Characterization of passband SSFP FMRI: A comparison with GRE at multiple field strengths

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INTRODUCTION. Balanced steady-state free precession (SSFP) has recently been proposed for functional MRI (FMRI) [1-3]. The goal is to obtain functional contrast that does not rely on long-T_E GRE, and is therefore relatively immune to the B_0 artefacts found in GRE BOLD. Two general classes of methods have been explored: transition-band SSFP attempts to detect the deoxyhaemoglobin frequency shift directly [1-2], while passband SSFP is believed to detect more BOLD-like signal changes [3]. In a previous work, we used matched GRE and SSFP acquisitions to investigate the signal and noise characteristics of the transition-band SSFP signal; this study applies the same approach to passband SSFP, where the source of functional contrast has been a recent topic of debate [5-7]. Here, GRE is exactly matched to SSFP, except that the GRE contains no banding, and exhibits the familiar T_2* BOLD contrast..

METHODS. Ten human subjects were studied on Siemens 1.5T and 3T scanners (5 subjects at each field). Images were acquired using 3D stack-of-segmented EPI [4]. Imaging gradients are refocused, and then followed by an optional spoiling gradient that converts the sequence between balanced SSFP (spoiling off) and GRE (spoiling on). Subjects were scanned during visual stimulation using GRE and SSFP protocols at five T_R (7, 13, 25, 36 and 50 ms, T_E=T_R/2, ≈3 s/vol). Flip angle was chosen to achieve a maximally flat SSFP passband (α=30º). Shim was targeted to the occipital lobe to minimize banding in visual cortex. Subjects were shown a visual stimulus (flashing checkerboard) for four blocks of 15 s preceded by 15 s of rest. Following standard FMRI, each subject's data were aligned and a region-of-interest (ROI) defined by thresholding the mean *z*-statistic across all runs (z≥3.0). Functional CNR and percent signal change were calculated within each subject's ROI. The functional contrast was modeled as the signal change (%) between active and resting states using Scheffler's equations for SSFP in the static dephasing regime [8], with a Gaussian linespread of variance σ^2, and activation parameters ΔT_2 and $\Delta\sigma$ (1.5T: $T_1/T_2/\Delta T_2$=900/80/2 ms, $\sigma/\Delta\sigma$ =8/0.12 Hz; 3T: $T_1/T_2/\Delta T_2$=1200/110/4 ms, $\sigma/\Delta\sigma$ =9.5/0.19 Hz).

RESULTS. Figure 1a shows example activation maps overlaid on the mean time-course images. The SSFP images exhibit banding in the frontal lobe due to the targeted shim. Activation for GRE and SSFP is very similar at long T_R, but at short T_R only the SSFP map shows significant activation. This pattern is also shown in Fig. 1b and 1c, where the contrast (percent signal change) is similar for the two methods at long T_R but diverges at short T_R. The GRE signal tends toward zero at T_R=0, whereas the SSFP signal has non-zero signal change at short T_R. Although the difference between SSFP and GRE at short T_R is subtle, it is also highly significant (paired t-test across subjects). The CNR of SSFP is considerably higher at short T_R (Fig 1d, similar results at 1.5T, not shown). This is related to the high SNR efficiency of SSFP, which is one of the major benefits of this technique. The SSFP contrast model is in excellent agreement with the data (Fig. 1e), Here, the shape of the curve at short T_R is primarily determined by the choice of ΔT_2, while the dephasing parameters (σ and $\Delta\sigma$) effect long T_R.

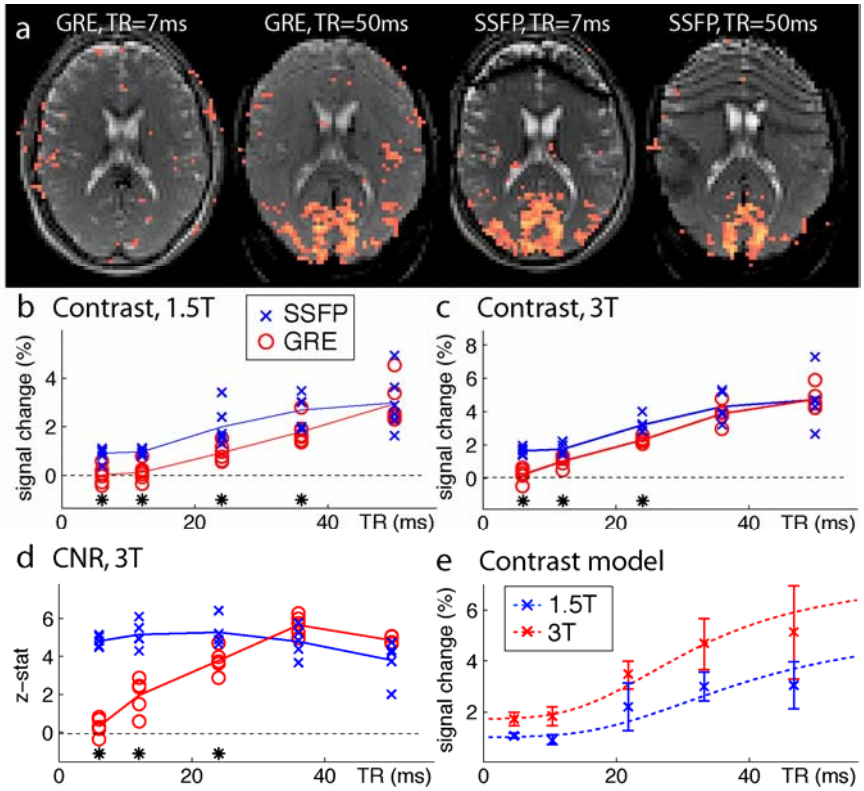

FIGURE 1. (a) Example activation maps. (b,c) Contrast (% signal change) at 1.5T and 3T, and (d) CNR at 3T. Each point is the mean of one subject's ROI. Asterisks indicate significant differences between SSFP and GRE (paired t-tests, p<0.01). (e) SSFP contrast model (dashed) with group results (e.g., SSFP data from (b,c) plotted as mean ± stdev).

DISCUSSION. Previous work in passband SSFP has variously attributed contrast to apparent T_2 changes [5], diffusion effects [6], and T_2* BOLD [7]. Given the match in functional contrast with GRE, our data are consistent with T_2* BOLD in both sequences at long T_R. This effect is supported by previous work [7], which only explored the long-T_R regime. At short T_R, SSFP functional contrast does not tend to zero. The most likely source of functional contrast at short T_R is T_2 BOLD from the SSFP stimulated echo pathways. Inflow could influence these results, but our data should be fairly insensitive to inflow due to the low flip angle, short T_R and choice of slices at the center of the 3D slab. These findings are consistent with the multi-flip-angle study of Bowen and colleagues at short T_R [6], who attributed it to diffusion around deoxygenated vessels (i.e., T_2 BOLD). A similar mechanism has been predicted and verified for whole blood [5]. Thus, our data seem to indicate that SSFP functional contrast transitions from a T_2 effect at short T_R to a T_2* effect at long T_R. This mechanism is consistent with previous studies, which initially appear contradictory, and with existing models for SSFP signal in the static dephasing regime [8].

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[1] Scheffler et al *NMR Biomed* 2001 [2] Miller et al *MRM* 2003 [3] Bowen et al *ISMRM* 2005 [4] Miller et al *MRM* 2005
[5] Dharmakumar et al *MRM* 2005 [6] Bowen et al *ISMRM* 2006 [7] Zhong et al *ISMRM* 2006 [8] Scheffler & Hennig *MRM* 2003