Phase information in transition-band SSFP fMRI (BOSS fMRI)

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Introduction

Until recently, the task-correlated phase signal change in fMRI has been ignored in the data analysis. Only in a few studies has this phase data been utilized, assuming that it is restricted to large veins [1,2]. However, in transition-band SSFP (BOSS) fMRI, the task-correlated phase signal change has been considered to be a primary source of the functional contrast [3]: the BOLD induced frequency shift creates large phase signal changes due to a sharp phase transition (π over a few Hz) near the resonance frequency. In a preliminary experiment [4], we reported that the number of phase activation was comparable to that of the magnitude. Here, we investigate the characteristics of the task-correlated phase signal change in SSFP fMRI. Both high-resolution (1 mm^3) experiments and computer simulations were performed to explore the properties of this phase activation.

Simulation and Experiment

The transition-band SSFP fMRI is based on a bulk frequency shift induced by a fractional oxygen saturation change of blood. If a cylindrical vessel is assumed, this frequency shift is defined as follows: $\Delta f_{iv} = \gamma Hct\Delta\chi(1-Y)B_0(\cos^2\theta - 1/3)$, $\Delta f_{ev} = \gamma Hct\Delta\chi(1-Y)B_0(R/r)^2\sin^2\theta\cos(2\varphi)$ [2]. If a voxel contains n independent veins, the magnetization of the voxel becomes

$$M = (1-\alpha)\mathrm{P}(f_{off}) + \sum_{i=0}^{n}\int_{\alpha_i}\mathrm{P}(f_{off}+\Delta f_i)d\alpha_i$$

where α is the total volume (including extra-vascular) of all veins, f_{off} is the off-resonance frequency, α_i is the volume of the i^{th} vein, Δf_i is the frequency shift induced by the i^{th} vein in the $d\alpha_i$ space, and P is the SSFP magnetization profile. Based on these equations, the off-resonance, TE, vessel orientation and field strength dependencies were investigated by simulations. Two different voxels (1 mm³ each) were modeled: 1) a voxel with a single large vein (R = 0.4 mm or 60 µm, Y from 0.61 to 0.73), and 2) a capillary voxel consisting of small veins (R = 4 µm, Y from 0.77 to 0.85) distributed by 0.5sinθ, and occupying 2% of the voxel. The default simulation parameters were B_0 = 1.5 T, θ = 0º, TR/TE = 15 ms/7.5 ms, FA = 5º, T1/T2 = 780 ms/80 ms (specified in the Results section if different).

For the experiment, a 1.5 T GE EXCITE system was used with a 3-inch surface coil (except for T1 reference scans). To identify the locations of large vessels, a high-resolution venogram (16 cm^2, 0.5 x 0.5 x 1 mm^3, TR/TE = 70 ms/40 ms, FA = 25°, NEX = 12) was obtained using a venogram sequence. For the SSFP fMRI studies, a 3D spiral sequence, (16 cm^2, 1 mm^3, TR = 15 ms, FA = 5°, interleaves = 10, 16 ~ 18 slices, 5 subjects) was utilized to cover a volume every 3 sec. The stimulus was a flashing checkerboard (15'' on/off for 2' 18''). The magnitude and phase data were processed individually to create "magnitude" and "phase" z-score maps using FEAT FSL ($p < 0.01$).

Results and Discussion

1) Off-resonance: A single large vein (R = 0.4 mm, $\theta = \pi/6$) reveals a 2.2 Hz frequency shift and maximum 50% and 0.60 rad signal changes (intravascular, Fig. 1a). The capillary voxel revealed about a 2% magnitude and a 0.013 rad phase change (Fig. 1b). The magnitude and phase activation profiles showed different off-resonance sensitivity.

2) TE: The contrast levels are relatively uniform throughout the readout period, and large functional contrasts exist even at TE = 0 (Fig. 1c) because the SSFP profile does not change much over TEs. These results were expected and considered to be a major benefit of SSFP fMRI; it does not require a long echo time to acquire functional contrast.

3) Vessel orientation: The intra- and extravascular phase activation on different vessel orientations (R = 60 µm, $0 \le \theta \le \pi$) were simulated over a range of off-resonance frequencies (Figs. 1d,e). The intravascular phase signal decreased as the angle increased from 0 to 0.96 and became negative from 0.96 to $\pi/2$. In the extravascular case, the phase signal increased (both positively and negatively, depending on the off-resonance) as the angle increased to $\pi/2$.

4) Field strength: The maximum activation levels and the FWHM off-resonance coverage of the intravascular phase signals were plotted over 0.5 T to 7 T (the single vein case, Fig. 1f). The intravascular phase signal change begins to saturate as the field strength increases because the phase transition provides a π phase shift over a narrow frequency band; once the frequency shift becomes larger than this band, the phase change is saturated.

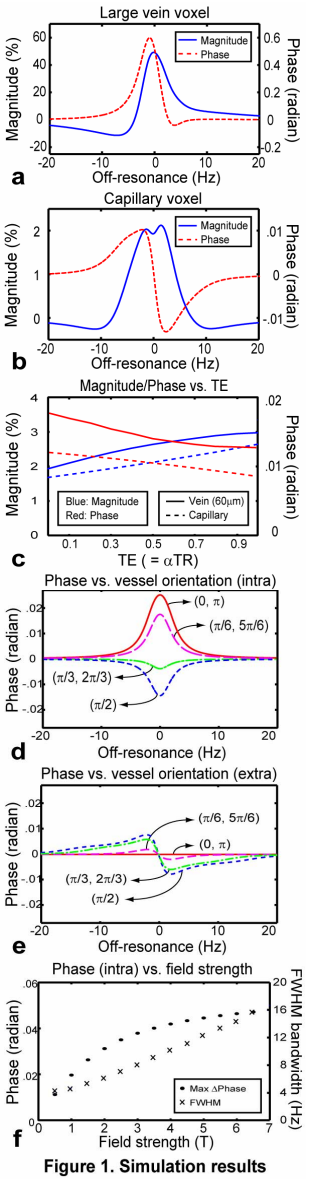

Figure 1. Simulation results

5) Experimental results: Fig. 2 shows the activation maps. The number of phase-activated voxels (1505, averaged) was comparable to that of the magnitude-activated voxels (1491, averaged). Only 396 voxels show both magnitude and phase activations (green), whereas most of the other activated voxels show either magnitude (red) or phase (blue) activations. This result was expected from the simulation since the magnitude and phase revealed different off-resonance activation sensitivities (Figs. 1a,b). The experimental results agreed approximately with the simulation results, in the sense that the maximum signal change in the experiments (50.6%, 0.64 rad) were similar to the simulation results of the single large vein case (50%, 0.60 rad), whereas the mean signal change (9.24%, 0.11 rad) were relatively close to (and higher than) the capillary case (2%, 0.013 rad). These phase signal change levels are much larger than in GRE-fMRI [2]. The venogram results (Fig. 3, vein: blue, gray matter: green circle) demonstrate that not all phase activations are localized to the large veins (vein: yellow), indicating that the phase also provides localized activations. Based on these results, it is plausible that the phase signal change can be beneficial to include in the activation maps. Moreover, several methods (higher fields, respiration compensation, longer scan time) can further increase the detectability of this phase activation, allowing more gray matter activation to be detected by the phase activation. To include this phase activation, a complex analysis method can be used. The large vein contribution can be reduced by [5-7].

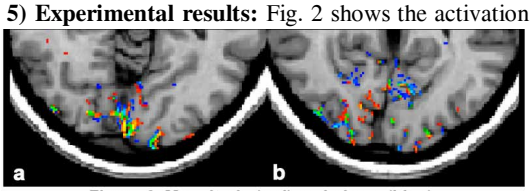

Figure 2. Magnitude (red) and phase (blue)

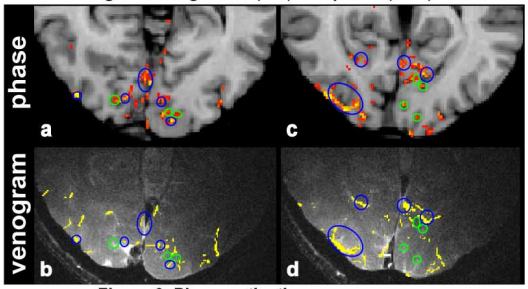

Figure 3. Phase activation vs. venogram

[1] Hoogenraad, MRM, 39(1):97 [2] Menon, MRM, 47(1):1 [3] Miller, MRM, 50(4):675 [4] Lee, 12th HBM, 711 T-AM [5] Barth, 14th ISMRM, p893 [6] Hulvershorn, NI, 24:216 [7] Song, MRM, 35(2):155