Whole Brain Segmented Echo-Volumar-Imaging increases fMRI Sensitivity compared to Multi-Slice Echo-Planar-Imaging

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Objective Improving temporal resolution in fMRI is desirable to resolve regional onset latencies, to improve deconvolution of physiological noise and to reduce motion sensitivity. Echo-Volumar imaging (EVI) [1-3], Inverse Imaging (InI) [4] and highly undersampled projection imaging (PI) [5] achieve temporal resolution for whole brain mapping on the order of 100 ms, however at the expense of geometrical distortion in case of EVI and spatial blurring in case of InI and PI. In this study we developed whole brain EVI on a clinical 3 T scanner using multiple-slab excitations and 3D spatial encoding within each slab to reduce geometrical distortion. A direct fMRI sensitivity comparison with conventional multi-slice EPI was performed using an auditory-gated motor-visual task.

Methods FMRI data were acquired on 13 subjects in 22 scanning sessions using a clinical Siemens 3 T scanner equipped with a 12-channel head array coil. EVI acquisition parameters were: TR=280 ms, TEeff=28 ms, α=10°, 4 slabs in AC/PC orientation, slab thickness: 24 mm, inter-slab gap=10%, FOV: 256 mm, reconstructed image matrix per slab: 64x64x8, 4-fold GRAPPA acceleration, 6/8 partial Fourier acquisition, readout duration: 51.7 ms, reconstructed isotropic voxel dimensions: 4 mm, measurements: 600. Additional data were collected in 2 subjects with TR: 135 ms, 2 slabs (42 mm thick), 16 slices and 6 mm slice thickness. In-plane reconstruction of complex images was carried out online on the scanner. Reconstruction in the third dimension, and real-time fMRI analysis was performed on an external workstation using TurboFIRE software [6]. Steady state data acquisition, image reconstruction and real-time fMRI analysis was performed with time delays of less than 1 TR period. EPI data acquisition was additionally performed in 4 of the subjects using TR: 2000 ms, TE: 28 ms, 32 slices, slice thickness: 4 mm, inter-slice gap: 0 %, FOV: 256 mm, acquisition matrix: 64x64, isotropic voxel dimensions: 4 mm, measurements: 84. The auditory-gated visual-motor paradigm consisted of simultaneous 2 Hz right index finger tapping and eyes open (4 s duration) versus rest and eyes closed. EVI and EPI scans were collected in randomized order. Data analysis of concatenated scan repetitions was performed with SPM8 using spatial normalization, autoregressive modeling and corrected p-threshold of 0.001. For details see [7]. Real-time and retrospective single scan analysis using spatial normalization and simultaneous General Linear Model and correlation analysis was performed with TurboFIRE using identical t-threshold as with SPM8.

Results Spatial resolution along the z-direction was comparable for EVI and EPI as verified on phantoms. FMRI sensitivity was larger at 30° compared to 10° and 90° flip angle, consistent with the computed Ernst angle. However, a 10° flip angle was chosen to minimize in-flow effect and large blood vessel enhancement. Maximum t-score, extent of activation and percent BOLD signal change were significantly higher with EVI at TR: 280 ms compared to EPI (**Figure 1, Table 1**), both using TurboFIRE (p<0.05) in real-time and retrospectively, and using SPM (p<0.05). Spatial signal-to-noise ratio was 187:1 for EVI and 430:1 for EPI. Temporal contrast-to-noise ratio in BA17/18 was larger with EVI (~6) compared to EPI (~4.2). Excellent activation and strong signal changes in BA17/18 were measured at TR: 135 ms (**Figure 2, see right**).

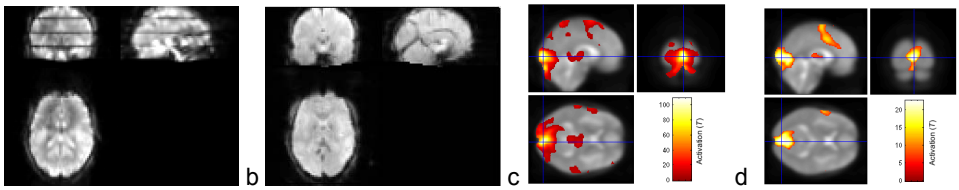
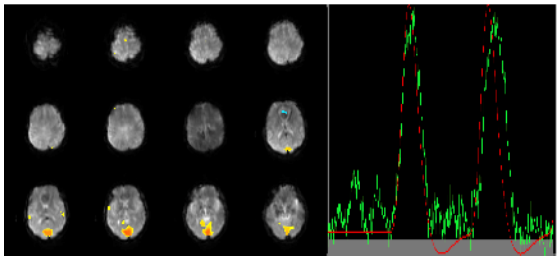


Figure 1: Whole brain (a) EVI and (b) EPI raw data. Single-subject SPM8 activation maps with (c) EVI and (d) EPI. Considerably larger extent and intensity of activation was measured with EVI. Note the difference in maximum t-scores (EVI: 108.7, EPI: 23.6).

Analysis	EVI		EPI	
Method	T max	No. Voxels	T max	No. Voxels
TurboFIRE	24 (10)	496 (357)	8 (2)	105 (114)
SPM	85 (33)	2479 (449)	23 (1)	1092 (801)

Table 1: Max. T-scores/extents of activation in occipital lobe (STDEV.)



Discussion The surprisingly high fMRI sensitivity of EVI is in part due to the larger number of volumes per unit time compared to EPI at only moderate reduction of spatial SNR, and due to the long readout that maximizes BOLD sensitivity per unit time, comparable to multi-echo EPI [8]. However, t-scores and extents of activation with SPM8 have to be interpreted with caution, since the correlation structure of the SPM8 model does not appear to be sufficiently rich to explain the structure of the data. We are working on a temporal pre-whitening procedure to remove temporal data correlation by autoregressive models. Current limitations of multi-slab EVI include signal loss at slab intersections, geometrical distortion along the slice direction and g-factor related noise enhancement. These may be mitigated using large-scale array coils and optimized RF pulses. We are currently investigating combination of 2*D* parallel imaging with compressed sensing [9] and super-resolution reconstruction [10].

Conclusion Multiple-slab EVI provides considerable improvement in temporal resolution and fMRI sensitivity compared to EPI. However, image quality, quantification of contrast mechanisms and validity of statistical analysis require further attention to make this new methodology acceptable for neuroscience and clinical research applications.

References 1. Rabrait C, et al. J Magn Reson Imag. 2008 27(4):744. 2. van der Zwaag W, et al. Magn Reson Med. 2006 56(6):1320. 3. Witzel, T, et al. Proc ISMRM 2008; 1387 4. Lin F-H, *et al*., *Neuroimage* 49 (2010) 3086. 5. Grotz T, et al., Magn Reson Med. 2009 62(2):394. 6. Posse S., *Human Brain Mapp* 12:1 (2001) 25. 7. Mutihac R, et al. Abstracts ISMRM 2011 (submitted). 8. Posse S. *et al*., *Magn Reson Med*, 42:1 (1999) 87. 9. Lustig M, et al. Magn Reson Med. 2007 58(6):1182. 10. Otazo R, et al. Neuroimage. 2009 1;47(1):220. *R.M. is supported by the Fulbright Program. We thank Edward Bedrick for advice on statistics.*