Whole-brain artifact-suppressed SSFP fMRI in a single paradigm run: Alternating SSFP

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Introduction

Pass-band balanced Steady State Free Precession (pbSSFP) is an alternative to Gradient Recalled Echo Echo Planar Imaging (GRE-EPI) for functional MRI (fMRI), offering reduced image distortion and signal dropout and increased signal to noise ratio efficiency. Although pbSSFP acquisitions suffer from dark band artifacts at specific off-resonance frequencies, these can be eliminated by careful shimming, for small volume coverage, or by combining two acquisitions with complementary RF phase cycling increments [1], for whole-brain applications. However, the two-acquisition method involves repeating the functional paradigm [1]; artifact-free images are generated by combining two images acquired several minutes apart, resulting in prohibitive temporal resolution for many neuroscientific applications. Results from a recent Monte Carlo study [2] suggested that pairs of images with complementary RF phase cycling can be acquired sequentially in time, if RF catalyzation is used to reduce the signal fluctuations caused by changing the RF phase cycling increment. This alternating pbSSFP (altSSFP) technique would remove the need for repeat runs of the functional paradigm and provide temporal resolution similar to GRE-EPI. In this study we use a hypercapnic challenge in the rat to verify previous Monte Carlo results [2].

Methods

Acquisition: A Magnex Scientific 3T magnet (gradient: 0.2T/m, slew rate: 450T/m/s) interfaced with a Varian DirectDrive Console was used for imaging. A 52mm inner diameter quadrature RF coil (built in-house) was used for transmit/receive. Long-Evans rats (N = 6, 221-263g) were anesthetized by intraperitoneal injection of urethane (1.6g/kg) and immobilized using a head holder with ear bars (built in-house). A nose cone was placed over the snout for administration of gases. The hypercapnic challenge was preceded by a 1min baseline during which the rat breathed medical air. This was followed by 4min of 5% CO2 (balance air) alternated with 4min of medical air, repeated thrice. Two pbSSFP data sets (with different RF increments) and three altSSFP fMRI data sets (with different flip angles) were collected (parameters in Table 1). A 20-pulse linear ramp RF catalyzation [3] preceded each image acquisition in altSSFP. Twenty dummy RF cycles preceded each pbSSFP acquisition to maintain a 2:1 pbSSFP to altSSFP temporal resolution ratio to facilitate analysis. Scan order was randomized across animals. AltSSFP image pairs were combined using sum of squares [4].

Analysis: FMRI motion correction was performed in Statistical Parametric Mapping [5]. After temporal (480s cutoff) and spatial (825µm full width at half maximum) smoothing, fMRI statistical analysis was performed with the FMRIB Software Library [6] using the general linear model. A brain mask was applied to exclude non-brain tissue. Activation was modeled as a boxcar function representing the hypercapnia paradigm convolved with a sine basis function (120s window). Z scores were calculated using a cluster-level correction for multiple comparisons ($z > 2.3$, $p < 0.05$).

Results and Discussion

Whole-brain BOLD activation from a single run of the functional paradigm is possible with altSSFP (Figure 1). Image volume time (i.e., time to acquire each image pair) was 3s – typical of GRE-EPI. The sensitivity of altSSFP was compared to conventional pbSSFP in high-signal (pass-band) and low-signal (stop-band) regions (Figure 2). High (low) signal regions were identified as those pixels above (below) the median pixel intensity within the brain mask in pbSSFP images. Relative to pbSSFP, altSSFP-30° and -45° exhibit significantly ($p < .05$) enhanced sensitivity in stop-bands (Figures 2-3), while providing comparable sensitivity in pass-bands. AltSSFP-60° exhibits significantly ($p < .05$) reduced sensitivity in pass-bands and does not significantly ($p > .05$) recover stop-band activation.

Conclusion

AltSSFP permits whole-brain fMRI from a single run of the functional paradigm, with similar temporal resolution to GRE-EPI. This novel fMRI technique should permit neuroscientific investigation in brain regions currently inaccessible to GRE-EPI (due to signal dropout) and two-acquisition pbSSFP (due to low temporal resolution).

References

[1] Lee MRM 2008; 59:1099; [2] Patterson 19th ISMRM, 2011; p1630; [3] Deshpande MRM 2003; 49:151; [4] Bangerter MRM 2004; 51:1038; [5] Worsley NeuroImage 1995; 2:173; [6] Smith NeuroImage 2004; 23(S1):208.

Sequence	flip (°)	RF increment (°) (image 1 – image 2 …)	Tvol (s)
1 pbSSFP	30	180 – 180 – 180 …	1.5
2 pbSSFP	30	0 – 0 – 0 …	1.5
3 altSSFP	30	180 – 0 – 180 – 0 …	3.0
4 altSSFP	45	180 – 0 – 180 – 0 …	3.0
5 altSSFP	60	180 – 0 – 180 – 0 …	3.0
Common to all: 3D spiral-out, TR = 10.1 ms, TE = 0.7 ms, 8 shots, matrix = 64x64x16, FOV = 35x35x24 mm			

Table 1: Pulse Sequence Parameters. Tvol = image volume time.

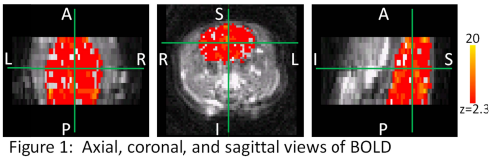

Figure 1: Axial, coronal, and sagittal views of BOLD activation in altSSFP-45° (representative animal).

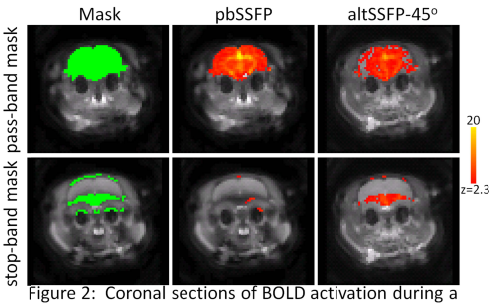

Figure 2: Coronal sections of BOLD activation during a hypercapnic challenge in pass-band (top row) and stop-band (bottom row) masks (representative animal).

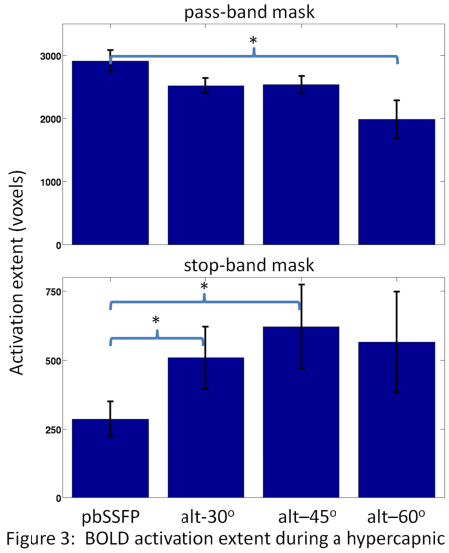

Figure 3: BOLD activation extent during a hypercapnic challenge in pass-band and stop-band signal masks. Mean +/- SEM across rats (N=6).