Characterization of SSFP FMRI signal and noise: 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). The frequency sensitivity of the SSFP signal is used to detect changes in deoxyhemoglobin concentration [1-2]. The goal is to obtain BOLD-like functional contrast that does not rely on long-T_E GRE, and is therefore relatively immune to the image distortion and signal dropout found in GRE BOLD. While it has been argued that functional contrast in SSFP is based on the direct interaction of deoxyhemoglobin frequency shifts with the SSFP signal "bands", the source of signal changes has yet to be investigated in depth. It is likely that other sources of functional contrast contribute to SSFP signal changes, including T_2 or T_2* dephasing (traditional BOLD contrast), as well as CPMG-like exchange dynamics [5]. The frequency-dependent signal modulations that create functional contrast in SSFP are also sensitive to physiological sources of field drift [3-4], creating the potential for increased physiological noise. In this work, we attempt to clarify some of these issues by characterizing the functional signal components in both GRE and SSFP at short T_R over three field strengths. Here, short- T_R GRE can be though of as matched to SSFP in all senses (including T_2/T_2* BOLD contrast), except that GRE contains no SSFP signal band [6]. A secondary goal was to evaluate low flip angle SSFP for FMRI at high field, which might be useful due to low SAR and reduced image distortion.

EXPERIMENTS. 15 healthy human subjects were studied on Siemens 1.5T, 3T and 7T scanners (5 subjects at each field). Images were acquired using 3D stack-of-segmented EPI [3]. 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 two T_R (12 and 36 ms) spanning a useful range for SSFP. Flip angle was chosen to maximize SSFP contrast (α=4º/7º for T_R=12/36 ms, about half the Ernst angle), and the echo time was T_E= T_R/2 . For each protocol, three 2-minute runs were acquired, for a total of 12 runs per subject. Following standard FMRI analysis (without smoothing), each subject's data was aligned and a region-of-interest (ROI) defined by thresholding the mean *z*-statistic across all runs (*z*>2). Thermal SNR, functional CNR, signal change (ΔS) and timeseries noise (η) were calculated within each subjects' ROI.

RESULTS. Figure 1 shows results of the ROI analysis. SNR was significantly higher in SSFP than in GRE, as expected in the high-signal SSFP bands, although the difference was less pronounced at 7T. The signal change (ΔS) in SSFP was found to be significantly higher at 1.5T and 3T, but the methods have essentially converged at 7T. This may reflect the increasing dominance of T_2* BOLD contrast in balanced SSFP as either T_E or field strength increase. Timeseries noise (η) is also observed to exhibit significant field-strength dependence, with SSFP noise increasing more rapidly with field strength than GRE noise. This is likely to represent a stronger sensitivity to physiological noise in SSFP, such as field-dependent respiratory drifts [4]. The CNR reflects a combination of ΔS and η, favoring SSFP at low field due to greater signal contrast, and GRE at high field due to lower noise.

DISCUSSION. Each pair of GRE-SSFP experiments indicates whether the presence of the SSFP signal bands improves functional contrast or introduces noise; in general both occur, and the CNR reflects the resulting balance. At low and medium field, SSFP has higher contrast (ΔS), indicating that SSFP contrast results in part due to the presence of SSFP bands. As field strength increases, the timeseries noise η also increases. The SSFP images at 7T with long TR exhibit less banding than at low field, which may indicate that the signal is only partially in the balanced SSFP condition. In this case, the presence of SSFP bands may simply introduce instability to the signal. Interestingly, although these results suggest that SSFP may not be well-suited to 7T, they also demonstrate that robust GRE signal can be acquired at high field even with low flip angle (4-7º) and short TR (12-36 ms). Prospective noise reduction methods for SSFP have been explored [4], and may be able to reduce timeseries noise, so that SSFP is more viable at medium field strengths. Caution should be taken in applying these results to conventional GRE BOLD since the protocols used in this study were optimized for SSFP.

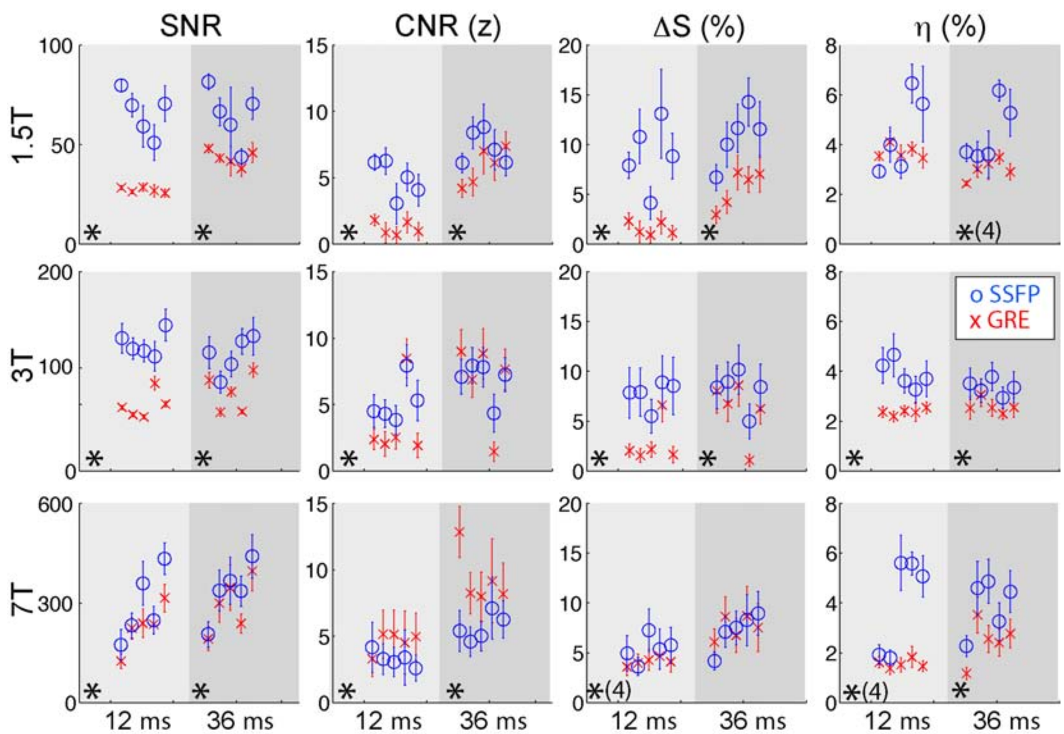

FIGURE 1. Individual subject results (mean±stdev) within the ROI for each condition (SSFP vs GRE, 12 vs 36 ms TR). SNR is the mean signal to noise ratio; CNR is the functional contrast-to-noise ratio (z statistic); CNR reflects the ratio of ΔS (signal change) to η (FMRI timeseries noise). Significance ($p<0.001$) is indicated by an asterisk (and a cardinality if a subset passed significance). No asterisk indicates that less than half of subjects were significant, or that significant but contradictory results were found.

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