Impact of TE on Short-TR Pass-band b-SSFP BOLD Contrast at 3T

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Introduction Pass-band balanced steady-state free precession (pbSSFP) sequences have been shown to be sensitive to BOLD fMRI free of susceptibility artifacts such as signal dropout and image distortion commonly seen in gradient-echo EPI [1]. Although the contrast mechanisms have not been thoroughly understood, it is believed that susceptibility induced field inhomogeneity, water proton diffusion in susceptibility-induced field gradients, and intra-vascular T2 changes all contributed to the final complicated pbSSFP BOLD contrast [2]. These mechanisms may independently contribute to the final BOLD contrast in pbSSFP sequences. Long-TR/TE pbSSFP is believed to have strong T2*W component similar to traditional gradient echo sequences and short-TR/TE pbSSFP is dominated by T2W contrast. It has been shown that bSSFP can fully refocus off-resonance frequencies ranging between ±1/(2TR), and shows a linearly increasing T2* sensitivity for varying TRs around TR/2 [3]. A recent Monte Carlo simulation of phase-cycled pbSSFP fMRI predicted a 30% improvement in CNR in large TR/TR ratio sequences compared to those with TE/2TR [4]. However, no experimental data have been presented so far to show the impact of TE in short-TR pbSSFP sequences mainly due to technical challenges.

In this study, we employed high bandwidth readout in combination with highly sensitive surface coil to acquire multiple echoes with a large TE distribution to investigate the impact of TE on pbSSFP BOLD contrast at relatively short TR regime (TR<10ms).

Methods Three healthy volunteers underwent fMRI on a 3.0 T clinical MR scanner (Philips Achieva) using a 6.0 cm circular surface coil positioned close to human visual cortex. A single quasi-coronal slice transsect visual cortex was acquired using a multi-echo 2D b-SSFP sequence. The sequence employed EPI type of gradient scheme to achieve fast data acquisition with high readout bandwidth. Local high order shimming was performed before b-SSFP dynamic data acquisition. Imaging sequence parameters include: TR/FA=9.8ms/35º, acquisition spatial resolution =1.5x2.4x5.0mm, NSA = 4, and readout bandwidth = 128 kHz. 11 echoes were acquired with TE=1.0+n*0.59 ms (minimum/center/maximum TE=1.59/4.5/7.5 ms). Sequence temporal resolution = 3.0s. fMRI studies were performed with visual stimulus (10 Hz flickers) and a paradigm of 30 s stimulus off, followed by three testing cycles (30s stimulus on/30s stimulus off). Multiple measurements were acquired on each subject. MR activation map was analyzed using FSL (FMRI Software Library, FMRIB, Oxford, UK), activated clusters were thresholded with Z>1.6 and cluster size threshold P<0.05. Percentage pbSSFP signal changes were calculated at 80% of the maximal values.

Results A consistent trend of increasing BOLD response with increasing TE was observed as shown in Figure 1. The BOLD percent increased from about 4% at TE~1.6 ms (echo number 1) to about 6% at TE~7.5 ms (echo number 11). In addition, the overall number of activated pixels also increased with increasing TE. The number of activated pixels at the same statistical threshold almost doubled at the longest TE compared to shortest TE (Figure 2), indicative of improved functional contrast.

Discussion Previous studies have focused on the contrast mechanisms of relatively long-TR pbSSFP, which is less commonly used in fMRI studies due to potential banding artifacts. We employed a fast pulse sequence to acquire multiple echoes with a large range of TE in a short-TR pbSSFP sequence. This design excluded possible variations due to motion and physiological noise if separate experiments were performed for each TE. We found that although a small TE/TR ratio resulted in about ~4% BOLD fMRI response in short-TR pbSSFP, a large TE/TR ratio increased BOLD sensitivity, in agreement with an earlier Monte Carlo simulation [3].

In addition, images with TE/2TR did not show obvious contamination from physiological noises in the current experimental setup. This can be partially explained by the inherent insensitivity to such noise in short-TR pbSSFP. In the current study, all images were acquired under well-established steady-state of bSSFP. In segmented phase-cycling b-SSFP fMRI studies, sensitivity to BOLD contrast due to susceptibility frequency offset is compromised during transient phases. Its sensitivity to BOLD relies more on the T2*W component rather than the T2W one when compared to non-segmented pbSSFP. Therefore, using a large TE/TR ratio is relatively more important to achieve high BOLD sensitivity in segmented pbSSFP. Overall, k-space trajectories leading to larger TE (e.g., reverse partial Fourier readout, spiral-in trajectory, and “out-in” radial readout) have advantages in pbSSFP fMRI studies to obtain high BOLD sensitivity.

Conclusion By using a large TE/TR ratio (i.e., TE/TR ratio approaching unity) in short-TR pbSSFP sequence, BOLD contrast sensitivity can be improved compared to the traditional pbSSFP sequences with TE/TR<0.5. Therefore, k-space trajectories leading to larger TE should be used to enhance pbSSFP BOLD sensitivity at 3T.