High field balanced-SSFP fMRI: A BOLD technique with excellent tissue sensitivity and superior large vessel suppression

C. V. Bowen[1], R. S. Menon[1], J. S. Gati[1]

[1]Imaging Research Laboratories, Robarts Research Institute, London, Ontario, Canada

Introduction

Although T2*-weighted gradient echo based fMRI has become a standard acquisition tool for neuro-scientific investigation, many questions still exist as to the spatial specificity of the functional patterns observed relative to neuronal activity. Two main problems persist with T2* weighted fMRI: (i) an oversensitivity to oxygenation changes in large draining veins located distal to the site of activation; and (ii) an inability to perform robust T2* fMRI analysis in regions of strong field inhomogeneity like the frontal and temporal lobes. Alternative approaches, such as spin-echo or other T2 based methods, have been proposed to alleviate the issues associated with T2* approaches. However, a strong reduction of sensitivity to BOLD contrast prevents the practical implementation of these approaches. Recently, balanced SSFP (b-SSFP) (also known as TrueFISP or FIESTA) have been proposed as a BOLD sensitive approach that relies on the inherent sensitivity of b-SSFP to off-resonance signal changes [1]. Although possessing spin-echo like properties [2], fMRI acquisition through this approach has relied on careful shimming of specific regions to within a few Hz of the critical transition bands [1], or to the acquisition of multiple off-resonance images with image recombination strategies that strongly hamper temporal resolution [3].

This paper proposes the use of b-SSFP at high field (4T) using on-resonance acquisitions without shimming in regions of interest to the edge of the b-SSFP transition band. Also, this method doesn't rely upon multiple acquisitions to ensure spectral coverage of the b-SSFP transition band for each pixel. We show b-SSFP fMRI acquisitions have far greater sensitivity to the BOLD mechanism than gradient echo acquisitions with matched TR/TE. Additionally, we demonstrate using high resolution imaging that b-SSFP has comparable sensitivity to traditional EPI based fMRI acquisitions, but superior suppression of BOLD based signal changes within large vessels. A contrast mechanism is suggested based upon microscopic banding of b-SSFP signal surrounding the micro-vasculature of the cerebral cortex.

Theory

The NMR signal at the readout time (TR/2) for b-SSFP is well described as a spin-echo, with the spin echo refocusing along either the +y' or –y' axis of the rotating frame [4]. The specific axis for spin-echo formation depends upon the local off-resonance frequency of the NMR signal, and alternates direction for adjacent off-resonance bands having full width defined by 1/TR. In addition, a large reduction in signal magnitude is observed at the specific off-resonance values corresponding to these transition boundaries. For conventional b-SSFP acquisitions, the microscopic field offset patterns formed around cylindrical vessels of the microcirculation produce patterns of magnitude banding and alternate axis spin-echo refocusing as are more typically observed on macroscopic scales. However, in the case of intra-voxel banding, these properties may contribute to intra-voxel signal reduction through cancellation of signal refocused along opposing axis of the rotating frame.

Methods

All experiments were performed on a 4T Varian/Siemens whole body scanner using b-SSFP sequences developed in house. A transmit-receive, 2-element, quadrature surface coil (7"/element) placed posteriorly on the head was used for transmission and detection of signal. Three oblique slices were prescribed from a sagittal scout (3 mm each, 2 mm gap) and oriented in a plane coincident with the calcarine sulcus. During the visual stimulation paradigm, a series of 70 b-SSFP, GRE (19.2x14.4 cm fov, 128x96, 9/4.5 ms TR/TE, α=25) or EPI (19.2x19.2 cm fov, 128x128, 4 shot, 750/15 ms TR/TE, α=40) images were acquired to evaluate functionally related signal changes in the primary visual cortex. A block stimulation paradigm was used alternating between 30 seconds of fixation and 30 seconds of a reversing checkerboard repeated for 3.5 minutes. Each data set was analyzed using a pixel wise cross-correlation (Stimulate; CMRR, UMN) at a conservative threshold value of .225 and mapped as the percentage signal change onto a T1-weighted anatomical reference. During each session, a corresponding high resolution T2* weighted GRE venogram (19.2x14.4 cm fov, 256x192, 50/30 ms TR/TE, α=25) was collected to evaluate the source of functional signal changes.

Results and Discussion

The images in Fig. 1 show functionally related activity in the posterior region of human visual cortex as detected using the b-SSFP and EPI methods described above. The high resolution venogram is shown for reference to illustrate the origin of the functional activation. Black lines corresponding to large venous vessels, as observed in the venogram, have been superimposed onto the b-SSFP and EPI maps to highlight obvious large vessel signal. The colorbar on the right shows the relative percent signal change in significantly activated voxels as assessed through cross-correlation analysis. One clear observation is that some regions of large signal change that are present within the T2*-weighted EPI maps coincide with draining venous vessels, while the signal sensitivity in the b-SSFP maps are not necessarily central to these vascular structures. The corresponding GRE data were not included in the figure since no voxels passed the statistical cross-correlation test above threshold. This result is consistent with a lack of T2*-weighting in the GRE images, preventing BOLD contribution from either vessel or tissue regions, however it strongly suggests an alternate contrast mechanism exists for b-SSFP relative to matched GRE acquisitions. Finally, for regions of activation not directly attributable from the venogram to draining veins, both b-SSFP and EPI exhibit comparable percent signal changes as indicated by the matched colorbar used for each map.

Conclusion

BOLD based fMRI activation maps obtained with short TR balanced-SSFP demonstrate excellent sensitivity in active brain regions comparable to widely accepted T2* techniques. Additionally, the b-SSFP approach shows an inherent insensitivity to BOLD changes in large draining vessels and therefore provides a superior method for the suppression of large vessel activation relative to T2*-weighted EPI. Our experiments have shown that GRE acquisitions with matched TR/TE show no sensitivity to BOLD contrast providing significant evidence of a unique contrast mechanism for b-SSFP acquisitions. We believe that the b-SSFP method possesses adequate sensitivity, along with superior large vessel signal suppression to that of traditional T2*-weighted approaches and may provide an alternative tool for neuro-scientific investigation.

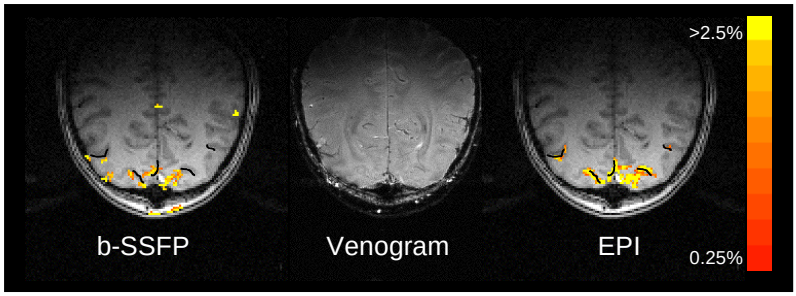

Figure 1: b-SSFP vs EPI activation patterns

References

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