Improving contrast to noise ratio of resonance frequency contrast images (phase images) using bSSFP

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Introduction

Recent MRI studies have exploited subtle magnetic susceptibility differences between brain tissues to improve anatomical contrast and resolution. These susceptibility differences lead to resonance frequency shifts which can be visualized by reconstructing the signal phase (phase imaging) in GRE [1]. In this work, a new bSSFP based method that significantly improves the CNR efficiency of phase images has been evaluated at 3 T and 7 T as well as by computer simulation. The results show substantially improved CNR efficiency (2.85 ± 0.21 times at 3 T and 1.71 ± 0.11 times at 7 T) compared to the GRE data in a limited spatial area.

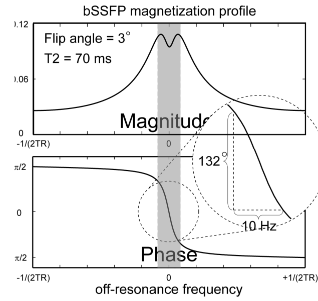

Fig. 1 balanced SSFP profiles for a small flip angle (3°)

Methods

In bSSFP, a large phase transition over a narrow frequency band occurs near the resonance frequency (the shaded area in Fig. 1). If a small frequency difference between different tissue types (*e.g.*, gray and white matter) exists over this phase transition frequency band, it will create a substantial contrast in the phase image. Hence, bSSFP can provide significant phase amplification for acquisitions with a short TE. In addition, the high SNR of bSSFP makes it uniquely suitable for the detection of frequency differences between tissue types.

Ten subjects (five for 3 T and five for 7 T) were scanned (IRB-approved). The scan parameters were optimized for GRE and SSFP separately. At 3 T, a 3D acquisition was used for both GRE and bSSFP whereas a single slice was acquired at 7 T. For GRE, the TE and the duration of the readout were approximately matched to the average T_2^* of brain tissues (45 ms for 3 T and 30 ms for 7 T). The TRs (66.8 ms at 3 T and 50 ms at 7 T) were well below T_1 and chosen to reduce scan time and decrease the effects of drift and instabilities. Flip angles were set to the Ernst angles (18° for 3 T and 14° for 7 T). For bSSFP scans, the TR was set to 10 ms and the readout duration and acquisition BW were chosen to fully utilize available time to maximize SNR. The choice of SSFP TE (4.5 ms at 3 T and 4.8 ms at 7 T) was not critical as it does not change bSSFP profile significantly. The flip angle was set to 3° to optimize the signal near the on-resonance frequency. The scan time was 6.68 times longer with GRE (400.8 sec) compared to bSSFP (60 sec) at 3 T and 5 times longer with GRE (72 sec) at 7 T compared to bSSFP (14.4 sec). Other parameters such as FOV, resolution, and slice thickness were the same in both GRE and bSSFP. At 7 T, multiple flip angles were acquired both in GRE and bSSFP to avoid suboptimal SNR due to B_1 inhomogeneity and inaccurate flip angle calibration. Due to unpredictable field drift, data at five different center frequencies each shifted by 3 Hz were acquired for bSSFP (7 T only). Only one center frequency was used for CNR comparison. This multi-CF acquisition is not necessary if drift is compensated in real-time [2]. First order shimming was targeted to visual cortex for 3 T and sensory motor area for 7 T. Real time shimming was used at 7 T to reduce respiration effects [3].

Computer simulation was performed to investigate the characteristics of the bSSFP phase imaging method. Several properties such as phase CNR change over frequency shifts, off-resonance frequency, and flip angle have been simulated and compared to GRE.

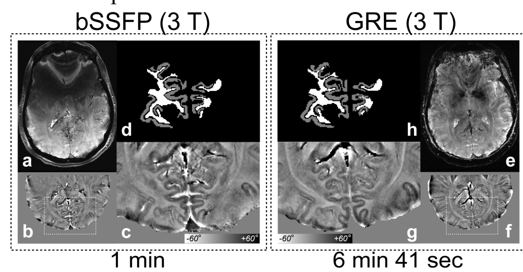

Fig. 2 bSSFP vs GRE at 3 T. (a) bSSFP magnitude, (b-c) phase and (d) ROI; (e) GRE magnitude, (f-g) phase and (h) ROI. The CNR efficiency is 2.85 times larger in bSSFP

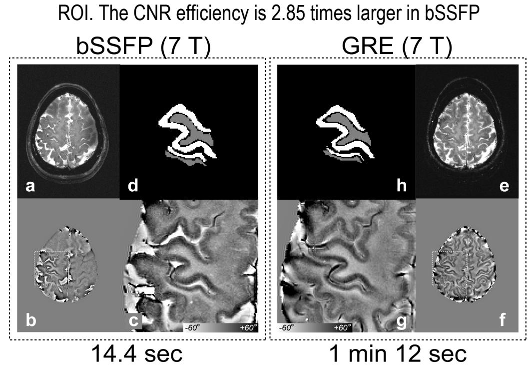

Fig. 3 bSSFP vs GRE at 7 T. a) bSSFP magnitude, (b-c) phase and (d) ROI; (e) GRE magnitude, (f-g) phase and (h) ROI. The CNR efficiency is 1.71 times larger in bSSFP

Results

Sample bSSFP and GRE images at 3 T are shown in Fig. 2. The posterior side of brain where shim was targeted shows high signal intensity in the bSSFP magnitude image and the phase image shows strong phase contrast (0.443 ± 0.062 rad averaged over all subjects) between the GM and WM (TE = 4.5 ms). This is larger than that of the GRE at TE = 45 ms (0.386 ± 0.045). Hence it demonstrates the phase amplification effect at the transition band of bSSFP. The CNR efficiency (that took into account the different scan time) was 2.85 ± 0.21 higher in bSSFP compared to GRE. This is slightly below the 3.5-fold improvement predicted by the simulations. At 7 T, the CNR effciency advantage of the bSSFP method was reduced but still significant (1.71 ± 0.11) (Fig. 3). The gain is smaller than the 2.8-fold improvement expected by the simulations. The discrepancy may originate from deterioration of bSSFP performance due to residual B_0 variability related to drift and respiration. CSF shows large negative phase only in bSSFP. This is attributed to a long T_2 of CSF that makes the bSSFP phase transtion extremely steep, magnifying frequency contrast. This effect helps to distinguish the gray matter and CSF boundary better in the bSSFP images. The simulation shows approximately 4 Hz (8 Hz) BW for a 1.4 Hz (4 Hz) frequency shift at 3 T (7 T). At each technique's optimal flip angle, sensitivity of CNR to B1 variatins was similar. Assuming a 50 % variation from the optimum flip angle, the minimum CNR in bSSFP is 82% of the maximum whereas it is 79% in GRE.

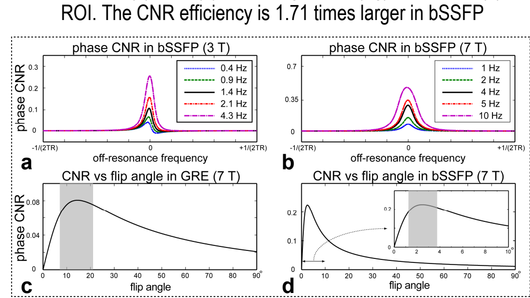

Fig. 4 Computer simulation. (a, b) phase CNR as a function of off-resonance and frequency shift, (c, d) flip angle dependence

Discussion

One drawback of the proposed method is the limited spatial coverage due to its restricted dynamic range. The phase amplification effect only occurs over a small frequency range, outside of which the contrast is strongly reduced. Off-resonance due to macroscopic susceptibility variations and/or imperfect shimming may severely limit the extent of the region with optimal contrast. A number of methods such as higher order shim, local shim, new shim algorithm, B_1 shimming [4] may be applied to improve the spatial coverage. It is also possible to use multiple shifted center frequency scans to improve the spatial coverage, albeit at the expense of CNR efficiency.

References [1] Duyn, PNAS, 2007, p11796 [2] Lee, MRM, 2006, p1197 [3] van Gelderen, MRM, 2007, p362 [4] Heilman, ISMRM, 2009, p251