Optimizing Phase Correction for Multi-Shot DWI with Conjugate Gradient Method and Oversampling

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INTRODUCTION: Multi-shot techniques, such as PROPELLER (1) and self-navigated interleaved spirals (SNAILS) (2), have demonstrated great utility for high resolution diffusion-weighted imaging (DWI). Recently, a conjugate gradient (CG) method that corrects for phase variation induced by physiologic motion was introduced and demonstrated to improve the image quality of multi-shot DWI dramatically. Moreover, this technique can be easily combined with the SENSE (3) reconstruction for parallel imaging. However, little is known about how trajectory design parameters affect their navigation capabilities or how to optimize trajectories for multi-shot DWI motion correction. With the CG method we can evaluate the phase correction capability relative to different readout strategies and their trajectory design parameters in the presence of k-space undersampling and phase map errors. In this study, we demonstrate more optimal strategies for motion correction can be achieved with a combination of both CG phase correction and **k**-space oversampling. We show that trajectories that oversample the center of **k**-space have more favorable properties for phase correction than critically sampled trajectories. CG phase correction achieves the best image quality in the least-square sense, while a well-balanced oversampling of the center k-space increases the tolerance for trajectory imperfection (e.g. due to eddy currents) and errors in phase map, thus offers more robustness for multi-shot DWI.

METHOD: The CG method treats the motion induced phase error as an additional encoding term in the encoding function. Multi-shot data acquired in **k**-space can be expressed in a matrix and vector format as (4),

$$\mathbf{d} = \mathbf{E}\,\mathbf{m} \qquad [1]$$

Here, **d** is **k**-space data stored in a column vector; **m** is image space data stored in the same fashion; and **E** is the encoding matrix including both Fourier encoding and phase error terms. A least-squares solution of Eq.[1] is given by,

$$\mathbf{m} = (\mathbf{E}^{\mathbf{H}}\mathbf{E})^{-1}\mathbf{E}^{\mathbf{H}}\,\mathbf{d} \qquad [2]$$

The accuracy of this solution depends on the matrix condition of $\mathbf{E}^{\mathbf{H}}\mathbf{E}$, which, in turn, is determined by the k-space trajectory and phase variation.

Six readout trajectories were evaluated with this CG phase correction algorithm, including interleaved EPI (iEPI) (4), conventional density spiral ($\alpha = 1$) and four variable density spiral with pitch factors α of 2, 3, 4 and 5. Motion induced phase errors were added to each interleaf. Two sets of simulation were performed: one with estimation errors in phase maps and the other with k-space undersampling. All trajectories contain 20 interleaves. In the first set of simulation, true phase maps were not used for phase correction; specifically, ±5% random perturbations were introduced to the phase maps which simulate error in phase map estimation. In the second set of simulation, undersampling the **k**-space was achieved by skipping every other interleaf, while maintaining a perfect phase map. *In vivo* DTI was acquired with SNAILS at various α values.

RESULTS: Figure 1 shows a representative set of images reconstructed for different trajectories under various conditions. Figure 1(a) uses the complete k-space data and has perfect knowledge of phase maps. Figure 1(b) uses phase maps that deviate from the true phase map by ±5%. Figure 1(c) uses perfect phase maps but only half k-space data. CG reconstructed images are compared to images reconstructed using only first-order correction. Figure 2 compares reconstruction errors for various trajectories. It is clear that increasing oversampling factor at the center k-space improves the trajectory's tolerance to distortions of phase map and **k**-space trajectory. Even with a reduction factor of 2, the image with $\alpha = 4$ demonstrates good quality, while severe aliasing artifacts can be seen in EPI and conventional spiral images. Figure 2 compares in vivo FA maps. Best image quality is achieved with both CG algorithm and k-space oversampling.

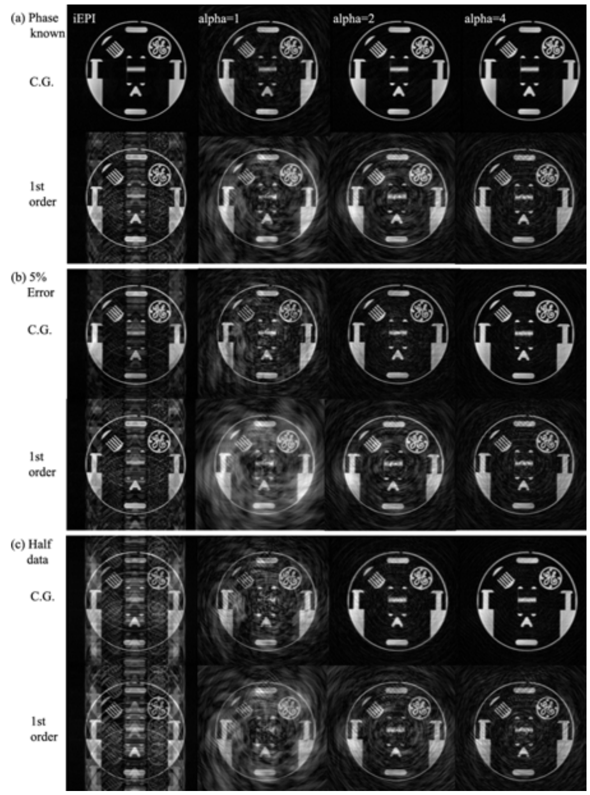

Figure 1. Comparison of phase correction capability of different trajectories under three conditions: (a) phase map is perfectly known; (b) phase map used for reconstruction contains 5% error; and (c) only half of the data are used, but with known phase maps. In each group, the first row shows CG reconstructed images and the second row shows images with only first-order correction. The trajectories from left to right are: iEPI, conventional spiral ($\alpha = 1$), VD spiral with $\alpha = 2$, and with $\alpha = 4$.

DISCUSSION: The CG phase correction method has the capability to accurately reconstruct multi-shot diffusion weighted images acquired with arbitrary trajectories, provided that the **k**-space trajectories and the phase maps are accurate. In practice, however, the accuracy is degraded due to errors in the trajectories and in the phase maps. Inaccurate reconstruction also arises from **k**-space undersampling, which can appear, for example, from gradient imperfection and parallel imaging. This image degradation can be alleviated by choosing a more suitable readout trajectory.

Quantitatively optimizing the trajectory for motion correction is a difficult task because there is a lack of a suitable metrics in comparing high resolution diffusion weighted images. Our initial simulations indicate that CG phase correction algorithm combined with trajectories that oversample the center of **k**-space provide more robust phase correction capability and better image quality. For example, the VD spiral was able to reconstruct a diffusion weighted image of good quality by using only half of the **k**-space data. On the other hand, **k**-space undersampling resulted in severe artifacts in both iEPI and conventional spiral. Additionally, in practice, the estimated phase maps always contain errors. Therefore, it is important for the trajectories to have minimum sensitivity to the phase map imperfection. Our simulations show that, when combined with the CG algorithm, trajectories that oversample the center **k**-space offer more tolerance for phase map errors. In conclusion, CG phase correction and oversampling are two important factors for minimizing motion artifacts and optimizing multi-shot high resolution DTI.

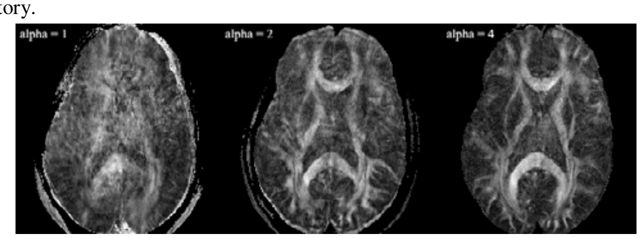

Figure 2. Comparison of *in vivo* SNAILS acquired 256x256 FA maps with different oversampling factors: $\alpha = 1$ (left), $\alpha = 2$ (middle), $\alpha = 4$ (right).

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