FMRI using high flip-angle alternating steady state balanced SSFP supported by Monte Carlo studies

S. A. Patterson[1,2], S. D. Beyea[1,3], and C. V. Bowen[1,3]
[1]Institute for Biodiagnostics (Atlantic), National Research Council Canada, Halifax, Nova Scotia, Canada, [2]Physics, Dalhousie University, Halifax, Nova Scotia, Canada, [3]Physics, Biomedical Engineering and Radiology, Dalhousie University, Halifax, Nova Scotia, Canada

Introduction The need exists for a functional MRI (fMRI) technique capable of artifact-free whole brain coverage, with good blood oxygenation level dependent (BOLD) contrast to noise ratio (CNR), and high temporal resolution. Conventional gradient echo (GRE) BOLD fMRI suffers from signal dropout in regions of magnetic field inhomogeneity, limiting coverage, while spin echo fMRI has reduced BOLD CNR and lower temporal resolution than GRE. Recently, passband balanced SSFP (pbSSFP) has attracted interest as a functional imaging technique because it can provide artifact-free whole brain coverage with good BOLD CNR [1]. However, an experimental implementation of pbSSFP fMRI with good temporal resolution has yet to be developed.

PbSSFP images contain characteristic low signal banding artifacts at specific off-resonance frequencies, with locations that can be shifted by altering the RF phase cycling increment. Hence two pbSSFP images with complementary RF phase cycling increments, termed 'on-resonance' and 'off-resonance' acquisitions, can be combined, via maximum intensity projection (MIP), to produce a single artifact-free image. Alternating between on- and off-resonance acquisitions induces transient oscillations in the MRI signal that necessitate a delay in image acquisition to avoid phase encode ghosting. Current whole brain pbSSFP fMRI implementations avoid these oscillations by acquiring a time course of on-resonance images followed by a time course of off-resonance images. However, the artifact free images thus produced consist of two images acquired several minutes apart, resulting in poor temporal resolution. To achieve temporal resolution typical of GRE based fMRI (1-5s), the paired on- and off-resonance images must be acquired sequentially by alternating between the two steady states. Further investigation is needed to determine if alternating steady state pbSSFP (altSSFP) acquisitions can maintain BOLD contrast and signal stability while providing the temporal resolution typical of GRE fMRI.

This study used a Monte Carlo model to investigate BOLD signal and contrast characteristics in altSSFP, with the goal of optimizing acquisition parameters. Simulations of RF catalyzed sequential on and off-resonance acquisitions were performed at 4T, with volume times (defined as Tvol, the time to collect both images) varying from 1-5s. Simulation results showed that BOLD contrast decreases as Tvol is decreased in altSSFP acquisitions. Interestingly, the use of higher flip angles (45-60°) than those typically used for artifact suppression in brain tissue (25-30°) produced larger and more uniform BOLD contrast with off-resonance conditions. This was observed for both altSSFP and conventional pbSSFP simulations. In summary, simulations suggest that high flip angle (45-60°) altSSFP acquisitions preserve up to 90% of the BOLD contrast observed in conventional pbSSFP acquisitions while providing good temporal resolution (2-3s volume times). This demonstrates the potential of altSSFP for fast, high CNR, whole brain fMRI acquisitions.

Methods Monte Carlo simulations [2-3] of BOLD contrast were conducted at $B_0 = 4T$. Tissue voxels ($T_1 = 1383ms$, $T_2 = 70ms$) were modeled as randomly oriented vasculature containing 2% (by volume) R = 3μm vessels. BOLD activation was simulated by an increase in blood oxygenation (Y) from .7 (resting) to .8 (active). Intravascular T_2 varied with blood oxygenation according to the Luz-Meiboom equation [4-5]. AltSSFP fMRI simulations were conducted with volume times (Tvol) ranging from 1 to 5s. Flip angles (α) of 30, 45, and 60° were explored. Normalized signal (S/M_0) and contrast ($\Delta S/M_0$) were computed for a range of off-resonance angles (θ) spanning the bSSFP signal profile. Two methods of acquiring on- and off-resonance images were simulated. The first method involved terminating the on- (off-) resonance acquisition with an α /2 flip-back pulse, crushing the remaining transverse magnetization, and commencing the off- (on-) resonance acquisition with either α /2 [6] or linear [7] catalyzation. The second method involved smoothly increasing the RF phase cycling increment by 360 degrees over the acquisition volume time [8]. In both cases several consecutive volumes were simulated before data recording to ensure a volume to volume steady state had been established.

Results and Discussion

Figure 1

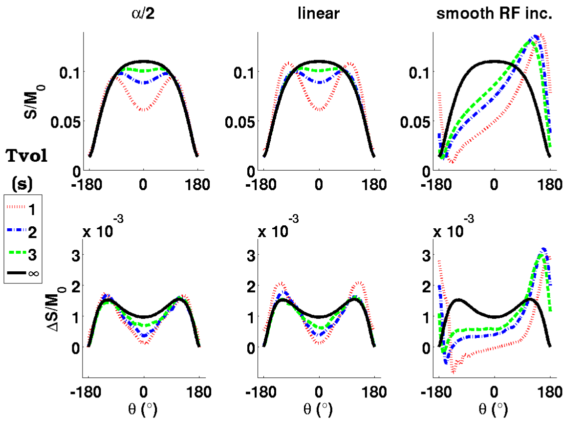

Figure 2

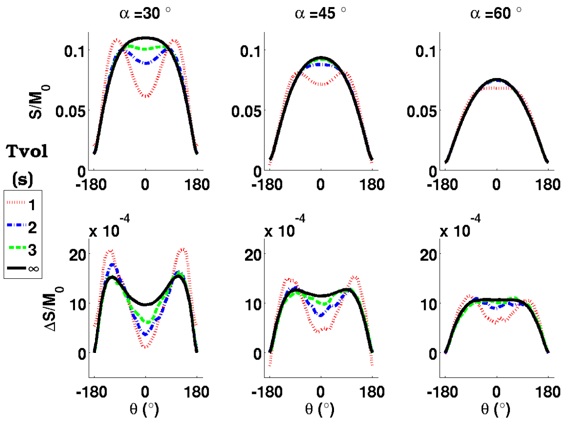

Figure 1 plots normalized signal, S/M_0, (top panels) and corresponding BOLD contrast, $\Delta S/M_0$, (directly below) as a function of off-resonance angle (θ) for altSSFP ($T_R/T_E/\alpha$ = 10 ms/5 ms/30°). Plots are shown at Tvol/2 (the end of the on-resonance RF train) for volume times (Tvol) of 1, 2, and 3s. Conventional pbSSFP is plotted for comparison (Tvol = ∞). Signal and contrast are plotted for α/2 (left panels) and linearly catalyzed (centre panels) acquisitions, along with the method of smoothly increasing the RF phase cycling increment (right panels). BOLD contrast is reduced in altSSFP and increases with Tvol. Severe asymmetries in the signal and contrast profile result from smoothly varying the RF phase cycling increment. While similar contrast profiles are produced by the α/2 and linear catalyzation methods, the linear method was better at reducing transient signal and contrast oscillations following changes in RF phase cycling increment (data not shown). **Figure 2** plots normalized signal and contrast for the linearly catalyzed simulation at 3 different flip angles (α = 30, 45, and 60°). Increasing the flip angle results in increased BOLD contrast magnitude in the passband (for short Tvol) and increased BOLD contrast uniformity throughout the passband (for all Tvol, including conventional pbSSFP). Up to 90% of the pbSSFP BOLD contrast can be preserved for 2s volume time altSSFP acquisitions when a 60° flip angle is used, compared to only 40% when the experimentally conventional 30° flip angle is used.

Conclusion To achieve sufficient temporal resolution with pbSSFP fMRI, alternating between two steady states to eliminate banding artifact is necessary. Monte Carlo simulation results suggest altSSFP can provide artifact-free whole brain coverage with 2-3 s temporal resolution and up to 90% of the BOLD contrast observed in conventional pbSSFP, if the correct imaging parameters are chosen. Recommended acquisitions involve 1) altering the RF phase cycling increment by 180° halfway through the acquisition, followed by use of a linearly increasing flip angle catalyzation to minimize signal fluctuations 2) using flip angles between 45 and 60° and 3) encoding the centre of k-space late in the data acquisition train. These parameters are anticipated to produce spatially-uniform sensitivity fMRI maps (see flat contrast vs. off-resonance angle (frequency) in fig. 2, α = 60°), despite up to 30% signal variation following MIP post processing due to off-resonance signal intensity variation.

References

[1] Lee MRM 2008; 59:1099 [2] Boxerman MRM 1995; 34:555 [3] Miller MRM 2008; 60:661 [4] Dharmakumar MRM 2005; 53:574
[5] Duong MRM 2003; 49:1019 [6] Deimling 2nd ISMRM, 1994; p495 [7] Deshpande MRM 2003; 49:151 [8] Foxall MRM 2002; 48:502