A Model for SSFP FMRI

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Introduction. Steady-state free precession (SSFP) has benefits for functional MRI due to its ability to obtain contrast at short T_R (and T_E), reducing distortion and signal dropout [1-3]. Several contrast mechanisms have been proposed depending on whether imaging is performed in the pass band or transition band of the SSFP frequency profile [1-6]. We explore a static dephasing regime (SDR) model for SSFP FMRI contrast that describes the interaction of the SSFP profile with BOLD frequency dispersion. It has been suggested that the SDR model could describe BOLD-induced changes in linespread [1], but comparison with real data has been limited [5]. Here, we show that the SDR model can be extended to include changes in both T_2 and linespread during activation to encapsulate the full range of previously-reported signal behavior.

Signal Model. The SDR models the detected signal in an SSFP experiment as the theoretical signal profile blurred by the voxel linespread, as given in Eq 1, where ω_0 is the resonance frequency, S is the detected signal, M_{xy} is the theoretical SSFP signal profile, P is the intra-voxel frequency distribution (linespread) and $\otimes$ denotes cross correlation (similar to convolution). The sensitivity of SSFP to frequency means that modulations of the linespread create signal changes even at short T_E. This behavior must be modeled as a change in P, rather than as a T_2* change. We use a Gaussian distribution with changing variance (rest: P=N(σ); active: P=N(σ+Δσ)). We can also extend the model to incorporate T_2 changes (due to diffusion in the extravascular space) directly in the SSFP signal M_{xy} [6]. The SDR model was implemented in Matlab with free parameters ΔT_2, σ and Δσ. Relaxation times were assumed to be T_2/T_1=100/900 ms (1.5T) or T_2/T_1=90/1200 ms (3.0T).

Methods. Data were obtained on Siemens 1.5T and 3T scanners using balanced SSFP with a 3D stack-of-segmented EPI acquisition described in [7]. SSFP FMRI data were acquired with varying: T_R, off-resonance frequency, and flip angle. Subjects viewed a visual stimulus (15 s on/ off, 2 mins total). Following standard FMRI analysis, percent signal change was extracted from a region-of-interest (thresholded activation maps). The SDR model was fit to the data in Matlab (`nlinfit`), using a two-stage process. Initial fits had three free parameters (σ, Δσ and ΔT_2). Fitted parameters with a large 95% confidence interval were considered to be poorly constrained and were set to fixed values in a second iteration. For example, fits to multi-T_R data had reasonably-constrained fits for Δσ (CI=0.08–0.16 Hz) and ΔT_2 (CI=1.28–2.65 ms), but not σ (CI=5–26 Hz), which was subsequently set to a fixed value.

Results. Model fits to passband SSFP data at multiple T_R (α=30°, 10 subjects, details in [4]) are shown in Fig. 1b. The model fit was sensitive to Δσ and ΔT_2, but not σ. As shown in Fig. 1a, the SDR model attributes signal at short T_R to ΔT_2, corresponding to T_2 BOLD (SE-like) contrast, while signal at long T_R is a combination of ΔT_2 and Δσ, corresponding to T_2* BOLD (GRE-like) contrast. This is in good agreement with previous data showing convergence of SSFP to GRE at long T_R, but persisting contrast in SSFP at short T_R (and T_E) [4]. Figure 2a depicts the model fit to transition-band SSFP data (α=4°) at multiple off-resonance frequencies (set by changing the phase cycling increment). This fit was sensitive to the linespread terms but not ΔT_2, in agreement with previous data suggesting that the interaction of the underlying frequency distribution with the SSFP signal profile drives functional contrast in the transition band [1-2]. Figure 2b depicts the model fits to data in the pass band acquired at a range of flip angles, which was primarily sensitive to ΔT_2, in good agreement with previous data [6,8].

Discussion. The SDR model is consistent with a broad range of SSFP FMRI data, and may be useful for optimizing protocols. For example, Fig. 3 predicts that for T_R=6 ms, maximum contrast requres low flip angle near the transition band (0 Hz), but for T_R=24 ms moderate flip angle in the pass band ($0.5T_R^{-1}$ Hz) maximizes contrast. The SDR model can be easily extended to include a blood compartment. One outstanding issue is whether this model is appropriate for the motional narrowing regime, where a more Lorentzian behavior is observed.

Equation 1: $$S(\omega_0) = \int P(\omega) M_{xy}(\omega - \omega_0) d\omega = P \otimes M_{xy}$$

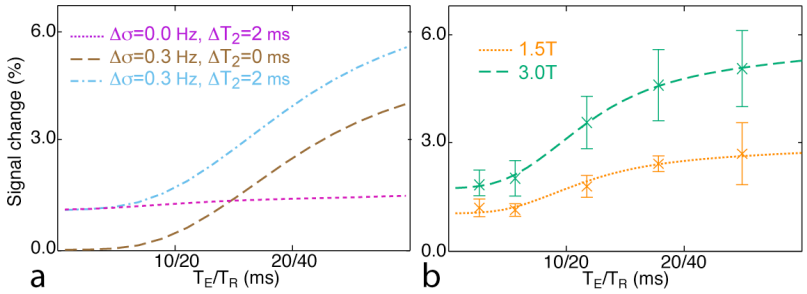

Figure 1: (a) Simulations of SSFP FMRI signal attribute signal at short T_R to ΔT_2, and a rise in signal at long T_R due to Δσ. (b) Model fits to a range of T_R (n=10, inter-subject mean ± stderr). Fixed σ=13 Hz. Fitted parameters at 1.5T: Δσ=0.13 Hz, ΔT_2=2.0 ms; at 3.0T: Δσ=0.33, ΔT_2=3.7 ms. Imaging in passband, α=30°; for other parameters, see [4].

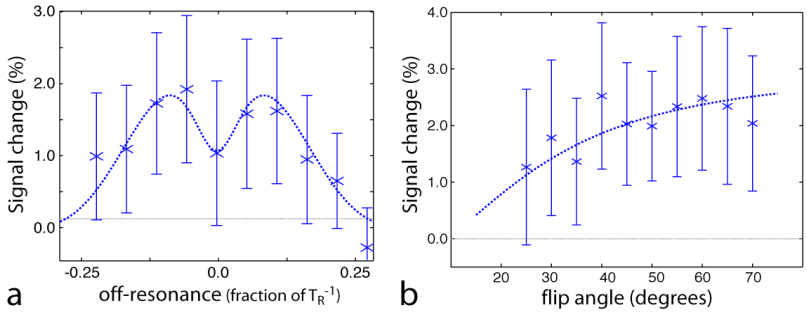

Figure 2: (a) Model fit to multi-frequency data (transition band, α=4°): ΔT_2=3.0 ms (fixed), Δσ/σ=0.31/7.1 Hz (fit). (b) Model fit to multi-flip data (pass band): ΔT_2=2.32 ms (fit), Δσ/σ=0.2/10.0 Hz (fixed). Data are from a single subject, plotted as ROI mean ± stdev. Acquisition: 3T, T_E/T_R=6/12ms, FOV=24x18x9 cm^3, matrix=80x60x30, BW=1302 Hz/pix.

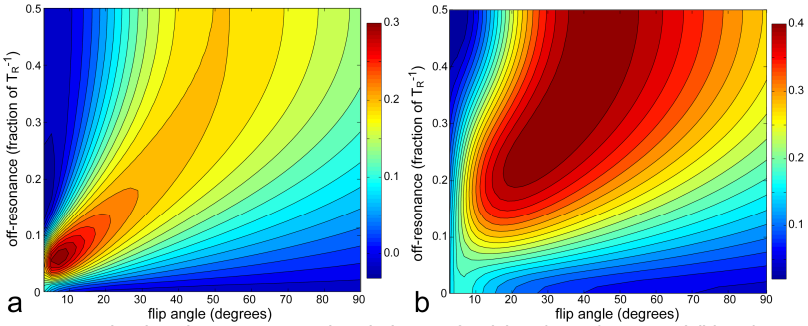

Figure 3: Simulated SSFP FMRI signal change for (a) T_E/T_R=3/6 ms and (b) T_E/T_R=12/24 ms. Simulation parameters: σ/Δσ=8.0/0.3 Hz, $\Delta T_2/T_2/T_1$=2/90/1200 ms.

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[4] Miller *NeuroImage* 2006 [5] Zhong *MRM* 2007 [6] Dharmakumar *MRM* 2005 [7] Miller *MRM* 2005 [8] Bowen *ISMRM* 2006