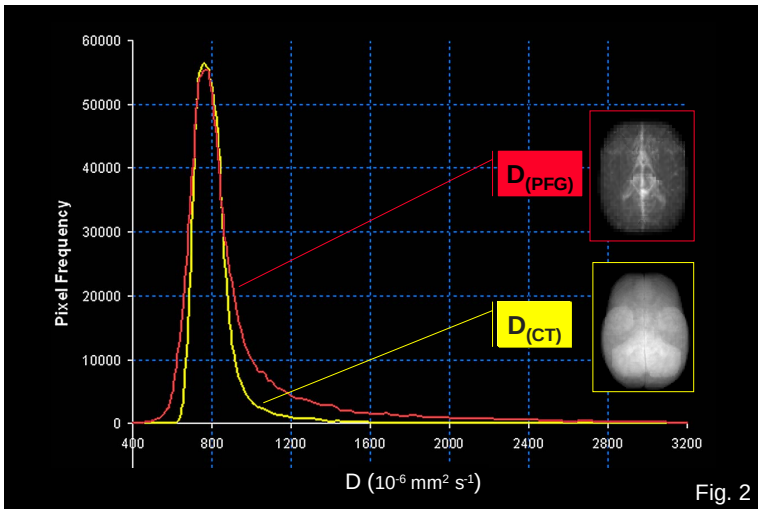

Fig. 2

Methods: Equations [1] and [2] were assimilated to the previously reported theory (**Ref.** 5). Brain images of a research subjects were acquired using a 1.5 T superconducting MR imaging system (NT-Intera Philips Medical Systems, N.A.). Mixed turbo spin echo (mix-TSE) is a multislice 2D pulse sequence that combines the principles of T1-weighting by inversion recovery and T2-weighting by multi-echo sampling into a single mixed MRI acquisition. Directly acquired images were post-processed, first with Q-MRI algorithms to generate the PD, T1, and T2 maps. PD maps were generated by reversing the T1 and T2 weightings of one of the mixed-TSE directly acquired images. A single shot spin-echo Echoplanar (SS-SE_EPI) sequence was used for PFG data acquisition. For both diffusion coefficient data sets, the brain was segmented using a dual-clustering algorithm and histograms were generated by pixel counting.

Results: Slice-matched $D_{(CT)}$ (top row) and $D_{(PFG)}$ (bottom row) axial diffusion coefficient maps at several locations are shown in **Fig.** 1. Nearly identical tissue appearance and contrast, particularly white-to-gray matter, are observed. Whole-brain histograms reflecting the $D_{(CT)}$ (yellow) and $D_{(PFG)}$ (red) are shown in **Fig.** 2. Both histograms are primarily unimodal and their spectral positions are nearly identical to within experimental error. The $D_{(CT)}$ distribution is measurably narrower than the $D_{(PFG)}$ distribution: increased broadening is probably the result of magnetic field inhomogeneities, to which SS-SE-EPI is considerably more vulnerable relative to the mixed-TSE sequence.

Conclusion: A T1 relaxation theory combining the effects of magnetization transfer and solvent water micro-kinetics has been developed and incorporated into a ***correlation time diffusion coefficient*** algorithm. This was used for 3D mapping the correlation time diffusion coefficient ($D_{(CT)}$) distribution of the human brain, leading to excellent quantitative agreement relative to standard ***pulsed-field-gradient diffusion MRI***. It is concluded that magnetization transfer has a substantial effect on T1 relaxation for tissues containing a restricted pool of ^{1}H protons that exchanges magnetization-with the solvent.

References

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