Blood Oxygenation (BOX) Level Dependent Functional Brain Imaging using Steady-State Free Precession

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Introduction A new fMRI method that detects brain activation-induced blood oxygenation changes using balanced-SSFP imaging is introduced. The conventional BOLD imaging technique suffers from image distortion, signal dropout and low spatial and temporal resolution. The proposed method, which we refer to as BOX (Blood Oxygenation), eliminates most of the problems mentioned above. Changes in the concentration of the paramagnetic deoxyhemoglobin introduce frequency shifts and T_2 relaxation time changes. Previous methods that incorporated balanced-SSFP for fMRI mainly relied on the frequency shift to generate oxygen contrast. Such techniques have a major disadvantage that comes from the sensitivity to off-resonance. The BOX method exploits the T_2 changes to generate oxygen contrast over a broad range of off-resonance frequencies. BOX provides oxygenation contrast with no visible image distortion or blackout while allowing high spatio-temporal resolution 3D coverage.

Theory Brain activation leads to a decrease in the concentration of deoxyhemoglobin. The BOLD method detects such changes in blood oxygenation level by detecting the T_2* effect created by the local susceptibility changes. In addition to such T_2* effects, T_2 relaxation times also change due to the intra-vascular [1] (in and out of red blood cells) and extra-vascular [2] (around the blood vessels) diffusion of water molecules through local field inhomogeneities. BOX imaging exploits the T_2 sensitivity of SSFP (Fig. 1) to detect oxygenation level changes in brain tissue.

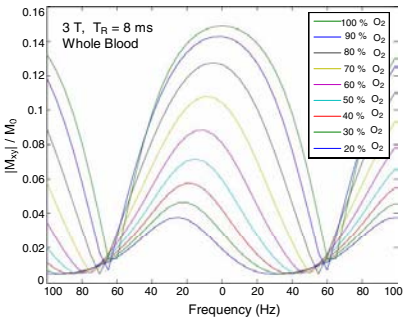

Figure 1 Balanced SSFP signal vs. oxygen saturation in whole blood (3 T, T_R / T_E = 8 / 4 ms). The SSFP signal was calculated from the two-pool model which was shown to have good agreement with the experimental data [1].

Methods To test the feasibility of BOX imaging for fMRI and demonstrate its flexibility incorporating different 3D imaging trajectories, 3DFT and 3D spiral experiments were performed. 3D imaging was used to minimize inflow effects and allow a true steady state to evolve. Both the 3DFT and the 3D spiral BOX experiments were compared with multi-slice single-shot EPI-BOLD experiments. The experiments involved a simple visual stimulus protocol with a 10 Hz contrast-reversing annulus grating in 15 s on / off blocks repeated four times. The experiments were conducted on a GE 3 T EXCITE whole-body scanner with a maximum gradient amplitude of 40 mT/m and maximum slew rate of 150 mT/m/ms.

The 3DFT BOX experiment used 24 x 24 x 3 cm^3 FOV with 0.94 x 3.75 x 3 mm^3 resolution. Flip angle was 60° with T_R / T_E = 8 / 4 ms (readout in A / P). A 3D volume was repeatedly acquired every 5.12 s, 25 times over 2 min 8 s. For the BOLD experiment, the FOV was 24 x 24 cm^2 and the resolution was 3.75 x 0.94 mm^2. Multi-slice imaging was performed to obtain 10 slices with a slice thickness of 3 mm. The flip angle was 60° with T_R / T_E = 2000 / 50 ms (readout in L/R). Temporal resolution was 2 s and multi-slice volumes were repeatedly acquired 60 times over 2 min.

The 3D spiral BOX experiment used 24 x 24 x 3 cm^3 FOV with isotropic 2 mm resolution. Flip angle was 60° with T_R / T_E = 8 / 0.64 ms. A 3D volume was repeatedly acquired every 2 s, 60 times over 2 min. For the BOLD experiment, the FOV was 24 x 24 cm^2 and the resolution was 2 x 2 mm^2. Fifteen slices were acquired with a slice thickness of 3 mm. The flip angle was 60° with T_R / T_E = 2000 / 50 ms. (readout in L/R) Temporal resolution was 2 s and multi-slice volumes were acquired 60 times over 2 min.

The data was analyzed with FEAT [4], including motion correction, temporal and spatial filtering (4 mm) and correlation analysis with the standard model for the hemodynamic response to the block stimulus. Activation masks were generated with a Z threshold of 2.3 and cluster threshold of $p<0.05$.

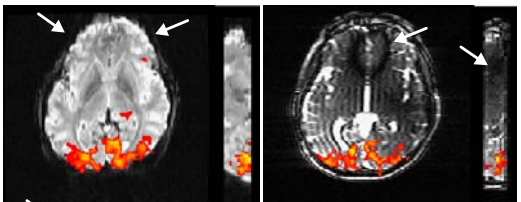

Figure 2 (a) BOLD and (b) 3DFT BOX comparison (axial, coronal, sagittal slices). The BOLD and BOX activation pattern generally show good agreement while the BOX activations is more localized. The arrows in (a) indicate regions with significant image distortion in BOLD imaging while BOX imaging shows a mere banding artifact (arrows in (b)).

Results The BOLD and BOX experiments show good agreement in the general area of activation. The BOLD activation (Fig. 2a, 3a) pattern appears more bulky while the BOX activation (Fig. 2b, 3b) appears more localized. The BOLD images also show image distortion that is more apparent in the region indicated by the white arrows in Fig. 2a and Fig. 3a. The BOX images show mere banding in the corresponding area (white arrows in Fig. 2b, 3b) which can be easily removed with two acquisitions (Fig. 3c).

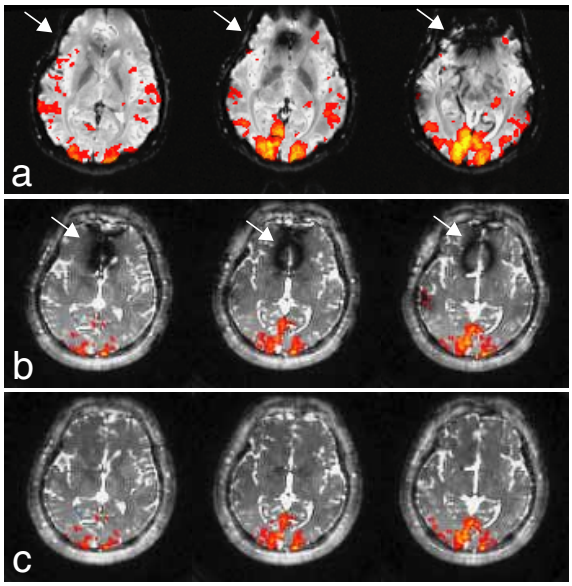

Figure 3 (a) BOLD and (b), (c) 3D spiral BOX comparison (axial slices). The banding artifact in the single-acquisition BOX images (b) can be easily removed using two acquisitions (c).

Discussion The new BOX imaging technique offers several key advantages over existing BOLD methods. The technique allows integration with 3D high-resolution imaging while allowing full-brain coverage including areas with large off-resonance such as the air-tissue interface. It is also expected to give activations in more localized regions near the smaller vessels of interest [2, 5]. With such advantages over BOLD fMRI, we expect the technique to be a promising new tool for fMRI.

References

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