Multiplexed Echo Planar Imaging with Sub-second Whole Brain FMRI and Fast Diffusion Imaging

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EPI generates a single 2D image in a fraction of a second, however, it requires 2-3 seconds to acquire multi-slice whole brain coverage for fMRI and even longer for diffusion imaging. We present an approach to reduce whole brain scan time that accelerates the multi-slice 2D acquisitions, while not significantly sacrificing spatial resolution. The Multiplexed-EPI (M-EPI) pulse sequence, **Fig 1** combines temporal multiplexing (*m*) utilizing the simultaneous echo refocused SIR EPI scheme [1] and spatial multiplexing (*n*) with *n* distinct slices excited with multibanded RF pulses (MB) and acquired simultaneously and separated by post-processing using sensitivity profiles of multiple receiver coils [2,3], to achieve an increased number of images (*m* x *n*) in a single EPI echo train. Incorporating both strategies in a single pulse sequence gives a "slice acceleration" equal to the product of the two acceleration factors. The overall time reduction is somewhat less than *m* x *n* -fold due to the echo train lengthening by SIR. A similar method of multiband combined with SIR factor 2 has been demonstrated in anatomic images [4]. Here preliminary applications of M-EPI investigated resting state fMRI and diffusion based tractography are presented.

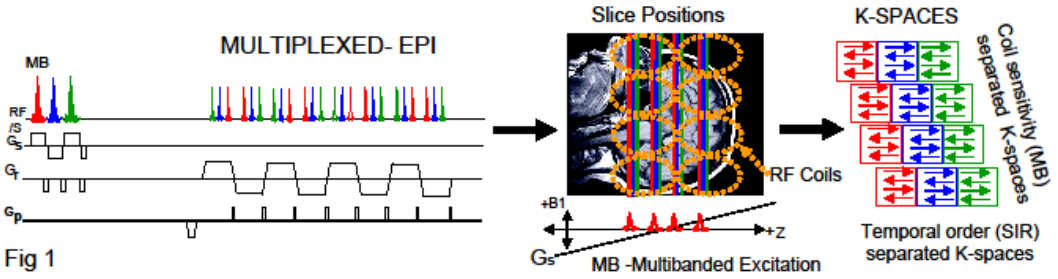


Fig 1

Methods As calibration data, an acquisition with matched SIR factor, and single slice excitation was obtained. A GRAPPA-type projection operator (matrix) is calculated over a 3x3 region [5], and used to estimate the elements in the matrix needed for separating the frequency-multiplexed signals. Feasibility of acceleration factors for M-EPI is different at 7T and 3T, given the differences in SAR, parallel imaging performance, SNR, and T2*. At 3T, using a 32 channel coil, we acquired images with *m* x *n* factors up to 4 x 4 for 2 mm isotropic pixels at 1680 Hz/pixel, matrix 96 x 96, 6/8 partial Fourier, parallel imaging with Reduction factor along phase encode (RPE) =2, TE=40 msec, and 60 slices. The TE varied by 2.5ms between adjacent SIR images. At 7T we tested the M-EPI sequence using 1.5 mm voxels, 128 x 128 matrix, BW/2400 Hz/pixel accelerations up to 3x2. For application to diffusion imaging at 3T we used the twice-refocused diffusion encoding sequence [6,7] incorporated for DSI with b-maximum of 4500 s/mm^2 and 256 b-value encodings, 3mm resolution, total acquisition time 8.5 min, TR/2000ms and signal bandwidth 2604 Hz/pixel acceleration of 2x2. 3D fiber track images, Fig. 5, were reconstructed with TrackVis Toolkit. For application to resting state fMRI at 3T, standard EPI at TR 2.5 s was compared to M-EPI with slice accelerations of 4 and 9 by *m* x *n* = 2x2 and 3x3 to achieve shorter TR 0.8 s, and TR 0.4 s respectively. For this we used 3 mm isotropic images acquired with: 2604 Hz/pixel, matrix 64 x 64, RPE =2, TE=40 msec, 36 slices. Comparisons of 3 different TRs in 10 min scans, in 3 subjects (at rest eyes closed) resulting in 9 datasets. RF flip angle was 90° for EPI and Ernst angles of 60° and 45° for TR= 0.8 s and TR= 0.4s.

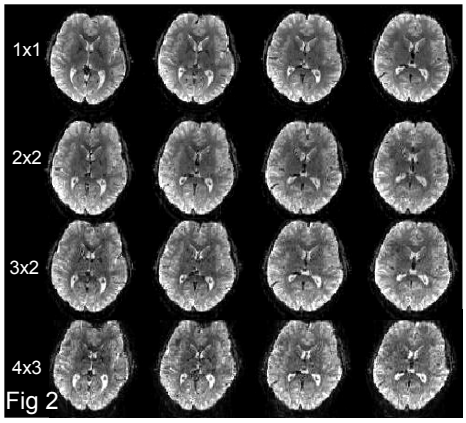


Fig 2

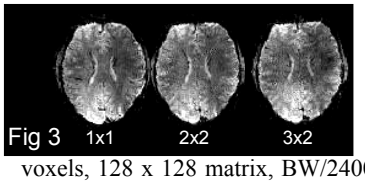
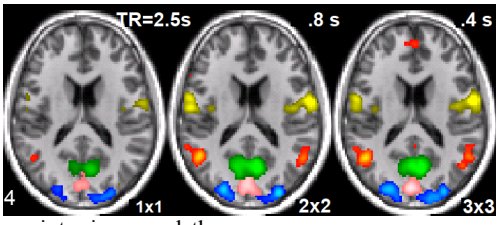


Fig 3

Results **Fig 2** shows M-EPI at 3T using 2 mm resolutions with different slice accelerations ranging from 4 to 12. The average time per slice is 72 ms (1x1), 23 ms (2x2), 18 ms (3x2), 10.5 ms (4x3) ms and 7.6 ms (4x4). These images were acquired with fully relaxed magnetization to demonstrate feasibility and calculate g-factors for accelerations (1x1)1.0, (2x2) 1.58 +/-0.34, (3x2) 1.61+/-0.69, (4x3) 3.37 +/- 0.89, and (4x4) 4.16 +/- 1.25. **Fig 3** shows 7T comparisons with increased frontal lobe susceptibility distortion. **Fig 4** (right) shows comparison of resting state networks (RSNs) at different TR, thresholded at Z>4. The RSNs shown cover visual areas, the default mode network and a sensori-motor network, identified with the different colors. The faster sampling rates of 0.4 s and 0.8 s TR yielding a larger number of total time points, improved the spontaneous neural fluctuations' Z-scores by as much as a factor of 60%, despite the ~50% lower SNR "per image" due to the faster TR (i.e., T_1 relaxation). **Fig 5** shows DSI fibertracks rapidly acquired in 8.5 m with high angular resolution (256 b values). **Discussion** The multiplexing of two slice acceleration techniques in M-EPI ameliorated physical limitations from specific absorption rate (SAR) and echo time (TE) lengthening than if only MB or SIR were used separately. SIR is ultimately restricted by the obligatory echo train lengthening and dependent sensitivity to distortions that are countered by use of parallel imaging to shorten the echo train. The MB technique, on the other hand, is limited by the ability to encode spatial information by the RF coil array alone, and potentially by SAR, especially at high fields, given MB pulses, when used to shorten the TR, will result in quadratic increases in power deposition with the number of slices excited relative to a single band pulse. **Conclusion** Multiplexed EPI resulted in significant increases in temporal resolution for whole brain fMRI, and substantial reductions in diffusion scan times. These increases can be used to shorten scan times, acquire higher spatial resolutions, increase diffusion encoding, or to investigate temporal dynamics of the fMRI response. **References** 1] Feinberg DA, MRM 2002, 2] Larkman DJ, MRM 2001, 3] Moeller S, MRM 2010, 4] Setsompop K, Proc. of ISMRM, 2010, 5]Wang Z, MRM 2005, 6] Feinberg DA, MRM 1990, 7] Reese TG, JMRI 2009. **Funded** in part by the NIH Human Connectome Project (1U54MH091657-01) and NIH grants P41 RR008079, P30 NS057091 and 1R44NS063537.



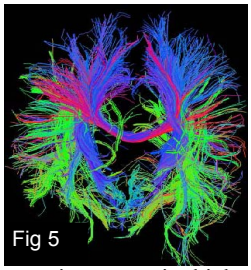


Fig 5