B_1-Sensitivity Analysis of qMT

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INTRODUCTION: B_1 mapping is an important measurement used in quantitative magnetization transfer (qMT) imaging, particularly at high field strengths (≥ 3.0 T) where B_1 can vary by ± 30% in a human brain (Fig. 1). For pulsed spoiled gradient echo (SPGR) qMT imaging experiments, B_1 maps are used as a corrective factor for the excitation flip angle (~5° to 15°) and MT saturation power (flip angles ~150° to 700°). Additional measurements necessary for qMT (e.g. T_1 mapping) may also require B_1 maps as a corrective factor; variable flip angle (VFA) T_1 mapping requires B_1 maps, while inversion recovery (IR) or Look-Locker typically do not[1]. Thus, local (e.g. artifacts) or global (e.g. systemic biases) inaccuracies in B_1 mapping[2] will propagate to the fitted qMT parameters differently, depending on the chosen T_1 mapping method.

We recently reported that the qMT pool-size ratio (F), an important myelin biomarker, is insensitive to a large range of B_1 inaccuracies when using VFA for T_1 mapping[3] (Fig. 1). Here we present a simulation-based analysis of the B_1 sensitivity of qMT, comparing how different T_1 mapping methods (VFA vs. IR) propagate the B_1 error to the qMT parameters. We show that the F parameter is very robust and insensitive to B_1 inaccuracies when VFA T_1 mapping is used, but this comes at the expense of a substantial increase in error of kf.

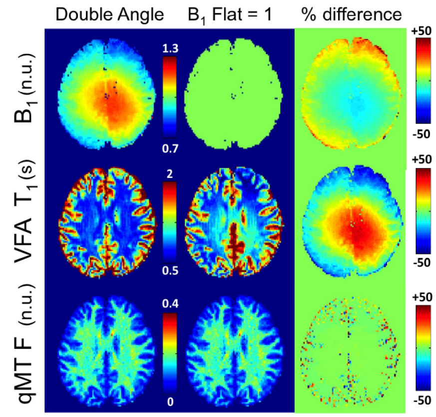

Figure 1. Comparison of VFA T_1 and qMT F maps using measured and nominal (B_1 flat = 1) B_1 maps at 3T[3].

METHODS: The Bloch-McConnell equations for magnetization exchange were solved using MATLAB (MATLAB2011a, The Mathworks Inc.) for a pulsed SPGR experiment by decomposing the pulse sequence into periods of instantaneous saturation of the free pool, constant irradiation of the restricted pool, and free precession[4]. Healthy white matter tissue parameters were fixed to the following values: F = 0.122, kf = 3.97 s^{-1}, R1f = 1.11 s^{-1}, R1r = 1.0 s^{-1}, T2f = 27.2 ms, T2r = 10.96 µs. The MT signal was simulated from the solution of the Bloch-McConnell equation for the following MT protocol: TR = 25 ms, $\alpha_{excitation}$ = 7°, Gaussian-Hanning MT pulses with a pulse duration of 10.2 ms, α_{MT} = 142° and 426°, logarithmically spaced off-resonance frequencies = 423.9 Hz, 1,087.5 Hz, 2,731.6 Hz, 6,861.6 Hz, and 17,235.4 Hz. The MT signal was subsequently fitted using the Sled and Pike method[5] for a linear range of 100 B_1 and 100 T_1 values (10,000 points in total); T_1 varied independently of B_1 for this step, and without any assumptions on the measurement method. B_1 ranged from 0.5 to 2 ($B_{1,true}$ = 1), and T_1 ranged from 0.1 s to 4 s ($T_{1,true}$ = 0.9 s). VFA signals were also simulated from the analytical SPGR equation[1]: TR =25 ms, α = 3° and 20°, $T_1 = T_{1,true}$. T_1 values were fitted from the VFA data for the B_1 error range. The fitted T_1 values were subsequently used in conjunction with their respective B_1 values to fit the MT signal.

RESULTS: Figure 2 shows the error (%) of the fitted qMT pool-size ratio, F, in the presence of a wide range of B_1 and T_1 inaccuracies ($B_{1,true}$ = 1, $T_{1,true}$ = 0.9 s). The superimposed lines show the range of errors expected from an experiment using a B_1 independent T_1 method like IR (solid line), and from VFA T_1 mapping (dashed line). Figure 3 plots the errors in qMT fitted parameters (F, kf, T2f, T2r) using B_1-independent (IR) and VFA measured T_1 (see lines in Fig. 2), for a range of B_1 inaccuracies typically observed in vivo. Errors in F induced by B_1 errors were greatly reduced using VFA T_1 mapping (Fig. 3a). A substantial increase in errors in kf occurs for VFA relative to IR (Fig. 3b), while T2r remains insensitive to B_1 inaccuracies for both cases.

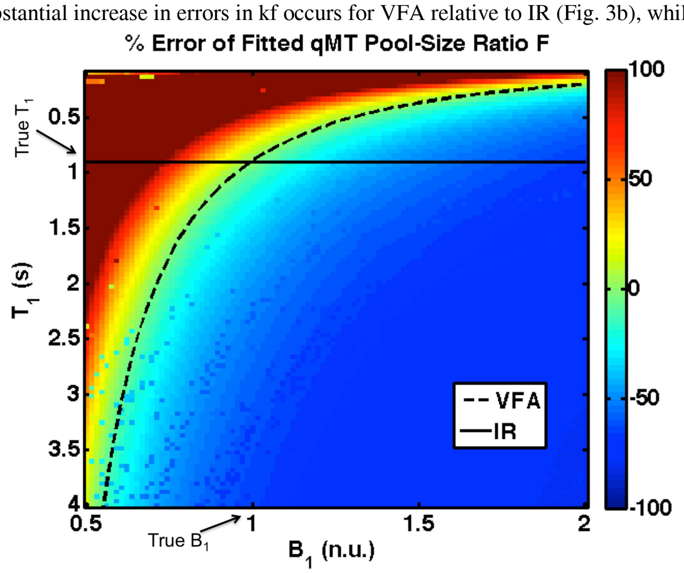

Figure 2. Percent error in fitted qMT F values in the presence of a wide range of B_1 and T_1 errors ($B_{1,true}$ = 1 n.u., $T_{1,true}$ = 0.9 s). The superimposed lines plot the T_1 distribution for a B_1-independent T_1 mapping method (IR, solid line) and VFA (dashed line).

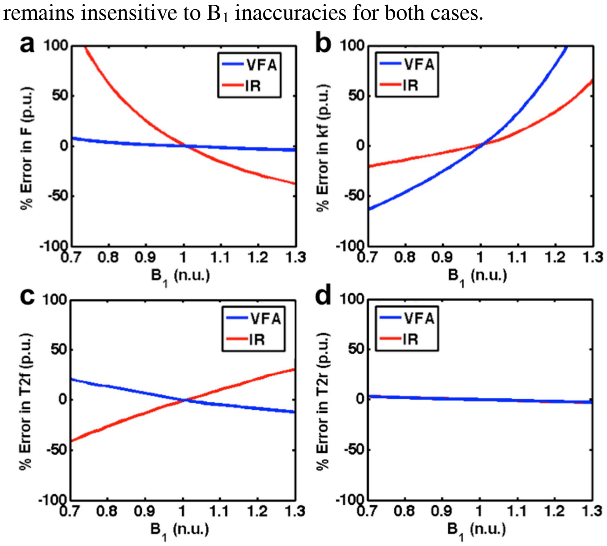

Figure 3. Percent error in fitted qMT parameters for a range of B_1 errors (**a** – pool size ratio (F), **b** – magnetization exchange rate (kf), **c** – free pool T2 (T2f), **d** – restricted pool T2 (T2r)). Fits using a B_1-independent T_1 measure (IR) are shown in red, and those using VFA T_1 mapping are shown in blue. See solid and dashed lines in Fig. 2 for B_1 dependence of IR and VFA T_1.

DISCUSSION: The qMT pool size ratio F was shown to be nearly B_1-error insensitive when using VFA T_1 mapping (Fig. 3a - blue). Using a B_1-independent T_1 measure such as IR produces large qMT F errors (from >100% to -45% for B_1 errors ranging from -30% to 30%, Fig 3a - red), while VFA T_1 mapping kept qMT F errors within a moderate range (7% to -3%, Fig. 3a - blue). The B_1 errors for the case of VFA were mostly absorbed by the kf parameters (Fig. 3b), in agreement with observations from previous in vivo work[3]. These results suggest that qMT imaging using B_1-independent T_1 measurement, and qMT methods that fixes qMT model parameters, may have increased sensitivity to B_1-inaccuracies. However, for applications where kf may be the biomarker of interest (e.g. cartilage imaging[6], systemic inflammation[7]), a B_1-independent measure of T_1 may be preferred instead of the VFA method. Further analytical sensitivity analysis of the qMT equations for different qMT measurement protocols could help determine optimal qMT protocols for reduced B_1-inaccuracy sensitivity.

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