K-Space Weighted Multi-Channel Regularization for Motion Correction in Multi-shot DWI

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Introduction: Multi-shot diffusion-weighted imaging (DWI) can provide high-resolution images with significantly reduced distortions. However, the images can be severely degraded by the motion-induced phase error that varies from shot to shot (1, 2). The conjugate-gradient (CG) based reconstruction (2) has been proposed to correct motion-induced artifacts. And accurate estimation of the phase error is required in this method. Besides, the CG algorithm only utilizes the phase information from the navigator image. In this work, we propose an effective algorithm based on Tikhonov regularization (3) to fully utilize acquired navigator data and further reduce the residual aliasing artifacts. Both single-coil and multi-coil simulations have been performed to demonstrate the feasibility of the proposed method.

Theory: In the navigated/self-navigated multi-shot DWI, data are collected in n shots via m coils, along with n×m navigator data. In this case, there are virtually n×m different channels. Each channel modulates the collected data and navigator data uniquely, dependent on phase error and coil sensitivity. Using the framework of Tikhonov regularization, our algorithm can be written as:

$$\vec{x}^{\vec{\lambda}} = \arg\min_{\vec{x}} \{ \| FPS\vec{x} - \vec{y} \|_2 + \sum_i \lambda_i^2 \| WFp_i s_i \vec{x} - \vec{y}_{0,i}) \|_2 \}$$

where λ_i ($i=1\ldots n_{shot}\times m_{coil}$) is the regularization parameter of the i-th channel. p_i and s_i are the phase error and sensitivity map of the i-th channel respectively. $\vec{y}_{0,i}$ is a vector formed by k-space navigator data of the i-th channel. $\vec{y}$ is a vector formed by all the acquired k-space data. $\vec{x}$ is a vector formed by the desired image to be solved for. F is the Fourier encoding matrix. P is the phase error map of all channels. S is the sensitivity map of all channels. W is the k-space weight matrix.

In Tikhonov method, the regularization is performed in image-domain with only one combined reference image as prior. In this work we consider the fact that the collected data from one channel should be the most correlated to the navigator data from the same channel. Consequently, if the reconstructed image is modulated by one channel and taken an inverse FFT back to k-space, the resultant data should be consistent with the corresponding navigator data from that channel. Based on this assumption, multiple channel-based regularization terms are added to fully use the information from each navigator data including both magnitude and phase. Since the navigator data $\vec{y}_{0,i}$ contain only a central portion of k-space data, a uniform regularization parameter for all frequencies which is used in standard Tikhonov method, is not appropriate and may degrade the reconstructed image. In this study our regularization is performed in k-space and a weight matrix W is used to allocate spatial frequency-varying weights to the regularization in k-space. In this way, we assign different regularization parameters to different spatial frequency bands. The equation is solved using CG algorithm.

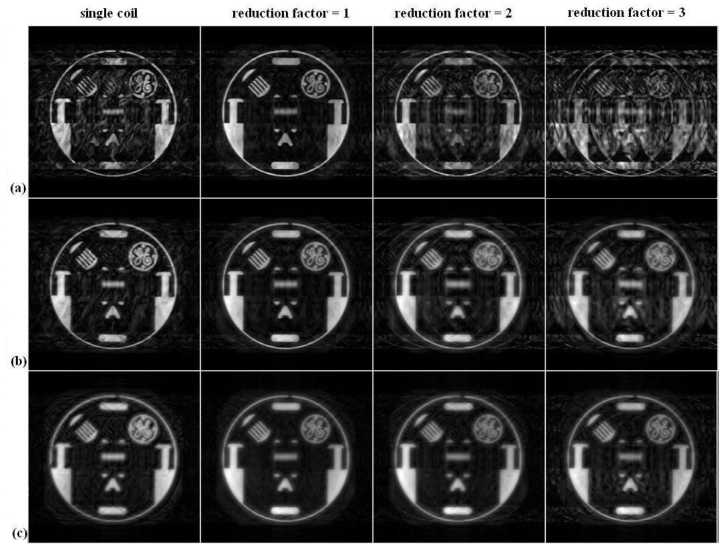

Fig.1: Simulation results of Navigated Multi-shot DW-EPI trajectory. (a) Standard CG algorithm; (b) Tikhonov regularization; (c) k-space weighted multi-channel regularization. The first column shows the results of single coil simulation. From left to right, the other 3 columns show multi-coil simulation results with reduction factor from 1 to 3.

Method: A phantom image (256×256) was acquired on a 1.5T GE SIGNA EXCITE using an 8-channel head coil. The motion-induced phase error was simulated by adding a random linear phase term to the image (2). The phantom k-space data were then computed by using an inverse FFT on the image along an 8-shot interleaved EPI trajectory. The central portion of k-pace with 32×32 matrix was taken out as navigator data. The phase error map and sensitivity map were generated using the navigator data.

Results: Figure 1 shows the results of both single-coil and multi-coil simulations. Some motion-induced artifacts can still be seen on the images reconstructed by standard CG and Tikhonov regularization (more severely degraded in the standard CG image), but are significantly diminished on the images reconstructed by our method with relatively sharp edges and clean background. Even with a large reduction factor, the multi-channel regularization provides considerably good images.

Discussion and Conclusions: The preliminary simulation results have shown that our method can effectively reduce motion-induced aliasing artifacts even though the navigator images have quite low resolution and the requirement for estimation of the phase error is not as crucial as required by the standard CG algorithm mentioned above. The conventional Tikhonov regularization only uses a combined reference image as prior information without treating each channel uniquely. By using multiple constrains and frequency-varying regularization parameters, the proposed method is more effective for motion correction in multi-shot DWI. The mathematical framework built in this work can also be used for other navigated/self-navigated multi-shot DWI trajectories. Some clinical applications will be conducted in the future.

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