A Transient Model of Off-resonance Saturation for Single-coil CASL

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Introduction: The saturation of macromolecules during single-coil continuous arterial spin labeling (CASL) perturbs the control and label water signals, and affects perfusion quantification. Off-resonance saturation models were developed previously for steady-state conditions using various line shapes [1, 2, 3]. We have adapted these models to address realistic transient conditions used in CASL, including amplitude modulated (AM) RF used in multi-slice CASL with AM frequencies (f_{AM}) of 0 and 125 Hz.

Theory: The 2-compartment model can be described by the set of symmetric Bloch equations in the presence of an RF field [2]. We introduced two parameters (C_a and C_b) to describe the instantaneous longitudinal relaxation rate for pools A & B for saturation times less than $5T_1$. The relative magnetization of free water pool (A) can be described by:

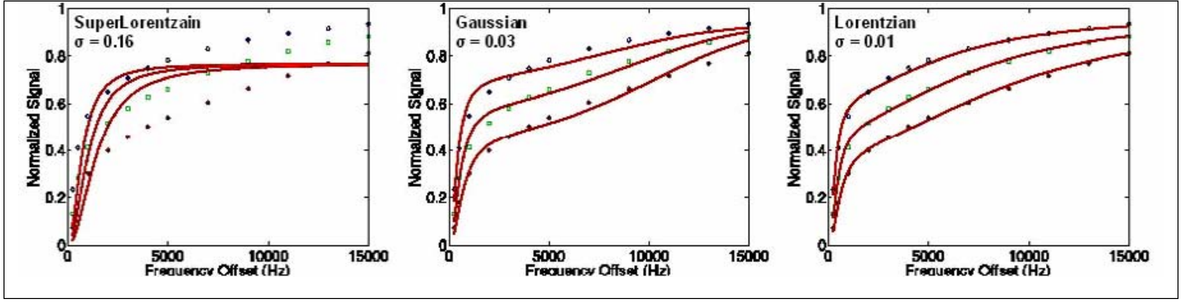
$$\frac{M_z^a}{M_0^a} = \frac{R_b\left[\dfrac{\tilde{R}\tilde{M}_0^b}{R_a}\right] - \tilde{R}\left[\dfrac{C_b}{R_a M_0^a}\right] + (R_{rfb} + \tilde{R} + R_b)\left(1 - \left[\dfrac{C_a}{R_a M_0^a}\right]\right)}{(R_{rfb} + \tilde{R} + R_b)\left(1 + (\dfrac{\omega_1}{2\pi\Delta})^2\left[\dfrac{1}{R_a T_{2a}}\right]\right) + \left[\dfrac{\tilde{R}\tilde{M}_0^b}{R_a}\right](R_{rfb} + R_b)}$$

where $\tilde{R} = RM_0^a$, $\tilde{M}_0^b = M_0^b / M_0^a$. $R_{a,b}$ is the longitudinal relaxation rate ($1/T_{1a,b}$). $M_0^{a,b}$ is the equilibrium longitudinal magnetization in the absence of any RF field. R is a fundamental rate constant such that $R_{ba} = RM_0^b$ and $R_{ab} = RM_0^a$ in which R_{ba} is a pseudo-first-order cross-relaxation rate constant from pool B to pool A. ω_1 and Δ are the amplitude and frequency offset, respectively, of the off-resonance saturation pulse. R_{rfb} is the line shape of the macromolecular pool B. There are seven parameters to be determined: $\tilde{R}$, R_b, $\tilde{R}\tilde{M}_0^b / R_a$, $1/R_aT_{2a}$, T_{2b}, $C_a/R_aM_0^a$ and $C_b/R_aM_0^a$.

Methods: Each off-resonance RF excitation (3.7 s pulse train at 92% duty cycle) was followed by a strong crusher gradient and then a 15-slice EPI acquisition (FA: 90^0, Matrix: 64x64, 100 ms post-labeling delay, superior to inferior acquisition) using a GE 1.5 T Signa MRI (LX) at the University of Pittsburgh MR Research Center. Different irradiation amplitudes $\omega_1/2\pi$ [78Hz, 110Hz and 156Hz (f_{AM} = 0); and 128Hz, 181Hz and 256Hz (f_{AM} = 125 Hz)] and 12 different offset frequencies [Δ, from 0.25 to 15 kHz] were used. Images were also acquired without off-resonance saturation for data normalization. A minimum of 15 repetitions was acquired for each frequency and amplitude. We performed a global fit to the model for each data set with 12 different offset frequencies and 3 irradiation powers, using the super-Lorentzian, Gaussian, and Lorentzian line shapes for the macromolecular pool B [1, 2, 3].

Results & Discussion: Figure 1 compares the fits for f_{AM}=0Hz using the different line shapes. The Lorentzian line shape provides the best fit for our gray matter (GM) and white matter (WM, not shown) saturation data for f_{AM} of both 0 and 125 Hz. The fitted parameters are in reasonable agreement with the literature (Table 1). The fitted values of $C_a/R_aM_0^a$ and $C_b/R_aM_0^a$ are less than 10^{-6}, indicating that saturation is near steady-state. The Lorentzian model allows us to calculate and correct the off-resonance saturation effects for different frequency offsets (e.g., slice locations) and saturation amplitudes (B_1) in our single-coil CASL experiments.

Figure 1. RF saturation data and fits for human gray matter at f_{AM} = 0 Hz.



References: 1. Grad et. al., *J Magn Reson*: 90:1-8(1990).
2. Henkelman et. al., *Magn Reson Med*: 29:759-766(1993).
3. Morrison et. al., *Magn Reson Med*: 33:475-482(1995).

Table 1. Fitting Parameters from Saturation Data ($R_b = 1s^{-1}$)

	$T_{2b}(\mu s)$	$R(s^{-1})$	$\frac{\tilde{R}\tilde{M}_0^b}{R_a}$	$\frac{1}{R_aT_{2a}}$	$\frac{C_a}{R_aM_0^a}$	$\frac{C_b}{R_bM_0^b}$	σ
GM at f = 0 Hz	34.2 ± 1.0	31.9 ± 0.6	2.44 ± 0.04	28.3 ± 1.2	$<10^{-6}$	$<10^{-6}$	0.0124
WM at f = 0 Hz	41.6 ± 1.1	28.4 ± 0.5	3.02 ± 0.04	28.1 ± 1.4	$<10^{-6}$	$<10^{-6}$	0.0124
GM at f = 125 Hz	34.1 ± 1.2	45.1 ± 1.0	1.90 ± 0.03	15.3 ± 0.8	$<10^{-6}$	$<10^{-6}$	0.0140
WM at f = 125 Hz	44.8 ± 1.1	46.7 ± 1.1	2.69 ± 0.04	17.6 ± 1.0	1.8×10^{-6}	1.9×10^{-6}	0.0111