Finite RF Pulse Effects on Quantitative Magnetization Transfer Imaging Using Balanced SSFP

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Introduction. In tissues, the signal of balanced steady-state free precession (bSSFP) is strongly dependent on magnetization transfer (MT) (1). Based on an extended bSSFP signal equation, taking MT effects fully into account, quantitative MT (qMT) parameters can be estimated within clinically feasible acquisition times (2). It has recently been shown that the effect of finite RF pulses can lead to considerable bSSFP signal modulations (3). As bSSFP-based qMT imaging uses RF pulse modifications, a correction for these effects has to be included. In this work, a modification to the two-pool bSSFP equation is analyzed, overcoming the assumption of instantaneous RF pulses in the derivation of quantitative MT parameters. Effects of the correction on the parameter maps are assessed in human brain.

Theory. Quantitative MT parameters, such as the bound pool fraction F, the forward exchange rate k_f and the transverse relaxation time of the free protons $T_{2,f}$ can be derived from a two-pool bSSFP signal equation by measuring the signal dependence on the RF pulse duration (T_{RF}) as well as the flip angle (α) dependence (2). The two-pool bSSFP equation assumes instantaneous RF pulses and therefore underestimates numerical simulations of a binary spin-bath model with increasing T_{RF} (Fig. 1, dashed blue line). Effects of finite RF pulses are captured by subtracting the part of the effective RF pulse duration, in which no relaxation takes place ($\zeta\cdot T_{RFE}$), from TR, leading to a reduction in the transverse relaxation rate $R_{2,f}$ according to

$$\tilde{R}_{2,f} := \left(1-\zeta\cdot\frac{T_{RFE}}{TR}\right)\cdot R_{2,f},$$

where $T_{RFE} := 1.20\cdot\frac{T_{RF}}{TBW}$, $\zeta \approx 0.68-0.125\cdot\left(1+\frac{T_{RFE}}{TR}\right)\cdot\frac{R_{1,f}}{R_{2,f}}$ and $R_{1,f}=\frac{1}{T_{1,f}}$, $R_{2,f}=\frac{1}{T_{2,f}}$

for slice selective pulses (3).

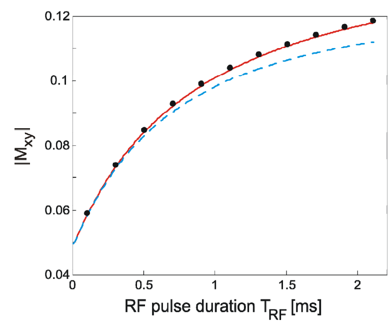

Fig. 1: Numerical simulation (circles) of a binary spin-bath model and analytical solution without (dashed blue line) and with RF correction (solid red line) for varying RF pulse duration T_{RF} (TR = 3 ms + T_{RF}, α = 35°). Two pool model parameters for frontal white matter were: $T_{1,f} = T_{1,r}$ = 733 ms, $T_{2,f}$ = 40 ms, F = 14.5%, k_f = 4.5 s^{-1}, G(0) = 1.4 · 10^{-5} s^{-1} (2).

Methods. All experiments were performed in 3D based on a 144×192×192 matrix yielding 1.3 mm isotropic resolution. A B_1 map was acquired to correct for deviations in the flip angle and $T_{1,f}$ maps were calculated according to DESPOT1 (4). The corrected two-pool bSSFP equation 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 qMT protocol was less than 15 minutes.

Results & Discussion. A comparison of the analytical two-pool bSSFP equation with a numerical simulation of the binary spin-bath model (Fig. 1) demonstrates that the finite RF pulse correction very effectively reduces the relative difference from about 5% to less than 1% for the longest T_{RF}. Figure 2 displays a single voxel fit in frontal white matter for a healthy volunteer. Exemplary parameter estimates are F = 14.9 ± 5.4 %, k_f = 6.8 ± 4.5 s^{-1}, $T_{2,f}$ = 44.0 ± 9.1 ms without RF pulse correction, and F = 13.1 ± 3.8 %, k_f = 6.2 ± 3.3 s^{-1}, $T_{2,f}$ = 39.0 ± 6.0 ms with RF pulse correction. Thus, parameters are reduced by about 10%, whereas confidence intervals are narrowed by about 30%, suggesting that the corrected equation describes the data more adequately. Parameter maps of a brain slice and relative differences between corrected and non-corrected results are shown in Fig. 3. Region of interest analysis yield similar changes in F (-1.9% and -1.2%), k_f (-0.5 s^{-1} and -0.5 s^{-1}) and $T_{2,f}$ (-5.3 ms and -5.0 ms) for frontal white matter and putamen.

Conclusion. Especially for high T_{RF}/TR, the assumption of instantaneous RF pulses is no longer valid and a correction has to be included in the analysis of bSSFP-based qMT imaging. This finite RF pulse correction improves the fitting quality considerably and reduces the values of F, k_f and $T_{2,f}$ by about 10%.

References. (1) Bieri et al., *MRM* **56**:1067-1074 (2006); (2) Gloor et al., *MRM* **60**:691-700 (2008); (3) Bieri et al., *MRM* **62**:1232-1241 (2009); (4) Deoni et al., *MRM* **53**:237-241 (2005).

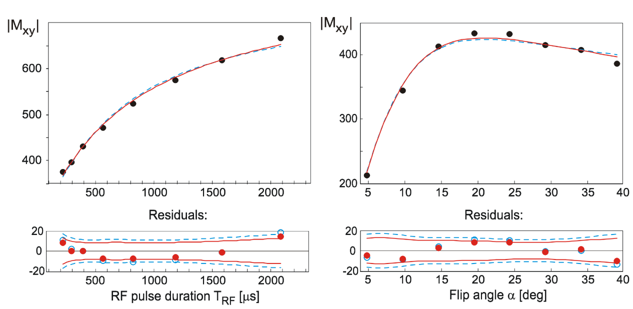

Fig. 2: Exemplary single voxel fit in frontal white matter using the MT-bSSFP equation without (dashed blue lines) and with (solid red lines) RF correction. Additionally, fitting residuals in units of M_{xy} and 95% confidence interval of the predicted data are shown (blue: non-corrected, red: corrected). Correction for finite pulse effects reduces F by 1.8%, k_f by 0.6 s^{-1} and $T_{2,f}$ by 5 ms and in this voxel.

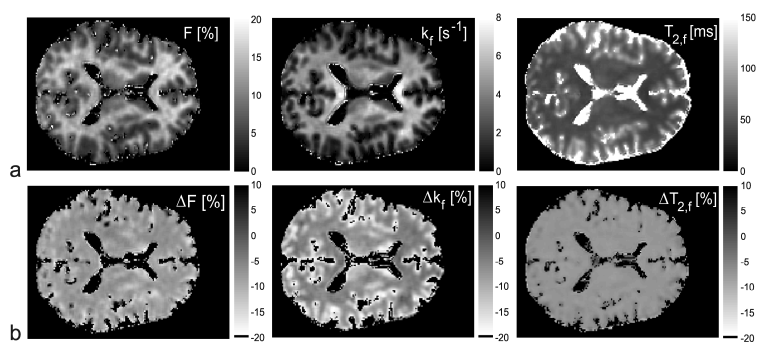

Fig. 3: (a) Maps of F, k_f and $T_{2,f}$ derived from two-pool bSSFP model fitting including a correction for finite RF pulse effects in a healthy volunteer. (b) Relative differences between corrected and non-corrected maps for the three fitting parameters.