Inherent Correction of Artifacts from Large-Scale Patient Motion in High-Resolution Multishot Diffusion-Weighted EPI

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TARGET AUDIENCE:
The aim of this work will benefit researchers and clinicians whose investigations require high-quality and high-resolution diffusion-weighted (DWI) or diffusion-tensor (DTI) images free of motion-induced blurring and artifacts.

PURPOSE:
DWI data are very typically acquired using single-shot echo-planar imaging (EPI) due to its relative insensitivity to minute patient motion. Large-scale patient motion, however, can cause significant geometric distortions in single-shot EPI. Additionally, a major drawback of single-shot EPI is its limited attainable spatial resolution [1]. Because of these reasons, small anatomical structures of clinical significance may be difficult to identify with single-shot DWI. To overcome the limitations in single-shot techniques and resolve these structures, a natural choice would be multishot EPI acquisition because of its capability to improve spatial resolution and reduce distortions. Multishot acquisitions have not yet been widely adopted for DWI mostly due to its amplified sensitivity to minute motion from one shot to another. That is, small motion during the application of diffusion gradients causes phase variations among shots and leads to artifacts in the reconstructed image [2], rendering it unusable. Furthermore, the presence of large-scale patient motion can result in image blurring, even in phase-corrected multishot DWI, and presents an additional challenge. If the shot-to-shot phase variations and degree of large-scale motion are known, this information can be used to reduce artifacts through improved image reconstruction. While it has been proposed that navigator echoes can be acquired with the data to estimate this information, the strategy is often at the expense of reduced imaging throughput since 2D navigators are required for accurate estimation [3]. To address these challenges we present a method to accurately estimate and correct motion-induced phase errors and large-scale head motion in multishot DWI without navigators, and thus produce high-resolution images with minimal artifacts capable of resolving small structures even in the presence of large-scale subject motion.

METHODS:
T2-weighted images and diffusion-tensor data (15 b-directions) were acquired on a 3T system (GE HD, Waukesha, WI) using a 4-shot EPI sequence with an eight-channel head coil (Matrix size = 128x128, FOV = 19 cm, Slice Thickness = 1.5 mm, TR = 7000 ms, TE = 65 ms, b-factor = 1000 s/mm^2) at two different head positions. Large-scale motion corruption was then produced by combining data (two interleaves each) from each head position. A slice known to contain the optic nerve was chosen for correction to determine if small structures could still be identified after motion correction. The complete correction technique consists of several steps. First, Nyquist artifacts are removed from the T2-weighted and DWI data using a recently developed iterative procedure [4]. Next, coil-sensitivity profiles are estimated from the T2-weighted image. The sensitivity profiles are used with the conventional SENSE procedure [5] to reconstruct an image from each undersampled interleave data, resulting in four unaliased full-FOV images for each b-direction. The motion-induced phase variations for every interleave in each b-direction are then determined from these images. For large-scale rotation and translation between interleaves, a 2D affine registration using FSL-FLIRT [6] is used to estimate the angle/displacement between all images and a reference image (chosen as the one with the maximum correlation coefficient among all images). Finally, the sensitivity profiles and estimated phase errors are used in a multiplexed SENSE-based reconstruction in which selected data, based on the estimated angles/displacements, from all interleaves are used to calculate the true uncorrupted signal in an image free of artifacts and blurring. All processing was performed in Matlab (The MathWorks, Natick MA) on a Linux machine (2.30 GHz CPU, 4 GB RAM). Ghost-to-noise ratios (GNR) and white/grey matter contrast-to-noise ratios (CNR) were calculated in the uncorrected and corrected images for quantitative analysis.

RESULTS:
Total computation time was approximately 6 minutes. Figure 1 shows the diffusion images before any correction (1a), after phase correction only (1b), and after phase and large-scale motion correction (1c). GNRs for the images (left to right) were: 1.43, 1.22 and 1.21. CNRs were: 1.28, 6.69 and 8.40. The thin optic nerve bundles could not be identified in the image with phase correction alone (2a), but are easily resolved in the image with phase and large-scale motion correction (2b).

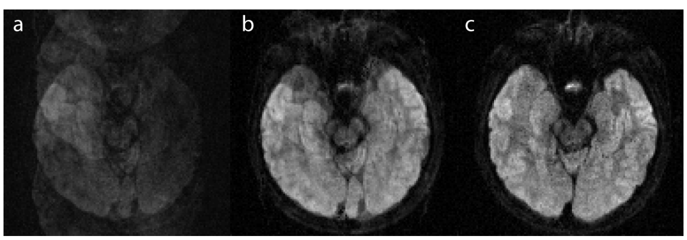

Figure 1: *(a)* Motion artifacts before correction, *(b)* reduced artifacts after phase correction only, *(c)* reduced artifacts and blurring after phase and large-scale motion correction.

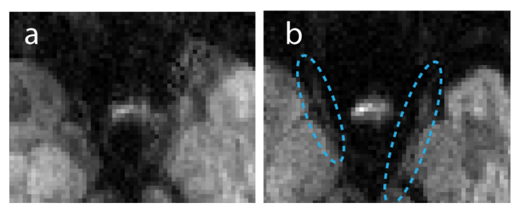

Figure 2: *(a)* Optic nerves are unidentifiable in image from Fig 1b. *(b)* Optic nerves are visible (blue ovals) in image from Fig 1c.

DISCUSSION:
A clear improvement is shown in image quality and noise metrics (GNR and CNR) after phase correction alone. The ghosting artifacts due to the motion-induced phase errors are largely suppressed. However, large-scale head movement still degrades image quality in the significant blurring effect even after phase correction. By inherently estimating the large-scale angles/displacements between head positions with preliminary SENSE images, and applying this information in the final image reconstruction, the blurring effect is greatly reduced to the point where white/grey matter contrast is recovered and fine structures (shown here with the optic nerve as an example) can be identified. In comparison to navigator-based reconstructions this method is advantageous in that it does not require any modifications to the acquisition sequence and allows for improved imaging throughput. Additionally, it demonstrates the capability of multishot acquisitions to produce high quality images free of motion corruption, and without the limited spatial resolution and geometric distortions as the result of single-shot acquisitions. Although this study is based on a 4-shot EPI acquisition, our technique is generic and can be readily extended to a greater number of shots, making it applicable in studies requiring even higher spatial resolutions.

CONCLUSION:
We show here that our technique is able to inherently correct for artifacts caused by motion-induced phase errors, and blurring artifacts caused by head movement in multishot diffusion-weighted EPI, all without reference or navigator echoes. As a result, small fiber structures which are otherwise unobservable can be readily identified in the final high-resolution images. It is anticipated that this technique would be valuable in clinical and neuroscience investigations in which detailed information of microstructures are needed.

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