High-quality and High-throughput Interleaved Diffusion Weighted EPI Enabled by Multi-band Multiplexed Sensitivity Encoding (MUSE) and Adaptive Partial Fourier Reconstruction

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

Purpose: A recently developed multi-shot DWI reconstruction strategy, termed multiplexed sensitivity encoding (MUSE) [1], can effectively remove aliasing artifact due to shot-to-shot phase inconsistencies without relying on navigator echo. However, the original MUSE technique has two limitations. First, the conventional partial Fourier (PF) reconstruction procedure (e.g., homodyne reconstruction[2] or Cuppen's iterative method[3]) included in the original MUSE framework is highly susceptible to motion-induced k-space energy peak displacement, resulting in undesirable residual artifacts. Second, the imaging throughput of multi-shot MUSE is significantly lower than that in conventional single-shot low-resolution DWI. To address these limitations, here we first develop a novel adaptive partial Fourier reconstruction procedure capable of producing high-quality multi-shot MUSE DWI, even in the presence of motion-induced k-data energy displacement. Next, we further generalize the MUSE reconstruction to accommodate multi-band data, so that high-throughput, high-resolution and high-quality DWI can all be simultaneously achieved.

Methods: In contrast to the conventional single-band MUSE procedure [1], where the non-adaptive partial Fourier reconstruction is performed prior to the parallel image reconstruction, the novel multi-band MUSE algorithm uses an adaptive and integrated partial Fourier reconstruction to eliminate artifacts associated with motion-induced k-space energy displacement. The new multi-band MUSE algorithm comprises five 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 [4]; 2) the k-space energy peak displacement corresponding to each k-data segment is quantified from the complex images derived from step 1; 3) shot-to-shot phase variation is calculated from full-FOV images produced in step 1 and then spatially smoothed; and 4) multiple k-space weighting functions are adaptively created, according to the k-energy energy peak locations measured in step 2, and used to weight each of the EPI segments for MUSE partial Fourier reconstruction; 5) the known coil sensitivity profiles and shot-to-shot phase variation information (step 3) are then 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. Note that the new adaptive and multi-band MUSE algorithm can be directly applied to single-band interleaved DWI data, and the results are superior to that obtained with the conventional non-adaptive MUSE implementation. Two data sets were acquired on a 3.0T MRI scanner (GE MR750, Waukesha, WI) for evaluating the developed algorithm. First, a single-band 4-shot interleaved EPI based DWI data set (matrix size: 256 x 256; PF factor: 60%) was obtained with an 8-channel coil and processed with four different reconstruction pipelines: i) MUSE without PF reconstruction, ii) Cuppen's PF reconstruction followed by MUSE, iii) homodyne PF reconstruction followed by MUSE, and iv) the new adaptive MUSE algorithm. The four sets of results were then compared. Second, a high-resolution 2-band 4-shot interleaved DTI data set (matrix size: 384x384, *b*=600s/mm2, PF factor = 56%) was obtained with a 32-channel coil and reconstructed with new adaptive and multi-band MUSE algorithm.

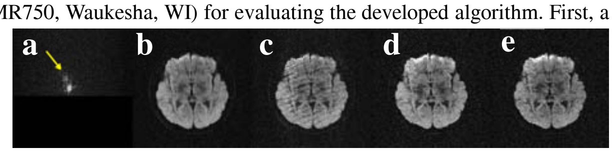

Fig.1 Single-band 4-shot interleaved DW-EPI data: (a) k-space data of segment # 4 demonstrates displacement of k-space echo energy peaks; (b) An image reconstructed by MUSE (without PF reconstruction) is blurred, c) An image reconstructed by Cuppen's PF reconstruction followed by MUSE has residual artifacts, d) An image reconstructed by homodyne PF reconstruction followed by MUSE has inaccurate contrast (also see Fig 2), and e) an image reconstructed with the new adaptive-MUSE algorithm has low artifact level and correct image contrast.

Results: The single-band DWI data with k-space energy displacement in its fourth EPI segment center (Fig 1a) were processed with four different reconstruction pipelines and the results are shown in Fig 1b to 1e, respectively. It can be seen that the image obtained with the new adaptive MUSE algorithm has the lowest artifact level and highest anatomic resolvability (Fig 1e), although the conventional homodyne-MUSE implementation can provide qualitatively similar results (Fig 1d). After excluding EPI segment #2 and #3 from the reconstruction, the residual artifact associated with k-space energy displacement is much more pronounced in the homodyne-MUSE produced image (Fig 2b with artificially elevated contrast as compared with Fig 2a), and the advantage of the new adaptive MUSE is evident (Fig 2c: correct contrast, low artifact level, high anatomic resolvability).The multi-band DWI reconstructed by 1) 2D Fourier transform and 2) our adaptive and multi-band MUSE algorithm are shown in Fig 3ab and Fig 3cd, respectively, where panels a and c show baseline T2-weighted images and panels b and d show DWI images. It can be seen in Fig 3ab that signals from one of the simultaneously excited slices are shifted by half of the FOV because of the embedded phase difference between two RF pulses. After applying the adaptive and multi-band MUSE method, signals from overlapping slices are effectively separated and color FA maps can be calculated (Fig 4).

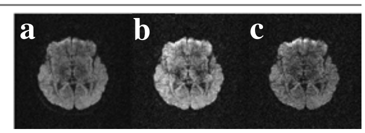

Fig.2 The same 4-shot interleaved DWI data as shown in Figure 1 after excluding k-space segment #2 and #3: (a) an image reconstructed by MUSE (without PF reconstruction), b) an image reconstructed by homodyne PF followed by MUSE, and c) an image reconstructed with the new adaptive-MUSE. All images are displayed at the same window level.

Discussion & Conclusion: The MUSE reconstruction can inherently measure the phase variations between shots without relying on navigator echoes, generating multi-shot DWI data with high spatial resolution and fidelity. However, the conventional PF reconstruction algorithm included in the original MUSE implementation is highly susceptible to k-space energy peak displacement, resulting in undesirable banding artifact (e.g., Fig. 1c). Although homodyne-MUSE can reduce the undesirable banding artifact, the k-energy displacement results in artificial signal elevation or reduction in the reconstructed images (e.g., Fig 2b). The novel adaptive-MUSE algorithm can eliminate these undesirable artifacts associated with motion-induced k-energy peak displacement. Since our generalized MUSE algorithm is compatible with the simultaneous multi-band imaging, we are now capable of producing high-resolution and multi-shot DWI data with a higher scan throughput (e.g., using 2-band or 3-band acquisition). In conclusion, the developed adaptive and multi-band MUSE algorithm can improve the imaging throughput of multi-shot interleaved EPI based DWI, and eliminate the undesirable artifacts associated with motion-induced k-space energy peak displacement.

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References: [1] Chen NK, et al., Neuroimage;72:41-47, 2013. [2] Noll DC, et al., IEEE Trans Med Img;10(2):154-163, 1991. [3] Cuppen JJ, et al., Medical physics;13(2):248-253, 1986. [4] Pruessmann KP, et al., MRM;(42):952-962, 1999.

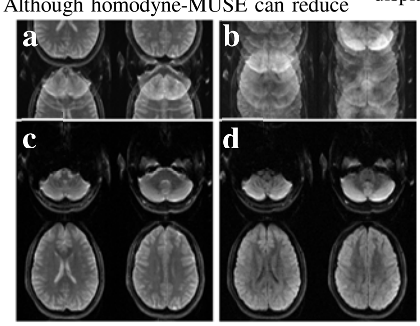

Fig.3 The multi-band DWI images with *b*=0 (a,c) and 600 s/mm^2 (b,d) reconstructed by 2D FT (a & b) and the developed multi-band adaptive-MUSE (c & d).

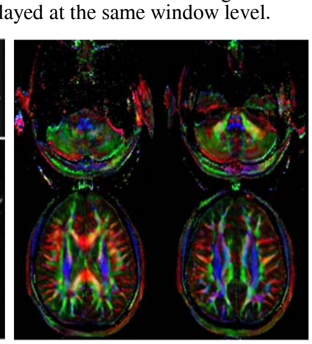

Fig.4 Color-coded FA maps were calculated from the data re-constructed by adaptive and multi-band MUSE algorithm.