Steady-state functional MRI using small-tip fast recovery (STFR) imaging

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Introduction: The majority of functional brain MR imaging studies use T2*-weighted gradient-echo sequences with single-shot readout (BOLD fMRI), which can provide high activation contrast but suffers from signal loss near air/tissue interfaces and off-resonance-induced image artifacts (distortions or blurring). Steady-state fMRI based on balanced steady-state free precession (bSSFP) uses segmented readouts and can produce excellent image quality, but is susceptible to dark "banding" artifacts in regions of high B0 inhomogeneity. Small-tip fast recovery (STFR) imaging is a recently-proposed steady-state imaging sequence that is a potential alternative to bSSFP [1,2]. STFR can provide bSSFP-like image contrast, but with reduced signal variations due to resonance offsets. STFR relies on a tailored "tip-up," or "fast recovery," RF pulse to align the spins with the longitudinal axis after each data readout segment (Fig. 1(a)). The design of the tip-up pulse is based on the acquisition of a separate off-resonance (B0) map. However, it is not yet known whether STFR is suitable for fMRI, and whether the functional contrast mechanism is the same as in passband bSSFP. Here we investigate the use of STFR for steady-state fMRI, using Monte Carlo Bloch simulations and experimental observations. Our simulations indicate that the functional contrast mechanisms for bSSFP and STFR are different: Whereas contrast in bSSFP fMRI is diffusion-driven, functional contrast in STFR fMRI arises primarily from the spectral properties of the steady-state signal profile (see Fig. 1(b)). Our simulations also predict that STFR fMRI produces enhanced activation contrast compared to bSSFP fMRI, and we present experimental evidence for this in visual cortex.

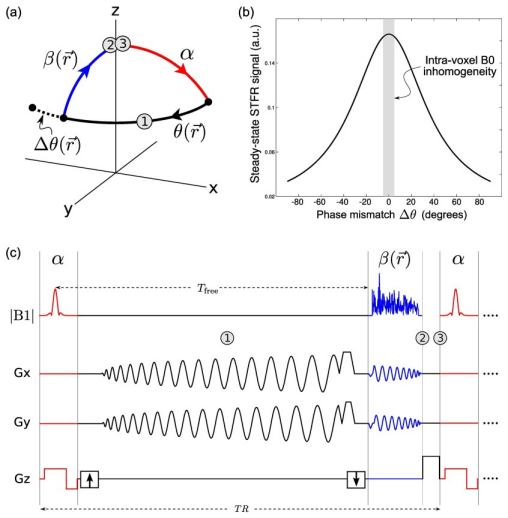

Figure 1: Small-tip fast recovery (STFR) imaging. (a) Steady-state spin path. The tip-up pulse (blue) is tailored to the local free precession angle $\theta(r)=\omega(r)T_{free}$. *In general, there will be a mismatch* $\Delta\theta(r)$ *between the tip-up phase and spin phase at end of the free precession interval. (b) Signal profile vs. phase mismatch. (c) STFR pulse sequence diagram, using a 2D spiral tip-up pulse and segmented 3D stack-of-spirals acquisition.*

Theory: Functional contrast in passband bSSFP is believed to arise from the interaction between random spin diffusion and microscopic B0 inhomogeneity [3]: During activation, blood oxygenation increases, which reduces the intra-voxel B0 inhomogeneity and hence reduces diffusion-related deviations in spin free precession angle between RF excitations. This effect can be modeled as an apparent T2 change, and may also be present in STFR given the similarities with bSSFP [1]. However, STFR offers another potential source of functional contrast: The STFR signal is sensitive to discrepancies $\Delta\theta(r)$ between the local B0 inhomogeneity and the B0 field assumed in the design of the tailored tip-up pulse (Fig. 1(a)), and hence may be sensitive to activation-induced changes in the intra-voxel B0 linespread (gray column in Fig. 1(b)).

Monte Carlo Bloch simulations: We simulated functional contrast in passband bSSFP and STFR by constructing a numerical 3D voxel model containing cylindrical vessels with random orientations, as in [3]. An example of the resulting microscopic B0 inhomogeneity is shown in Fig. 2. Spins were allowed to diffuse randomly between RF excitations, and a sufficient number of TRs were simulated to reach steady-state. We simulated both activation and rest states, under the assumption that venous blood oxygenation increases from 67 to 81% during activation [3,4]. To investigate the influence of spin diffusion on the steady-state signal, we fixed all spin locations and repeated the simulations.

Functional MRI observations: We performed high-resolution fMRI experiments with visual checkerboard stimulation and bilateral finger-tapping, using segmented stack-of-spirals imaging as shown in Fig. 1(c) (3 cm axial slab; 10 z partitions; 8 spiral kx-ky segments supporting 128x128 matrix size; FOV 24 cm; T_{free} ~ 10 msec; flip angle for STFR/bSSFP = 16°/32°). We used a GE 3T scanner with a quadrature T/R head coil. We designed a 2D tip-up pulse tailored to a 2D region-of-interest containing most of the central slice, but excluding the frontal sinus and ear canals.

Results: Figure 3 shows the simulated percent functional signal change for STFR and bSSFP, over a range of TRs and flip angles. Our simulations predict that STFR produces 3-5 fold increase in functional contrast compared to bSSFP, and that diffusion makes only a minor contribution to functional contrast in STFR (not shown). Figure 4 shows representative functional imaging results, showing not only that STFR fMRI can produce enhanced activation contrast compared to bSSFP as predicted, but also that the STFR functional maps tend to show fewer false (e.g., negative) correlations. However, we have observed variable bSSFP and STFR fMRI results across scan sessions, and the results presented here are preliminary.

Discussion and Conclusions: Monte Carlo Bloch simulations indicate that STFR fMRI can produce several-fold increases in activation contrast compared to passband bSSFP, and proof-of-concept in-vivo STFR fMRI observations using a 2D tailored tip-up pulse generally support this prediction. In the future, we plan to evaluate the feasibility of whole-brain STFR fMRI, which requires 3D tailored tip-up pulses. We expect the design of such 3D pulses to benefit greatly from parallel transmission systems, and from high-order gradient shimming.

[1] Nielsen et al, MRM 2012; [2] Heilman et al, ISMRM 2009; [3] Miller et al, MRM 2008; [4] Haacke et al, HBM 1997. *Grant support: NIH R21EB012674 and R01NS058576.*

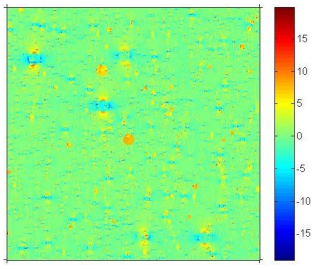

Figure 2: Microscopic B0 inhomogeneity (Hz) in the numerical voxel used in our Monte Carlo Bloch simulations. A 2D cut through the 1x1x1 mm³ voxel is shown.

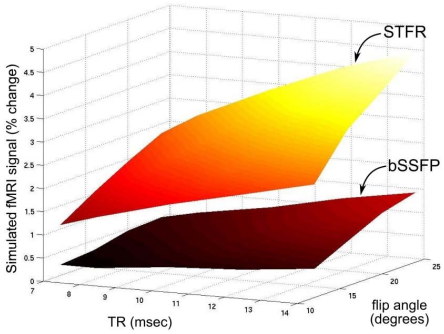

Figure 3: Monte Carlo Bloch simulation results: Percent functional signal change for STFR and bSSFP as a function of TR (7-14 ms) and flip angle (12-24° – the bSSFP flip angle is twice the value indicated). STFR fMRI is predicted to produce 3-5 fold signal increase relative to passband bSSFP.

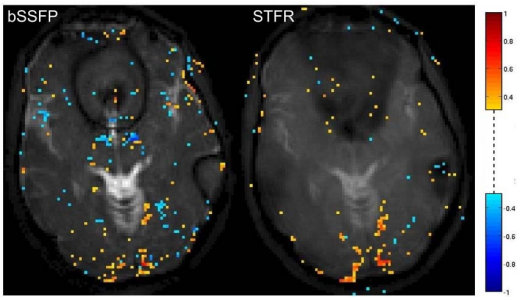

Figure 4: Comparison of bSSFP and STFR fMRI in visual cortex. Correlation values (thresholded at +/- 0.3, see colorbar on right) are overlaid on the corresponding bSSFP/STFR anatomical image. The location of activation patterns in visual cortex are generally in good agreement, but STFR tends to produce stronger correlation with the block task and fewer spurious correlations.