Magnetization Transfer Effects in Single Slice Spoiled Gradient Echo Imaging

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Introduction

We investigated magnetization transfer (MT) effects on the steady state MR signal for a sample subjected to a series of identical on resonance rf pulses, such as would be experienced while imaging a single slice using a spoiled gradient echo sequence. The MT coupling terms for a two-pool system were added to the Bloch Equations, and we derived the resulting steady state signal equation and compared this result to the conventional signal equation without MT effects. We found that the steady state signal is increased by a small amount because of MT. Consequences of this MT effect include 1) inaccuracies in T_1 values determined via steady state gradient echo methods and 2) the ability to quantify the MT parameters by fitting the gradient echo steady state signal to the signal equation appropriately modified to include MT effects.

Theory

We consider a two-pool system, which includes a free pool and a restricted pool. Bloch Equations are used to predict the steady state signal for a simple pulse sequence with the excitation pulse set on resonance. Coupling terms are added to the Bloch Equations to model the MT effects. The relaxation effects on the free pool during the rf pulse and the direct saturation effects of the rf pulse on the restricted pool were examined by numerical simulations, and proven to be small enough to be ignored. The transverse steady state signals for the free pool without and with MT effects are respectively:

$$M_{xy,f,ss} = M_{0,f}\sin\alpha\frac{1-E_1}{1-E_1\cos\alpha} \quad [1].$$

$$M_{xy,f,MTss} \approx M_{0,f}\sin\alpha\frac{1-E_3}{1-E_3\cos\alpha} \approx M_{0,f}\sin\alpha\frac{1-e^{-TR*R_1^{obs}}}{(1-f)e^{-TR*R_1^{obs}}(1-\cos\alpha)+1-e^{-TR*R_1^{obs}}} \quad [2]$$

where the subscript f denotes the free pool, subscript ss denotes the steady state signal. M_0 is the equilibrium magnetization. α is the flip angle of the excitation pulse. f is the ratio of the restricted pool size to the free pool size. $E_3 \approx (1-f)E_1/(1-fE_1)$, $E_1 = e^{-TR*R_1^{obs}}$, where TR is the repetition time, R_1^{obs} is the observed recovery rate, also known as the slow recovery rate. Assumptions that the pool size ratio f <<1 and $1/TR$ is smaller than the fast recovery rate have been made for the approximations in Eq. [2].

Numerical Simulations

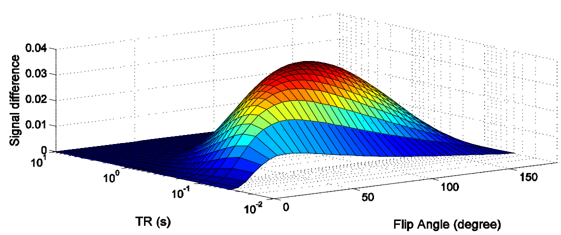

Fig.1. The steady state signal difference when MT effects are included and MT effects are ignored, as a ratio of the equilibrium magnetization $M_{0,f}$. MT parameters for white matter [1] were used.

Figure 1 shows that MT effects always increase the steady state signal by some small amount. Therefore, estimation of T_1 by the gradient echo method will be affected by MT. If we ignore the MT effects, and fit the data to Eq. [1], while the actual signal is described by Eq. [2], we will end up with a T_1 recovery rate that is a function of TR :

$$R = 1/TR*\ln((1-f*e^{-TR*R_1^{obs}})/((1-f)e^{-TR*R_1^{obs}}))$$

Numerically generated steady state signals including MT effects and with Gaussian noise added were used to test the determination of MT parameters. It was found that R_1^{obs} and f can be obtained by varying the flip angle α and the repetition time TR and fitting the resulting steady state signal to Eq. [2].

Results

2 samples, 0.2mM $MnCl_2$ and 0.2mM $MnCl_2$ +15% BSA (cross-linked), were measured on a 4.7T Varian system. Both spoiler gradients and rf spoiling techniques were applied to eliminate residual transverse magnetization. Dummy scans were performed before each data acquisition to ensure a steady state was achieved. The slice profile of the rf pulse was simulated by numerical methods to determine the flip angle at each position across the slice, and the integral of Eq. [2] across the slice was used in the data analysis.

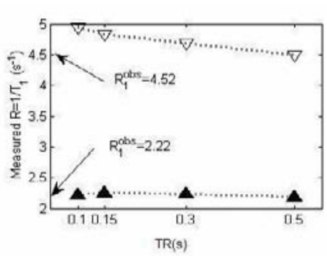

Fig.2. Measured recovery rate when ignoring MT for $MnCl_2$ (▲) and $MnCl_2+BSA$ (▽). The corresponding R_1^{obs} for each sample is obtained from a separate inversion recovery experiment.

Inaccurate T_1 quantification if MT ignored: T_1 is conventionally measured by setting a TR , varying the flip angle α , and fitting the gradient echo signal to Eq. [1]. Figure 2 shows that for samples with a non-zero pool size ratio, e.g. $MnCl_2+BSA$, ignoring MT will cause incorrect estimation of T_1 when choosing small TR .

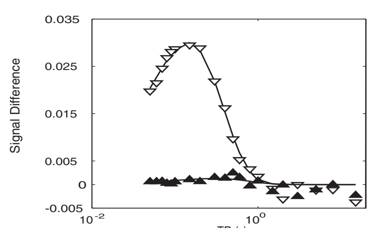

Fig.3. Difference between measured steady state signal and that calculated ignoring MT effects (from Eq. [1], with the knowledge of R_1^{obs} from the inversion recovery experiment) for the $MnCl_2$ sample (▲) and the $MnCl_2+BSA$ sample (▽). Solid lines are the fitting lines.

MT parameters determination: R_1^{obs} and f can be determined by choosing a flip angle α (e.g. 90°), a series of TR values, and fitting the measured gradient echo steady state signal to Eq. [2]. Figure 3 shows the fitting results. The fitted MT parameters are: $MnCl_2$: $f = 0.0051$, $R_1^{obs} = 2.2381 s^{-1}$; $MnCl_2+BSA$: $f = 0.1133$, $R_1^{obs} = 4.6019 s^{-1}$, they are very close to the literature values. [2]

References 1. Sled JG, Pike GB. Magn Res Med 46:923-931 (2001) ; 2. Gochberg DF, Gore JC. Magn Res Med 49:501-505(2003).