Correction of 3D motion induced artifacts in multi-shot diffusion imaging using projection onto convex sets based multiplexed sensitivity-encoding MRI (POCSMUSE)

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TARGET AUDIENCE: Researchers who are interested in motion-immune and high-resolution diffusion-tensor imaging (DTI).

PURPOSE: Multi-shot DTI can potentially produce images with significantly higher resolution as compared with single-shot DTI. However, multi-shot DTI is highly susceptible to motion induced phase errors and artifacts. Recently, the multiplexed sensitivity-encoding (MUSE) and augmented MUSE algorithms [1,2] were developed to remove 1) aliasing artifacts due to shot-to-shot phase errors, and 2) blurring artifacts originating from large-scale in-plane motion of multi-shot DTI data. However, artifacts resulting from through-plane motion in multi-shot DTI cannot be addressed, to our knowledge, with any existing technique. To address this limitation, here we propose a reconstruction procedure, based on projection onto convex sets of MUSE (POCSMUSE) [3], to effectively remove 3D motion induced artifacts in multi-shot DTI data.

METHODS: The developed method comprises two steps. First, we use the POCSENSE method [4] to estimate shot-to-shot data inconsistencies including 1) phase variations, 2) position changes and 3) motion-induced diffusion-encoding variations. Second, we jointly unfold the aliased voxels using POCSMUSE that incorporates coil sensitivity profiles, phase variations, position and diffusion encoding variations from all EPI segments, as described below:

Aliased Images obtained from the multiple EPI segments can be represented respectively as: $u_{i,\delta} = E_i S \Phi_{i,\delta} \Psi_{i,\delta} T_{i,\delta} p_\delta$, where $u_{i,\delta}$ is a vector containing the complex signals obtained from i-th segment and δ-th diffusion-gradient direction; E_i is the spatial encoding function of i-th segment,; S is the coil sensitivity profile; $\Phi_{i,\delta}$ is the shot-to-shot phase error; $\Psi_{i,\delta}$ is an affine matrix describing the position changes; $T_{i,\delta}$ is a matrix describing the changes in diffusion-encoding; and p_δ is a vector denoting the pixel-wise complex values of the un-aliased full-FOV image to be reconstructed. Some information (e.g., $\Phi_{i,\delta}$, $\Psi_{i,\delta}$, $T_{i,\delta}$) can be estimated with the POCSENSE method, and used as the input of POCSMUSE.. For example, the affine matrix $\Psi_{i,\delta}$ can be estimated by registering the SENSE-reconstructed images and the tensor correction matrix $T_{i,\delta}$ can then be calculated with rotation information from $\Psi_{i,\delta}$. [2]

As shown in Figure 1, the POCSMUSE framework 1) starts with an initial guess of source image (P_δ^0), 2) applies the sensitivity profiles and segment-specific signal variations (e.g., diffusion-encoding correction, position changes and phase variations) to produce a set of simulated images ($D_{i,j,\delta}$), 3) replaces parts of the simulated data with experimentally acquired k-space data (i.e., data projection), 4) demodulates the data produced by step 3 with known sensitivity profiles and shot-to-shot signal variations (e.g., position changes; phase variations) to generate an updated source image P_δ^n, which is further used as the input of step 1 until the iterative processes converge.

Our new method was evaluated with two sets of human brain DTI data obtained from a 3 Tesla scanner (General Electric). **1)** ***Multi-shot DTI in the presence of in-plane motion***: DTI data with 15 b-directions were obtained using a 4-shot interleaved EPI sequence with a 32-channel coil. The volunteer was asked to rotate his head (in-plane rotation) frequently during scans. **2)** ***Hybrid simulation of multi-shot DTI data in the presence of both in-plane and through-plane motion***: Two sets of DTI data with 15 b-directions were obtained using a 4-shot interleaved EPI sequence and an 8-channel coil. The volunteer remained stationary in each of the scans, but changed his head position between two scans. The hybrid simulation was performed by grouping the 1st and 3rd segments from k-space data of position #1, and the 2nd and 4th segments from k-space data of position #2, thereby creating a dataset affected by both in-plane and through-plane intrascan motion.

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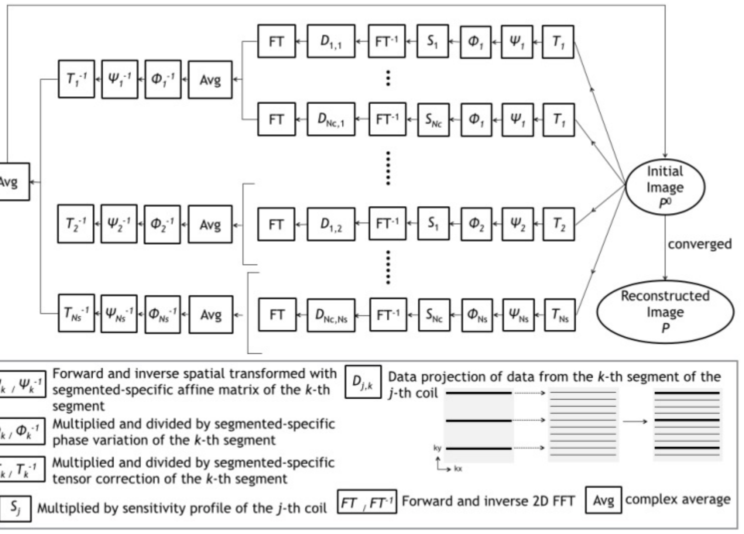

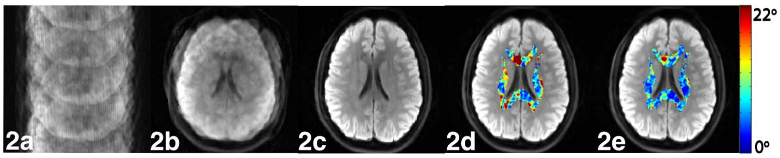

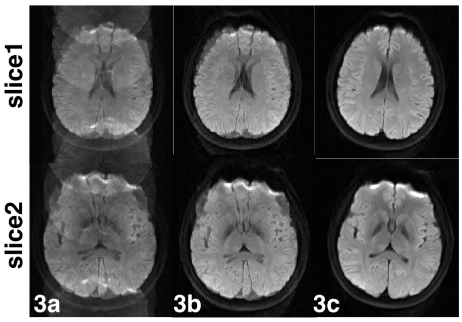

RESULTS: 1) ***DTI images with in-plane intrascan motion***: Fig. 2a shows a 4-shot DTI image reconstructed with 2D Fourier transform. Because of shot-to-shot phase variations and in-plane motion, the image is severely corrupted by aliasing and blurring artifacts. Fig. 2b presents an image reconstructed with POCSMUSE procedure with only phase correction but without large-scale motion correction, where there exists residual blurring artifact. Fig. 2c shows an image reconstructed with POCSMUSE procedure with phase, in-plane motion and diffusion-encoding contrast correction. Fig. 2d and 2e further compare the tensor errors in POCSMUSE images reconstructed without and with diffusion-encoding contrast correction, showing that the tensor errors can be reduced when motion-induced diffusion-encoding variation is included in the POCSMUSE reconstruction. **2)** ***Hybrid simulation of DTI with both in-plane and through-plane motion:*** Fig. 3a shows DTI images reconstructed with 2D Fourier transform, which is severely corrupted by motion-induced artifacts. Images reconstructed with the POCSMUSE procedure with phase correction only but without through-plane motion correction are shown in Fig. 3b, which are corrupted by blurring artifacts. Fig. 3c shows images reconstructed with POCSMUSE procedure that includes both phase and 3D motion correction, demonstrating that both in-plane and through-plane motion artifacts can be effectively removed with our new algorithm.

DISCUSSION: The newly developed method can produce high-quality and artifact-free multi-shot DTI data even in the presence of intrascan subject motion. In comparison to existing methods, the POCSMUSE method can much more effectively address artifacts originating from both in-plane and through-plane motion, and is generally compatible with arbitrary sampling trajectory. The computation time is about 70 minutes for reconstructing a complete set of DTI (15 b-direction) data using Matlab. Note that the compuation time can be further reduced with parallel computation. In conclusion, POCSMUSE is a general post-processing algorithm, robustly enabling high-quality and artifact-free multi-shot DTI.

REFERENCES:[1] Chen, NK *NeuroImage* 2013; 72:41 [2] Guhaniyogi, S *ISMRM* 2014; 4351 [3] Chu, ML *ISMRM* 2014; 0739. [4] Samsonov, AA *MRM* 2004; 52:1397.