Quantitative Magnetization Transfer Imaging Using Non-Balanced SSFP

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Introduction. Similar to balanced steady-state free precession (bSSFP), the signal of non-balanced SSFP (nb-SSFP, such as SSFP-FID or SSFP-echo) depends on magnetization transfer (MT) in tissues (1). Based on a binary spin-bath model, an extended SSFP-FID signal equation is presented and quantitative MT imaging (qMTI) is demonstrated ex-vivo and in-vivo. High correlation with literature values is observed.

Theory. A binary spin-bath model (restricted/free pool: subscripts '*f*'/'*r*'; fractional pool size: F; exchange rates: k_f, k_r; longitudinal, transverse 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 describe MT effects (2). Assuming that exchange decouples from relaxation processes within any TR, the common matrix formalism (3) for SSFP signal formation can be applied to solve the two-pool SSFP-FID differential equations:

$$\left\langle M_{xy} \right\rangle = M_0^f \sin\alpha \, \frac{H}{C}\left(\frac{C + DE_2^f}{\sqrt{D^2 - C^2}} - E_2^f \right), \qquad [1]$$

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

$C = E_2^f (E_1^f B - A)(1 + \cos\alpha)$, $D = A - BE_1^f \cos\alpha - (BE_1^f - A\cos\alpha)(E_2^f)^2$,

$H = M_0^f B(1 - E_1^f) + M_0^r (1 - E_1^r)(1 - f_k)$, $f_k = e^{-(k_f + k_r)TR}$, $f_w = e^{-<W>T_{RF}}$,

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

Eq. [1] is of the same form as the well-known single-pool SSFP-FID equation, but now comprises MT related parameters, such as F, k_f, and $\langle W \rangle$.

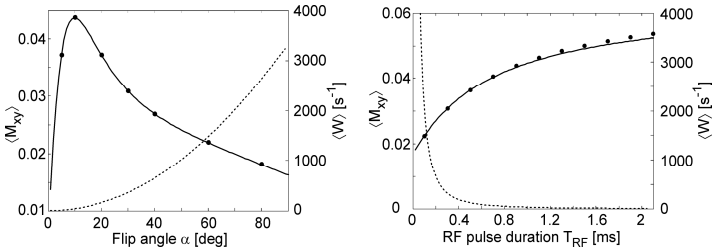

Fig. 1: Mean saturation rate $\langle W \rangle$ (dotted line), analytical solution (Eq. [1], solid line) and numerical simulation (circles) of the spin-bath model for SSFP for (a) varying flip angle α (TR = 3 ms and T_{RF} = 270 µs) and (b) RF pulse duration T_{RF} (TR = 3 ms + T_{RF}, α = 35°). Two pool model parameters (cartilage [6]) were: $T_{1,f}$ = 1.03 s, $T_{1,r}$ = 1 s, $T_{2,f}$ = 40 ms, F = 0.18, k_f = 11 s^{-1} ($G(0) = 1.0 \cdot 10^{-5}$ s^{-1}).

Methods. All experiments were performed in 3D on a 1.5 T system. Since SSFP-FID is flow/motion sensitive, first an ex-vivo muscle sample was used for comparison with bSSFP-qMTI (4) and to evaluate the accuracy of Eq. [1]. Ex-vivo muscle and in-vivo brain acquisitions were performed with a 144×192×192 matrix (1.3 mm isotropic resolution) and 6 outer averages were taken to reduce SSFP-FID flow sensitivity, whereas a 128×128×32 matrix (1.25 mm isotropic resolution) was used for cartilage acquisitions. A B_1 map was acquired to capture deviations in the flip angle. $T_{1,f}$ maps were calculated based on DESPOT1 (5). Eq. [1] was fitted pixelwise to a set of 8 SSFP-FID sequences with α = 35° and varying RF pulse durations T_{RF} ($TR_1/T_{RF,1}$ = 2.7 ms/0.23 ms, …, $TR_8/T_{RF,8}$ = 4.6 ms/2.1 ms), and 8 SSFP-FID sequences with TR/T_{RF} = 3.0 ms/0.3 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 about 30 minutes for muscle and brain and about 10 minutes for cartilage.

Results & Discussion. Numerical simulations of the spin-bath model show good agreement with Eq. [1] and thereby justify the separation of relaxation and exchange processes (Fig. 1). Good correlation is found in muscle between qMTI parameters of SSFP-FID vs. bSSFP : F = 7.8±0.6 vs. 6.6±0.5 %, k_f = 4.7±0.5 vs. 4.0±0.4 s^{-1}, $T_{2,f}$ = 50.5±3.0 vs. 50.9±2.5 ms ($T_{1,f}$ = 778±22 ms). In Fig. 2, results for qMTI using SSFP-FID are shown for human brain and articular cartilage. Exemplary values for regions of interest are for white matter (frontal lobe): F = 13.5±1.2 %, k_f = 6.9±1.3 s^{-1}, $T_{2,f}$ = 55.3±2.9 ms ($T_{1,f}$ = 744±20 ms), for gray matter (caudate nucleus): F = 8.0±1.3 %, k_f = 1.9±0.6 s^{-1}, $T_{2,f}$ = 93±23 ms ($T_{1,f}$ = 1200±39 ms) and for articular cartilage: F = 16.5±1.6 %, k_f = 10.5±1.7 s^{-1}, $T_{2,f}$ = 39.5±5.8 ms ($T_{1,f}$ = 826±67 ms). Good correlation with literature values is found. Compared to qMTI using bSSFP, SSFP-FID is insensitive to off-resonance artifacts, thus offering a wider range of applications, but measurements are complicated by the flow and motion sensitivity of non-balanced SSFP.

Conclusion. Quantitative MT imaging on various tissues was performed using non-balanced SSFP. In muscle, brain and articular cartilage MT model parameters, such as F and k_f, agree with the ones derived from common methods. SSFP-FID benefits from high signal-to-noise ratios, short acquisition times, and off-resonance insensitivity, and hence provides a promising framework for high-resolution qMTI.

References. 1. Bieri et al., *MRM* **56** (2006) 2. Henkelman et. al. *MRM* **29** (1993) 3. Freeman et al., *JMR* **4** (1971) 4. Gloor et al. *MRM* **60** (2008) 5. Deoni et al. *MRM* **53** (2005) 6. Stanisz et al. *MRM* **54** (2005)

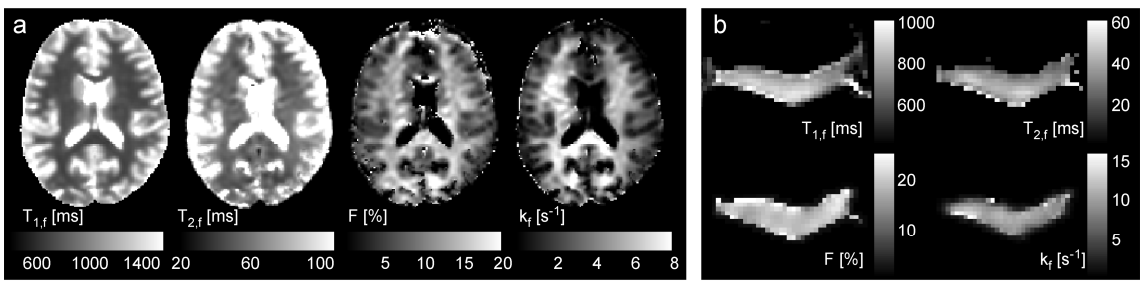

Fig. 2: QMTI sample images using SSFP-FID in (a) human brain and (b) human patellar cartilage. Map of $T_{1,f}$ calculated using DESPOT1; and maps of $T_{2,f}$, F, and k_f derived from two pool SSFP model fitting (Eq. [1]) in a healthy volunteer.