High-resolution diffusion weighted MRI enabled by multiplexed sensitivity-encoding using projection on convex set (POCSMUSE)

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INTRODUCTION: Diffusion-weighted imaging (DWI) data acquired with interleaved EPI sequence are highly susceptible to inter-segment phase variations and aliasing artifacts induced by motion in the presence of strong diffusion weighting gradients. The multiplexed sensitivity-encoding (MUSE) method [1] was recently reported to reliably remove aliasing artifacts in interleaved Cartesian EPI based high-resolution DWI data. A major limitation of the MUSE method is that the number of EPI segments cannot be larger than the number of receiving coils, otherwise the phase variations among different segments cannot be estimated by conventional SENSE from ill-conditioned inverse problem. Another limitation is that the existing MUSE framework is only compatible regularly sampled data in Cartesian k-space, and DWI data obtained with arbitrary or randomly sampled k-space trajectory cannot be reconstructed with MUSE. To address the aforementioned challenges and to fully enable high-resolution interleaved DWI for different imaging paradigms (including random sampling in non-Cartesian k-space with a large number of segments), here we report a novel and efficient approach to solve the reconstruction problem through developing a MUSE algorithm based on projection onto convex set (POCS) [2]. The new technique, termed POCSMUSE, can provide high-quality image without navigator echo, and can be generally applied to DWI data acquired with arbitrary k-space trajectory.

METHODS: The developed POCSMUSE method comprises two steps. First, we use the POCSENSE method [2] for iteratively estimating phase information of different EPI segments. Second, we jointly unfold the aliased voxels with the estimated phase information from all EPI segments using multiplexed sensitivity-encoding method based on POCS. Here we discuss the POCSMUSE procedure for reconstructing aliasing-free images from DWI data using a 2-shot interleaved EPI sequence with three receiving coils. It should be noted that POCSMUSE can be generally extended to different number of EPI segments and coils. Two aliased Images obtained from the two EPI segments can be represented respectively as: $U_{i,j} = F_i S_j P_i D$, where F_i is encoding function of *i*-th segment, including 2D Fourier and inverse Fourier function and sampling function (i = 1,2), S_j is the sensitivity profiles for the *j*-th coil (j=1,2,3); D is the magnitude signal to be reconstructed, and P_i is the motion-induced phase errors for two shots. We use the POCSENSE method to reconstruct full-FOV images of two segments and can estimate P_i from them. Since the iterative scheme of POCSENSE provides a simple access to integrate multiple linear and nonlinear regularizations into the reconstruction process, we apply a phase-smoothing regularizer to smooth the estimated phase map from each iteration of POCSENSE.

After the POCSENSE estimation, we can jointly calculate the true magnitude signal D with the estimated phase information of all EPI segments using the POCSMUSE method. The algorithm of POCSMUSE is described as follows: 1) starting with an initial guess image D^0, 2) multiplying D^n with the sensitivity profiles and estimated phase map from each segments to get $D_{i,j}^n$, i=1,2 and j=1,2,3 (2 shots and 3 coils), 3) applying data projection to $D_{i,j}^n$ and combined all of them to get $D^{n+1} = \sum_{i=1}^{2}\sum_{j=1}^{3} \alpha_{i,j}\, D_{i,j}^n$, where $\alpha_{i,j} = S_j^*\, P_i^* / \sum_{i=1}^{2}\sum_{j=1}^{3} S_j P_i$, 4) applying linear and nonlinear constraint to D^{n+1} 5) checking if the result is converged: If yes, D^{n+1} is the reconstructed magnitude signal; If not, returning to step 2.

The developed technique is evaluated with diffusion-tensor data with 15 b-directions obtained from a 3 Tesla scanner (GE HD, Waukesha, WI) using a 4-shot interleaved EPI sequence with a 8-channel coil (matrix size = 256x256, FOV = 240 mm x 240 mm, slice thickness = 5 mm, TR = 5 ms, TE = 65 ms). We performed conventional MUSE and POCSMUSE method on the following data: 1) fully-sampled data from four segments and eight coils, 2) fully-sampled data from four segments and randomly selected three coils, and 3) randomly-downsampled data (40 out of 64 ky lines in each segment) from four segments and eight coils.

RESULTS: Reconstructed trace-DWI images of two selected slices are show in two rows of Figure 1. The raw DWI (i.e., with correcting for inter-segment phase errors) are shown in Figure 1a; images reconstructed by MUSE and POCSMUSE from fully-sampled data of eight coils are shown in Figures 1b and 1c, respectively; images reconstructed by MUSE and POCSMUSE from fully-sampled data of only three coils are shown in Figures 1d and 1e, respectively; images reconstructed by POCSMUSE from randomly-downsampled data are shown in Figure 1f. It can be seen that the uncorrected images are severely corrupted by motion-induced artifacts, and the MUSE and POCMUSE method can both produce aliasing-free images from well-conditioned data (1b and 1c). If the number of segments is larger than the number of coils (ill-conditioned data), the regularized POCSMUSE method can produce high-quality images and preserve all structural information (1e) while there exist pronounced artifacts in images produced by the ill-conditioned MUSE (1d). Moreover, from randomly-downsampled data, the regularized POCSMUSE method can provide images with quality comparable to fully-sampled data with only minor SNR penalty. These results demonstrate the robustness and feasibility of applying the POCSMUSE method to challenging and ill-conditioned interleaved DWI data.

DISCUSSION AND CONCLUSION: Here we presented a general and robust approach to enable high-resolution interleaved DWI with minimal restriction on acquisition paradigm (e.g., random k-space sampling). Specifically, in comparison to conventional MUSE method, the newly developed POCSMUSE method enables interleaved DWI with a greater number of shots. Furthermore, the POCSMUSE method is compatible with data obtained with arbitrary k-space trajectories.

The computation time for MUSE is about 10 minutes for reconstructing a 15 b-direction DWI data set, while iterative POCSMUSE requires 50 minutes for reconstruction. Therefore, we plan to further implement the POCSMUSE in a GPU parallel computation platform, to shorten the POCSMUSE computation time.

In conclusion, the developed POCSMUSE method is highly robust, and compatible with various DWI acquisition paradigms. It is expected that the method can benefit all clinical and neuro DWI studies requiring high spatial-resolution.

REFERENCES: 1.Chen,NK *NeuroImage* 2013; 72:41 2. Samsonov, AA *MRM* 2004; 52:1397