Modeling the Role of Membrane Permeability and T2 relaxation TE-dependent Signal Decay

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Introduction

Differential T2 relaxation rates in the intracellular and extracellular spaces can play an important role in filtering signals in diffusion-weighted MRI. Recently proposed models have fit diffusion weighted data in the brain by employing large differences in compartmental T2 relaxation times in addition to a low exchange rate between the intracellular and extracellular spaces [1]. However, it seems that large T2 differences, in combination with low exchange should indicate non-mono-exponential T2 in tissue, for which there is little evidence in gray matter [2]. In this abstract, we introduce a finite element model with compartment specific T2 relaxation, and use to it evaluate the effect of T2 and membrane permeability (P_{mem}) on signal decay and its fitting to single- and double-exponential relaxation.
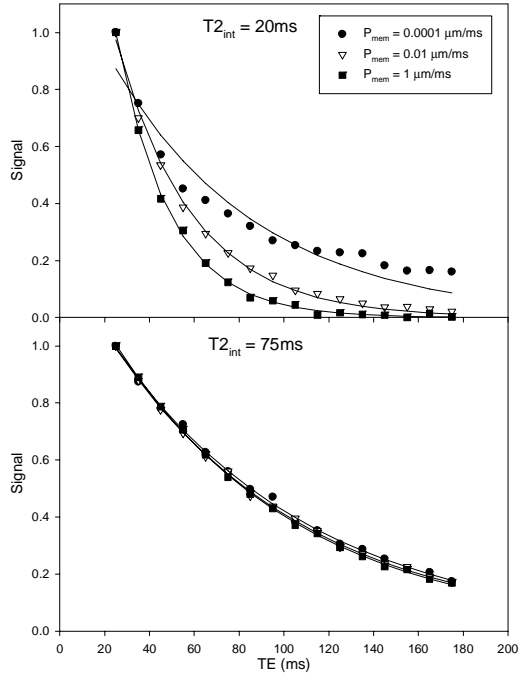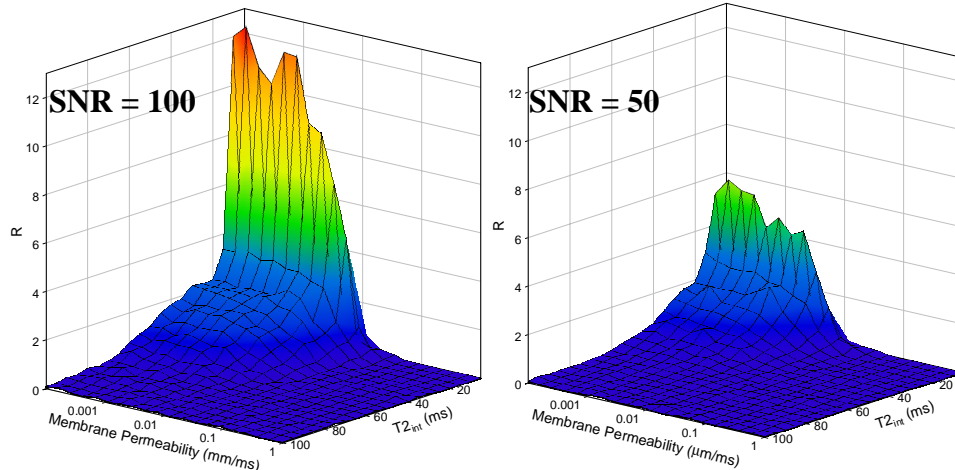
Methods

The finite element model was implemented in FlexPDE 5 (PDE Solutions Inc). The model solves simplified Bloch equations plus diffusive terms in a geometry of 2D square cells. The geometry consists of 10 µm cells, cell volume fraction = 80%, extracellular diffusivity = 3.0 μm^2/ms, intracellular diffusivity = 1.0 μm^2/ms, extracellular T2 ($T2_{ext}$) = 150ms, The signal from water is spatially integrated at specific time points to obtain signal decay with TE. TEs were chosen to correspond to those achievable by current MRI hardware, with a minimum TE=25ms followed in 10ms increments to a maximum TE=175ms. Zero-mean, Gaussian noise was added to each decay to simulate noise in an experiment and reported SNR corresponds to that of the first echo in the experiment. The magnitude of the noise plus the signal is taken to avoid negative signal values. The exponentiality of a signal decay is determined by comparing the residual squared sum of the fits to single- and double-exponential decays. We use $R=(e_1-e_2)/e_2$ as a measure of the change in residual, where e_1 and e_2 represent the residual squared sum of a fit to a single- and double-exponential, respectively.

Results

Figure 1 shows T2 related signal decay varying with membrane permeability and intracellular T2. Symbols represent simulated data while lines represent fitted single-exponential decays. At short $T2_{int}$, (20 ms) signal decay and fitted T2 vary considerably with P_{mem}, which does not occur at longer values of $T2_{int}$ Further, a single-exponential decay does not adequately represent signal decay in tissues with short $T2_{int}$ and little exchange. Figure 2 presents surface renderings of R over a parameter space of $T2_{int}$ and P_{mem} at SNR = 100 and 50. Larger values of R indicate poorer fits to a single-exponential, while R near 0 would indicate no statistical difference between fits.

Figure 1: Simulated signal decay and fits, varying membrane permeability and $T2_{int}$. R = 2.2, 0.68, and 0.0 for P_{mem} = 0.0001, 0.01 and 1 µm/ms respectively at $T2_{int}$ = 20 ms. Similarly, R = 0.20, 0.05, and 0.08 at $T2_{int}$ = 75 ms. SNR = 100.

## Discussion and Conclusion

The FE model predicts a large region of P_{mem} and $T2_{int}$ values within which relaxation is monoexponential. Signal decays in geometries with little exchange and low $T2_{int}$ have high R values, and are best described by double-exponential curves. For example, at $T2_{int}$= 20ms and P_{mem} = 0.0001 µm/ms signal decay is biexponential (Fig. 1). However, at $T2_{int}$= 20ms and P_{mem} = 0.01 µm/ms, signal decay can be considered monoexponential, with R=0.68 (Fig. 1). Noise has the effect of making curves more monoexponential, with R = 0.25 at $T2_{int}$=20ms, P_{mem} = 0.01 µm/ms and SNR = 50. With $T2_{int}$ = 75 ms, half that of $T2_{ext}$, signal decay is monoexponential over all P_{mem} values. These findings indicate that the presence of low $T2_{int}$ (compared to $T2_{ext}$) and low P_{mem} are not necessarily incompatible with experimentally observed monoexponential T2 relaxation.

References

1. Vestergard-Poulsen et al. JMRI 2007, 26:529
2. Does et al. MRM 2000, 43:837

Figure 2: Change in residual of fits to exponential decay in a parameter space of membrane permeability and $T2_{int}$.