Quantitative Magnetization Transfer Imaging Using Balanced SSFP

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Introduction. In tissues, the signal of balanced steady-state free precession (bSSFP) is considerably reduced as a result of magnetization transfer (MT) (1). An extended bSSFP signal equation is derived, based on a binary spin-bath model which takes MT effects fully into account. Using this new bSSFP signal model, *quantitative* MT model parameters such as the fractional pool size, corresponding magnetization exchange rates, and relaxation times are estimated in human brain. The results show high correlation with standard methods, but benefit from bSSFP's short acquisition times and high signal-to-noise ratios. This allows the acquisition of isotropic high resolution quantitative MT maps within clinically feasible acquisition times.

Theory. A binary spin-bath model (restricted/free pool: subscripts '*f*'/'*r*'; fractional pool size: *F*; exchange rates: k_f, k_r; longitudinal, transversal relaxation rates: $R^{r,f}_{1,2}$; absorption lineshape: $G(\Delta)$; frequency offset: Δ; mean saturation rate: $\langle W \rangle$; RF pulse: $\omega_1 = \gamma B_1$) is used to capture MT effects (2). Assuming that exchange decouples from relaxation processes within any TR, the common matrix formalism (3) for SSFP signal (S) formation can be used to solve the two-pool bSSFP problem, yielding

$$S \propto \sin\alpha \frac{(1-E_1^f)B + C}{A - E_1^f E_2^f B - (E_1^f B - E_2^f A)\cos\alpha}, \qquad [1]$$

where $A = 1 + F - f_w E_1^r (f_k + F)$, $B = 1 + f_k (F - f_w E_1^r (F+1))$,

$$C = F(1-E_1^r)(1-f_k),\ f_k = e^{-(k_f + k_r)TR},\ f_w = e^{-\langle W \rangle T_{RF}},$$

$$E_{1,2}^{r,f} = e^{-R_{1,2}^{r,f} TR},\ \langle W \rangle = \frac{\pi}{T_{RF}} \int \omega_1^2(t) G(\Delta) dt.$$

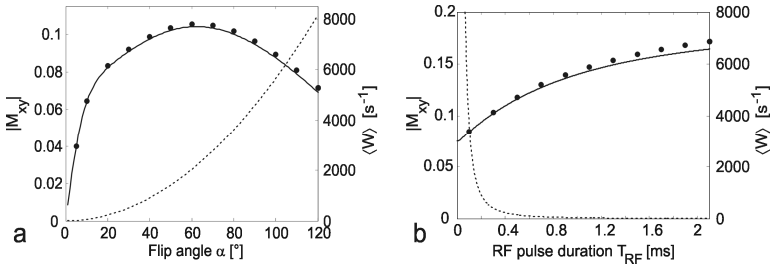

Fig. 1: Mean saturation rate $\langle W \rangle$ (dotted line), analytical solution (Eq. [1], solid line) and numerical simulation (circles) of the spin-bath model for bSSFP for (a) varying flip angle α (TR = 2.92 ms and T_{RF} = 230 μs) and (b) RF pulse duration T_{RF} (TR = 3 ms + T_{RF}, α = 35°). Two pool model parameters for white matter were: $T_{1,f}$ = $T_{1,r}$ = 585 ms, $T_{2,f}$ = 81 ms, F = 0.157, k_f = 4.45 s^{-1}, G(0) = 1.4 · 10^{-5} s^{-1}).

Eq. [1] is of similar form as the well-known single pool bSSFP equation but now incorporates MT related parameters, such as *F*, k_f and $\langle W \rangle$.

Methods. All experiments were performed in 3D based on a 144×192×192 matrix yielding 1.3 mm isotropic resolution. B_1 was measured to correct for deviations in the flip angle. $T_{1,f}$ maps were calculated from DESPOT1 (4). Eq. [1] was fitted pixelwise to a set of 8 bSSFP sequences with α = 35° and varying RF pulse durations T_{RF} ($TR_1/T_{RF,1}$ = 2.92 ms/0.23 ms, …, $TR_8/T_{RF,8}$ = 4.78 ms/2.1 ms), and to 8 bSSFP sequences with TR/T_{RF} = 2.99 ms/0.27 ms and varying flip angles (α_1 = 5°, …, α_8 = 40°) to yield *F*, k_f and $T_{2,f}$. Data acquisition time for the whole qMTI protocol was less than 30 minutes.

Results & Discussion. Numerical simulations of the spin-bath model validate Eq. [1] and thereby the separation of relaxation and exchange processes (Fig. 1). Within the applied range of flip angles, Eq. [1] slightly underestimates simulations by 1.1% in maximum (Fig. 1a). For RF pulse modulations (Fig. 1b), discrepancies increase with increasing T_{RF} (4.3% for T_{RF} = 2.1 ms). Good agreement between the analytical description and numerical simulation was found, and differences are most likely due to neglected T_2 effects during excitation processes. In Fig. 2, results from qMTI using the two-pool bSSFP model are shown for normal appearing human brain. Generally, MT related model parameters feature a highly similar contrast with good discrimination between gray and white matter brain structures. Good correspondence between the two-pool bSSFP and common qMTI models is observed: $F_{WM,1}$ = 14.4%, $F_{WM,2}$ = 14.5%, $F_{GM,3}$ = 6.5%, $k_{f,WM,1}$ = 4.6 s^{-1}, $k_{f,WM,2}$ = 4.5 s^{-1}, $k_{f,GM,3}$ = 2.3 s^{-1} (selected regions of interest, see Fig. 2). Reasons for slight discrepancies may be different approaches concerning the R^r_1 and the absorption line shape *G*.

Conclusion. A new qMTI framework based on two-pool bSSFP signal analysis was introduced. In human brain, MT model parameters, such as *F* and k_f, agree with the ones derived from common methods. Excellent signal-to-noise ratios and short acquisition times make bSSFP an ideal candidate for clinically feasible high resolution qMTI, as for multiple sclerosis.

References. 1. Bieri et al., *MRM* **56** (2006) 2. Henkelman et. al. *MRM* **29** (1993) 3. Freeman et al., *JMR* **4** (1971) 4. Deoni at. al. *MRM* **53** (2005)

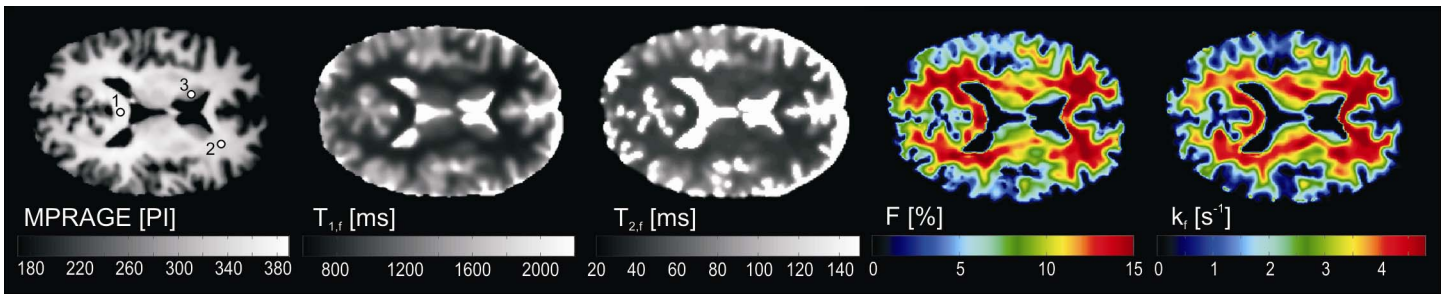

Fig. 2: Axial sample images from MPRAGE; $T_{1,f}$ from DESPOT1; and maps of $T_{2,f}$, F and k_f derived from two pool bSSFP model fitting (Eq. [1]) in a healthy volunteer.