Simultaneous Correction of Motion-Induced Artifacts and Diffusion-Encoding Corruption in Multishot Diffusion Tensor EPI

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TARGET AUDIENCE: The aim of this work will benefit researchers and clinicians whose investigations require high-resolution diffusion-tensor imaging (DTI) data free of corruption from motion.

PURPOSE: DTI data acquired with multishot EPI sequences have several advantages over data acquired with single-shot EPI, including reduced geometric distortions and improved spatial resolution [1]. However, multishot acquisitions have not yet been widely adopted for DTI due to its amplified sensitivity to motion from one shot to another. Specifically, small motion during the application of diffusion gradients results in phase errors among shots, causing ghosting artifacts, and large-scale motion results in pixel misregistrations among shots, causing blurring. Furthermore, when the large-scale motion involves rotation each shot will experience a different diffusion-encoding direction with respect to the patient reference frame. Therefore it is not sufficient to only correct the phase errors and pixel misregistrations among shots in DTI data. The altered diffusion-encoding among shots due to large-scale rotation must also be corrected, since neglecting these effects will result in inaccurate diffusion-weighted images and consequently inaccurate estimations of diffusion tensors. The challenge of correcting motion-corrupted diffusion-encoding in multishot acquisitions has not yet been widely addressed [2]. Therefore we present a new method to correct motion-corrupted diffusion-encoding in multishot DTI, thereby allowing reliable high-resolution diffusion images and accurate diffusion tensor information even in the presence of large-scale subject motion.

METHODS: The underlying diffusion-encoded image signal for a shot experiencing rotational motion can be expressed as: $\boldsymbol{I}_{\boldsymbol{\varepsilon},\boldsymbol{\gamma}}\left(\boldsymbol{W}_{\boldsymbol{\varepsilon}}[\mathbf{r}_\mathbf{p}]\right) = \boldsymbol{S}(\mathbf{r}_\mathbf{p}) \times \phi_{\boldsymbol{\varepsilon},\boldsymbol{\gamma}}(\mathbf{r}_\mathbf{p}) \times \boldsymbol{exp}\left[\left(\mathbf{b} - \mathbf{R}_{\boldsymbol{\varepsilon}}\mathbf{b}\mathbf{R}_{\boldsymbol{\varepsilon}}^{\mathbf{T}}\right)\boldsymbol{D}(\mathbf{r}_\mathbf{p})\right]$, where $\boldsymbol{\varepsilon}$ is the shot number, $\boldsymbol{\gamma}$ is the coil channel, $\mathbf{r}_\mathbf{p}$ is the spatial position in the image, and $\boldsymbol{W}_{\boldsymbol{\varepsilon}}$ is the spatial transformation (rotation and translation) due to large-scale motion of the shot. $\boldsymbol{S}$ represents the ideal diffusion-weighted image (i.e. $\boldsymbol{S}(\mathbf{r}_\mathbf{p}) = \boldsymbol{S}_\mathbf{0}(\mathbf{r}_\mathbf{p})\boldsymbol{exp}[-\mathbf{b}\boldsymbol{D}(\mathbf{r}_\mathbf{p})]$) free of motion-corruption, and $\phi_{\boldsymbol{\varepsilon},\boldsymbol{\gamma}}$ represents both the motion-induced phase error of the shot and sensitivity of the coil channel. The last exponential term represents the altered diffusion-encoding due to rotational motion, where $\mathbf{R}_{\boldsymbol{\varepsilon}}$ is the rotation matrix describing the motion, $\boldsymbol{b}$ is the applied diffusion b-matrix, and $\boldsymbol{D}$ is the diffusion tensor. When $\mathbf{R}_{\boldsymbol{\varepsilon}}$ is different among shots, as is usually the case for large-scale motion, each shot is encoded with a different diffusion-weighting given by the last term. Therefore these encoding-altering terms must be included during reconstruction in order to produce an accurate diffusion-weighted image $\boldsymbol{S}$. However, it is clear that the encoding-altering terms require a priori knowledge of the true diffusion tensors $\boldsymbol{D}$, which is not possible in practice. Our correction approach therefore involves an iterative procedure to correct the altered diffusion-encoding using progressively better estimates of $\boldsymbol{D}$. First we use a recently developed technique [3] in which large-scale pixel misregistrations and motion-induced phase errors (i.e. $\mathbf{W}_{\boldsymbol{\varepsilon}}$ and $\phi_{\boldsymbol{\varepsilon},\boldsymbol{\gamma}}$) among shots are estimated and corrected using a multiplexed SENSE-based reconstruction without diffusion-encoding correction. The resulting diffusion-weighted dataset is used to obtain rough initial approximations of the diffusion tensors via multivariate regression. These tensor approximations are then used to calculate the above encoding-altering terms. Next, a modified version of the original reconstruction technique is performed with these encoding-altering terms included, producing a more accurate diffusion-weighted dataset than the original. The new dataset is then used to obtain better approximations of the diffusion tensors, from which improved approximations of the encoding-altering terms are calculated. These new terms are included in a subsequent reconstruction, and the process is repeated in an iterative fashion. The performance of this technique was evaluated on the following data. T2-weighted images and diffusion-tensor data (15 b-directions) were acquired on a 3T system (GE HD, Waukesha, WI) using a 4-shot interleaved EPI sequence with a 32-channel head coil (Matrix size = 256x256, FOV = 19.0 cm, Slice Thickness = 4.0 mm, TR = 5000 ms, TE = 73 ms, b-factor = 800 s/mm^2). Two datasets were acquired: a stationary dataset used as a gold-standard, and a dataset in which a volunteer was asked to rotate his head continually by ±30-40^o during the course of the scan. The iterative reconstruction was performed on the motion-corrupted dataset and two quantitative measures were made: 1) fractional anisotropy (FA), and 2) angular deviation between the primary eigenvectors (V1) of the reconstructed dataset and the gold-standard dataset. All processing was performed in Matlab (The MathWorks, Natick MA) on a Linux machine (2.30 GHz CPU, 16 GB RAM).

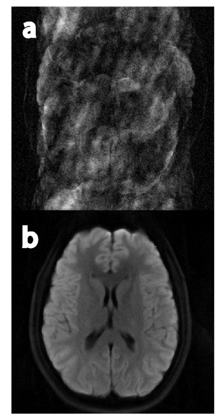

Figure 1: DWI images for *(a)* no correction, *(b)* phase, large-scale motion and diffusion-encoding correction.

RESULTS: Total computation time for the initial diffusion-weighted image was approximately 6.5 mins (26 secs/b-direction). Each subsequent iteration took approximately 2.5 mins (10 secs/b-direction). Figure 1 shows the reconstructed DWI images without any correction (direct FFT), and with 2 iterations of the correction method described. Figure 2 shows the FA maps and V1 angular deviation maps in the genu and splenium of the corpus callosum (CC) after phase correction only (2a), after phase and large-scale motion correction (2b), and after phase, large-scale motion, and diffusion-encoding correction with 2 iterations (2c). Mean FAs within the CC for the images (left to right) were: 0.57, 0.62, and 0.67. Mean V1 deviations were: 25.4^0, 14.9^0, and 9.2^0.

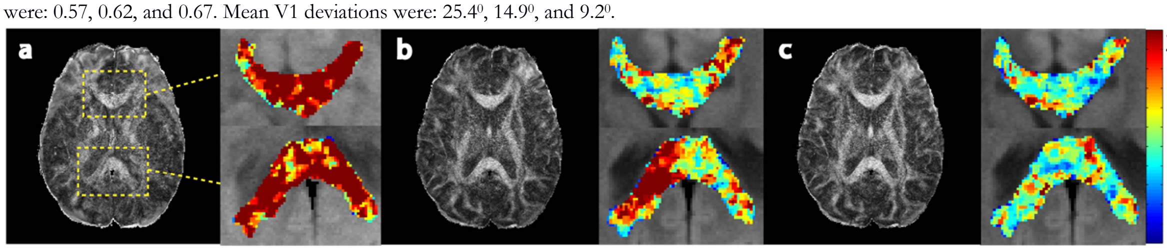

Figure 2: FA maps and V1 deviation for *(a)* phase correction only, *(b)* phase and large-scale motion correction, *(c)* phase, large-scale motion, and diffusion-encoding correction.

DISCUSSION: A clear improvement in FA and V1 angular deviation is seen after phase and large-scale motion correction, compared to phase correction alone. However there remain significant errors in the calculated V1, as demonstrated by the high V1 angular deviation, because the alterations in diffusion-encoding were neglected. After diffusion-encoding correction with 2 iterations of the described method there is a marked increase in FA values and also reduced V1 angular deviation, indicating that the tensors calculated from this reconstruction are closer to the gold-standard tensors. While computation times are generally a concern for iterative methods, we demonstrate that the time spent for each iteration is small compared to the initial reconstruction. This is because the majority of reconstruction parameters are generated during the initial reconstruction, and all subsequent iterations need only to modify these parameters with the encoding-altering terms, thereby taking significantly less time. Additionally, we show that only a few iterations are needed for appreciable improvements in tensor calculations. Although this study used a 4-shot EPI acquisition, our reconstruction technique can be easily generalized to a greater number of shots, making it applicable for studies requiring even higher spatial resolutions.

CONCLUSION: We show here that our technique is able to correct motion-corrupted diffusion-encoding, in addition to motion-induced phase errors and pixel misregistrations, in multishot diffusion-weighted EPI. As a result, diffusion tensor information which would otherwise be inaccurate can be estimated more precisely. We therefore expect that this method would be valuable for clinical and neuroscience investigations in which accurate high-resolution DTI information is needed.

REFERENCES: [1] Bammer R. European Journal of Radiology, 40:169-184 (2003), [2] Aksoy M, et al. Magn Reson Med, 59:1138-1150 (2008), [3] Guhaniyogi S, et al. Proceedings 21st Annual ISMRM, Salt Lake City, Utah, USA, 3765 (2013)

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