Monte Carlo Simulations of Phase Cycled pbSSFP fMRI Acquisitions

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Introduction: Recently, Pass-Band balanced-Steady State Free Precession (pbSSFP) sequences have been applied to Functional Magnetic Resonance Imaging (fMRI) [1-4]. These approaches have attracted interest because of resistance to magnetic susceptibility artifacts while maintaining good functional Contrast to Noise Ratio (CNR). Experimental studies using pbSSFP fMRI have reported reduced sensitivity to physiological noise [3] and large vessel suppression [1] when compared to matched T_E/T_R gradient echo sequences. Computer simulations investigating the pbSSFP contrast mechanism indicate that this increased neurovascular coupling results primarily from a larger diffusion contribution to contrast [5].

Despite numerous advantages, however, pbSSFP remains impractical as a whole brain fMRI technique because of limitations in temporal resolution. The removal of magnetic susceptibility artifacts with pbSSFP requires the acquisition of both on and off-resonance images, which are then combined in post processing, to produce a single artifact-free image. Phase cycling from on to off-resonance induces transient oscillations in the MRI signal which produce phase encode ghosts, preventing image acquisition for up to 3 seconds, for typical T_2/T_1 ratios in the human brain, until the signal re-stabilizes. This transient time must be reduced for pbSSFP to be pragmatic for fMRI studies. While specialized preparation sequences called catalyzation trains [6,7] have been shown to reduce the duration of signal oscillations in phase cycled pbSSFP anatomical images, the effects of catalyzation on functional CNR in pbSSFP fMRI has not been investigated.

This study used a Monte Carlo model to explore the signal and BOLD contrast behavior in phase cycled pbSSFP fMRI acquisitions. The transient signal behavior and functional contrast development were explored for different catalyzation trains and inter-acquisition delays permitting signal recovery. Simulation results show that functional contrast is reduced in phase cycled acquisitions. However, this contrast increases during the RF pulse train and for T_E/T_R ratios approaching unity, suggesting acquisition of the contrast encoding k-space centre late in the pbSSFP pulse train, and with large T_E/T_R ratio, to optimize functional CNR.

Methods: Simulations of pbSSFP acquisitions at $B_0 = 4T$ were conducted using Monte Carlo methods [8,9]. Grey matter voxels were modeled as randomly oriented vasculature consisting of 2% (by volume) R = 3μm vessels and 3% R = 100 μm vessels [9]. Activation was simulated by an increase in blood oxygenation from Y = .67 (resting) to Y = .75 (active) [10]. Functional contrast ($\Delta S/M_0$) was separated into that originating from susceptibility induced field offsets (F), water proton diffusion (D), and intra-vascular T_2 changes (T_2), with total contrast being that from all effects combined (FDT_2) [5]. Sequentially acquired on and off-resonance images were explored using both α/2 [6] and linear [7] catalyzation schemes ranging in length from 20 to 60 RF pulses. A single on (off) resonance acquisition consisted of the catalyzation train, followed by a 65 pulse pbSSFP sequence (α = 30°, T_R = 10ms), an α/2 flip-back with subsequent gradient spoiling of transverse magnetization, and an inter-acquisition delay that was varied between 0 and 1000 ms. These parameters are representative of a 2 shot spiral readout acquisition having 32 slices and two phase cycled acquisitions with 2.5s/volume. Several on and off-resonance images were simulated in this fashion to ensure an image to image steady state had been reached.

Results/Discussion:

Figure 1

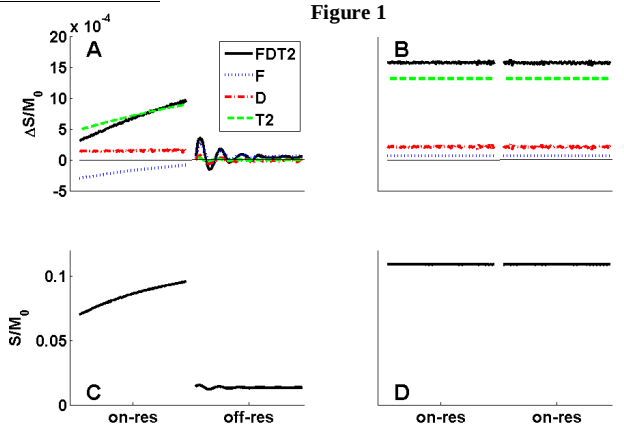

Figure 2

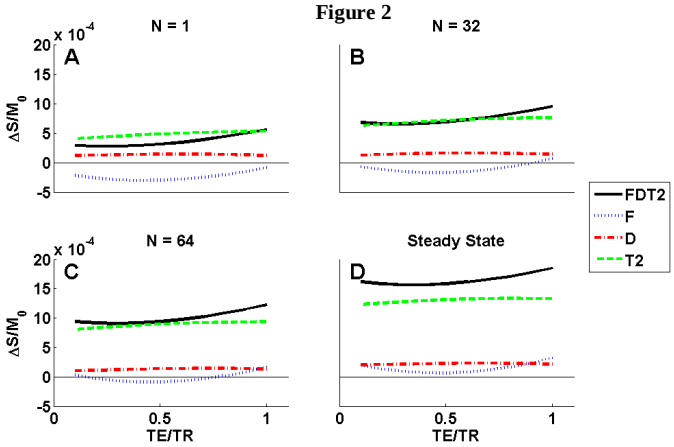

Figure 1 (a) and (c) show the contrast and signal, respectively, in phase cycled pbSSFP acquisitions ($T_E = T_R/2$) as a function of RF pulse number. Data shown is for an α/2 +59 α pulse catalyzation train with no inter-acquisition delay. The contrast and signal during catalyzation are not shown. For comparison, the steady state contrast (b) and signal (d) during an on-resonance acquisition are shown. Total contrast is reduced in phase cycled acquisitions (compare FDT_2 in (a) to that in (b)). However, this reduced contrast increases steadily during the data acquisition window, eventually reaching 2/3 of that achieved in full steady state. This suggests late centered k-space acquisitions be employed when acquiring phase cycled images to maximize functional contrast. The diffusion contribution to contrast reaches a steady state sooner than the T_2 and F contrast mechanisms. Since enhanced neurovascular coupling is derived from diffusion sensitivity, phase cycled acquisitions should not suffer any loss in neurovascular coupling when compared to images acquired in the steady state.

Figure 2 shows the relative contributors to pbSSFP fMRI contrast as a function of acquisition time, T_E, within a T_R cycle, during various stages in the data acquisition RF pulse train of Fig. 1. Figure 2 a, b and c show the functional contrast after the 1st, 32nd, and 64th RF pulse, respectively, while Fig. 2d shows the functional contrast in the fully developed steady state. At all stages in the RF train, the diffusion contribution to contrast is seen to be independent of T_E. This suggests that temporal resolution optimized spiral-SSFP acquisitions with $T_E \neq T_R/2$ would not sacrifice the favorable neurovascular coupling resulting from diffusion enhanced sensitivity of pbSSFP fMRI acquisitions. Additionally, a 30% improvement in CNR might also be expected for acquisitions with T_E approaching T_R compared to those with $T_E = T_R/2$.

Conclusion: Functional contrast in phase cycled pbSSFP fMRI acquisitions is reduced from its steady state value but steadily increases along the RF pulse train, reaching 2/3 of the steady state value for a 2.5s volume time acquisition. This suggests encoding the centre of k-space late in the RF train to maximize functional contrast. The diffusion component of contrast develops early in the pbSSFP RF train and is independent of T_E throughout it. As a result, phase cycled pbSSFP fMRI acquisitions should provide good or better neurovascular coupling than observed now with steady state acquisitions. Furthermore, temporal resolution optimized spiral acquisitions with T_E approaching T_R can be used in phase cycled pbSSFP fMRI to augment CNR as much as 30%, without sacrificing neurovascular coupling.

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