

Interleaved EPI Based fMRI Improved by Integration of Multiplexed Sensitivity Encoding (MUSE) and Simultaneous Multi-band Imaging

Hing-Chiu Chang¹, Shayan Guhaniyogi¹, Ying-Hui Chou¹, and Nan-Kuei Chen¹

¹Brain Imaging and Analysis Center, Duke University Medical Center, Durham, North Carolina, United States

Target Audience: Researchers and clinicians who are interested in high-resolution fMRI studies and technical improvement of segmented EPI.

Purpose: Interleaved EPI has greater potential than single-shot EPI because of its reduced geometric distortions, sharper point-spread function (PSF), and higher flexibility in achieving the optimal echo time (TE) for high-resolution functional MRI (fMRI) studies [1]. However, interleaved EPI based fMRI is highly susceptible to unstable aliasing artifacts across the FOV as a result of B0 drifting over time, physiological noises and subject motion. The recently developed multiplexed sensitivity-encoding (MUSE) post-processing algorithm can suppress the in-plane aliasing artifacts resulting from time-domain signal instabilities during dynamic scans [2]. In this study, the MUSE algorithm is further developed and generalized to accommodate high-throughput fMRI data obtained with a *multi-band* interleaved EPI pulse sequence, thereby suppressing both in-plane and through-plane aliasing artifacts and improving image throughput.

Methods: Figure 1 shows a 2-band 2-shot interleaved EPI pulse sequence using consecutive excitation RF pulses, with variable FOV-shift enabled by alternating the polarity of the second RF pulse. An additional pre-phasing gradient along the phase-encoding direction (i.e., the gray trapezoid) is added between two RF pulses to ensure that comparable echo times can be achieved for the two excited slices. While the original MUSE algorithm is capable of removing in-plane aliasing artifacts resulting from shot-to-shot phase inconsistencies of interleaved EPI, the through-plane aliasing artifact associated with multi-band imaging remains present. Here the MUSE algorithm is generalized to accommodate interleaved EPI data acquired with simultaneous multi-band imaging, and the produced images have higher SNR than those obtained with the conventional SENSE method [3]. The multi-band MUSE algorithm comprises three steps: 1) images free from both in-plane and through-plane aliasing artifacts are reconstructed from each of the multi-band EPI segments using the conventional SENSE algorithm; 2) the phase information obtained from step 1 is spatially smoothed; and 3) the smoothed phase information (from each of the simultaneously excited slices) obtained from step 2 and the known coil sensitivity profiles are incorporated into a mathematical framework that jointly solves the unknown magnitude source signals of (in-plane and through-plane) overlapping voxels from all EPI segments, producing a final set of images with higher SNR than those obtained from step 1. To evaluate the new multi-band MUSE algorithm in fMRI studies, finger tapping fMRI data (2.0x2.0x3.0 mm³) were acquired from two healthy volunteers using a 2-band and 2-shot interleaved EPI pulse sequence with a 32-channel phase array RF coil on a 3.0T MRI scanner (GE MR750, Waukesha, WI). The scan duration was 5 min, consisting of alternating resting blocks (30 sec each) and finger-tapping blocks (30 sec each). Imaging parameters included: in-plane matrix size 128 x 128, TR 2 sec, two simultaneously excited slices with comparable TE values of 24.86 and 25 msec, and 44 slices (22 excitations with 2 bands). The acquired k-space data underwent either 1) the conventional reconstruction (i.e., 2D Fourier transform followed by unfolding of the through-plane signals with SENSE) or 2) the developed multi-band MUSE reconstruction algorithm. The fMRI activation maps were calculated using the FSL-FEAT program (with 5mm spatial smoothing). Two produced image data sets were then compared in terms of the level of time-domain signal fluctuation and signal to fluctuation noise ratio (SFNR).

Results: The multi-band images reconstructed by 1) 2D Fourier transform and 2) the developed multi-band MUSE are shown in Figures 2a and 2b respectively. It can be seen that signals from one of the simultaneously excited slices are shifted by half of the FOV because of our embedded phase difference between two RF pulses. After applying the multi-band MUSE method, the two overlapped slices are effectively separated and functional activation associated with the finger-tapping task is properly identified (Fig. 2b). Quantitative measurements show that the MUSE reconstruction can produce images with lower in-plane aliasing artifact and lower time-domain signal fluctuation (by 12.5%). Figure 3 compares the temporal fluctuation noise levels (a, b) and SFNR (c, d) in images reconstructed with the conventional SENSE procedure (a: fluctuation noise= 246±29; c: SFNR= 62±22) and the multi-band MUSE algorithm (b: fluctuation noise= 215±20; d: SFNR= 69±23).

Discussion & Conclusion: The quality of fMRI data acquired with the multi-band interleaved EPI pulse sequence can be significantly improved using the new multi-band MUSE algorithm. Compared to the conventional multi-band SENSE reconstruction method, the proposed reconstruction method can reduce the noise fluctuation and increase SFNR as shown in Figure 3. Even though high-resolution fMRI protocols based on either single-shot EPI or parallel EPI have been previously developed, integration of multi-band interleaved EPI and MUSE reconstruction is potentially superior to existing approaches for several reasons. First, the geometric distortions of interleaved EPI data are smaller than that in single-shot EPI data, particularly when choosing a large acquisition matrix size for high-resolution imaging. Second, the PSF of interleaved EPI is sharper than that of single-shot EPI. Third, as compared with the conventional parallel imaging reconstruction, the developed MUSE reconstruction is less susceptible to undesirable noise amplification. Fourth, using the developed multi-band MUSE algorithm, the unstable aliasing artifacts can be effectively removed and thus the quality of high-throughput and high-resolution fMRI can be significantly improved. In conclusion, the generalized MUSE algorithm can accommodate multi-band interleaved EPI data, effectively and simultaneously eliminating both in-plane and through-plane aliasing artifacts and enabling high-throughput and high-resolution fMRI data.

Acknowledgement: This research was supported by NIH grant R01-NS074045.

References: [1] Yun SD, et al., Parallel imaging acceleration of EPIK for reduced image distortions in fMRI. *Neuroimage*; (73):135-14, 2013. [2] Chen NK, et al., A robust multi-shot scan strategy for high-resolution diffusion weighted MRI enabled by multiplexed sensitivity-encoding (MUSE). *Neuroimage*; (72):41-47, 2013. [3] Pruessmann KP, et al., SENSE: sensitivity encoding for fast MRI. *MRM*; (42):952-962, 1999.

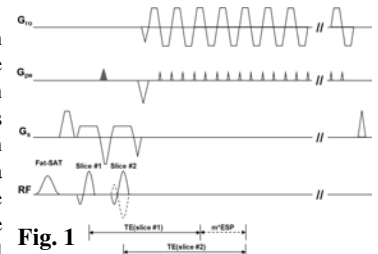


Fig. 1

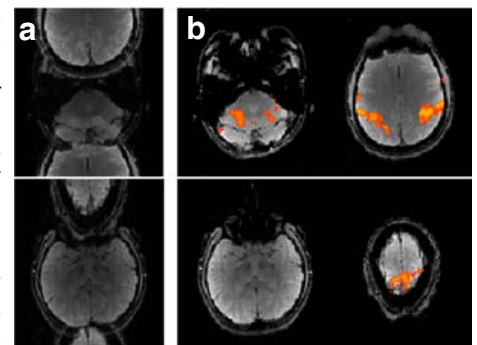


Fig.2 a) Two 2-band 2-shot images reconstructed by directly applying 2D Fourier transform, and b) multi-band MUSE reconstruction algorithm, the functional activation is displayed by color.

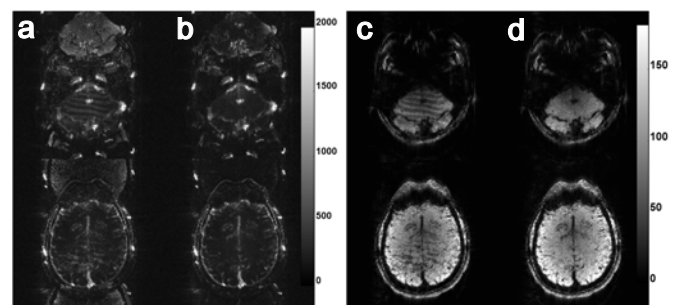


Fig.3 The temporal fluctuation noise levels in multi-band interleaved EPI data reconstructed with the a) conventional procedure and b) multi-band MUSE algorithm. The SFNR measures in multi-band interleaved EPI data reconstructed with the c) conventional procedure and d) multi-band MUSE algorithm.