Rescalable spillover prediction for optimization of pulsed magnetization transfer and CEST experiments

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Introduction

Magnetization transfer (MT) contrast employs RF labelling at specific offset frequencies from the water resonance and measures the apparent decrease in water signal S_{sat}/S_0 [1]. Long off-resonant labelling also affects the water proton pool directly. This weakening of the transfer effect, the so called spillover effect, becomes dominant especially for magnetization transfer by chemical exchange of labile metabolite protons (APT-, GAG-, creatine- CEST, [2,3,4]) with small chemical shift relative to water protons. For continuous wave RF irradiation analytical solutions are available for predicting spillover effects. As clinical scanners only permit pulses of maximum duration ~100ms, irradiation must be realized by RF pulse trains [5,6,7]. Therefore, the behaviour of direct water saturation of different RF pulse trains with gradient spoiling was studied with the goal to find an indicator for low spillover in this case.

Theory

Pulse trains are characterized by the B_1 cw power equivalent $B_{1cwpe}=\sqrt{\frac{\int_0^{tp} B_1^2(t)}{tp/DC}}$, pulse duration t_p, saturation time t_{sat} and duty cycle $DC=t_p/(t_p+t_d)$ leading to interpulse delay $t_d=t_p\cdot(1\text{-}DC)/DC$ and number of pulses $n=t_{sat}\cdot DC/t_p$.

These schemes are applied to the time-dependent Bloch equations at different offset frequencies yielding the reduced water z-magnetization $M_{zw}=S_{sat}/S_0$.

Map axes are B_{1cwpe} (vertical) and the maximum pulse bandwidth $BW=1/t_p$ (horizontal).

Materials & Methods

The time-dependent Bloch equations were solved using Matlab 7 (The Mathworks, Natick, MA, USA) by common numerical solutions [8] extended for non-constant ω_1. Relaxation times were T_1 in Bloch equations was chosen to be 450 ms, T_2 = 220 ms. For constant t_{sat} = 3 s (>>T_{1W}) and DC = 56%, B_{1cwpe} and t_p were varied. At $\Delta\omega$=1 ppm and 3.5 ppm maps of M_{zw} were simulated with spoiling after each 2.2-σ-Gaussian pulse realized by setting the transverse magnetization $M_{x,y}$ to zero. One simulation took ~6 hours. For comparison, M_{zw} was simulated also with cw-irradiation.

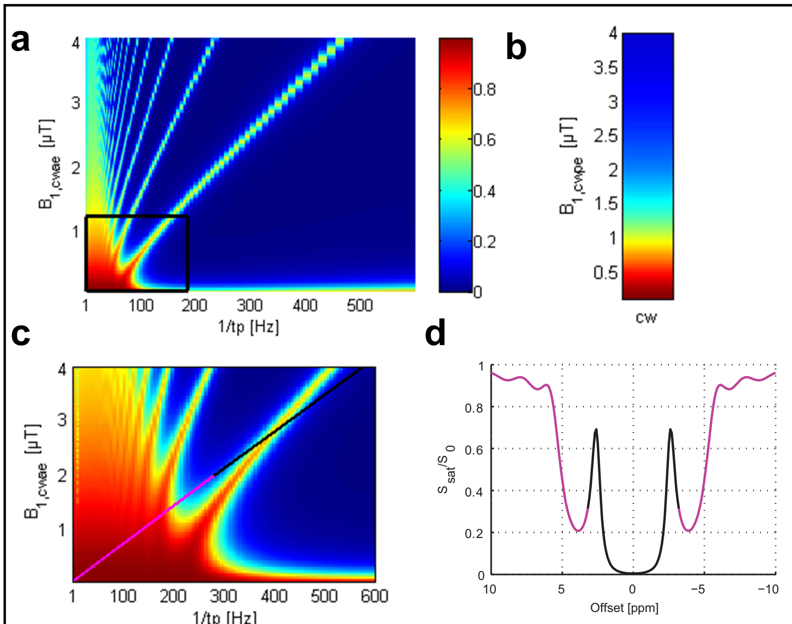

Figure 1: a) M_{zw} (B1,1/tp,1ppm), b) M_{zw} for cw, c) M_{zw}(B1,1/tp,3.5ppm) equals the segment of a), d) z-spectrum (B_{1cwpe}=2.01μT ,BW=1/3.54ms=282 Hz) in agreement with M_{zw} along solid line (pink-black) in d).

Results and Discussion

$M_{Zw}(B_1,1/t_p,1\text{ ppm})$ (Fig. 1a) has different regimes: cw-like for long pulses with BW < 50 Hz comparable to cw-spillover with cw power equivalent B_{1cwpe} (Fig. 1b). Here, relaxation dominates spillover behavior independent of the pulse shape (data not shown). For short pulses with BW>50 Hz and high B_1 spillover depends more and more on the off-resonant-flip-angle (lines with constant $B_1\cdot tp$). In Fig. 1a is the segment indicated which reflects M_{zw} for the offset 3.5 ppm which was separately simulated (Fig. 1c). The correlation of Fig. 1c) and the segment in a) indicates a scaling property regarding the irradiation frequency. This immediately implies firstly, that every M_{Zw}(B1,1/tp) map can be rescaled to another offset by rescaling the axes by the factor $\Delta\omega_{wanted}/\Delta\omega_{simulated}$ yielding the rescaling equality

$$\mathbf{M_{zw}(B_1,1/t_p,\Delta\omega_{ppm}) = M_{zw}(\Delta\omega_{ppm}\cdot B_1,\Delta\omega_{ppm}/t_p,1\ ppm)}.$$

Secondly, every line started at one pair of $(B_1,1/t_p)$ coordinates in Figs. 1a) and d) reflects a entire z-spectrum around the simulated offset frequency. Fig. 1d) shows the separately simulated z-spectrum to be appropriate to the contour line in d). Following the black line to infinity gives all M_{zw} for offsets smaller than 3.5 ppm. Following the pink line to the origin gives M_{zw} for all offsets larger than 3.5 ppm. Therefore, a single M_{zw} map for a specific pulse simulated at 1 ppm gives all information about direct water saturation for all simulated B_1, t_p and all irradiation offsets > 1 ppm. Deviations are possible due to the integer number of pulses leading to different spoiling effectivity and leaps in saturation time and fail reaching steady-state of saturation.

Conclusion

Pulsed saturation with gradient spoiling brings up different regimes of spillover: The cw-like regime and the off-resonant-flip-angle dependent regime. A single $M_{zw}(B_1,1/t_p)$ map at 1 ppm for a chosen pulse shape can be used to find optimal values for B_1 and t_p to obtain low direct water saturation at all offsets of interest >1 ppm. Furthermore, for all simulated $B_1,1/t_p$ the z-spectra of direct water saturation and also symmetric MT (data not shown) are given by a M_{zw} map. Therefore, M_{zw} in the rescalable basis of $(B_1,1/t_p)$ provides an elegant and quick tool for low spillover indication in pulsed magnetization transfer experiments.

References

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