JOINT ESTIMATION BASED PHASE ERROR CORRECTION IN MULTI-SHOT SPIRAL DIFFUSION WEIGHTED IMAGING

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TARGET AUDIENCE: Researchers and clinicians interested in high resolution DWI
PURPOSE: Multi-shot spiral imaging is a typical method used to achieve high resolution in diffusion-weighted imaging (DWI). However, it has been shown that involuntary motion of the subject will lead to phase errors in image space [5], and the phase inconsistencies between different shots will introduce artifacts in the final reconstructed image. Traditionally, with variable-density spiral (VDS) technique or navigator data, such artifacts can be removed [4]. Iteratively Regularized Gauss-Newton method (IRGN) [1] has been used as a method of joint estimation of sensitivity map and objects function, and also has been mentioned as an alternative to conventional reconstruction methods in DWI using EPI trajectory [2]. Here, we extended IRGN algorithm in multi-shot spiral imaging of DWI to jointly estimate motion induced phase errors and the object function. Preliminary results show that by using little amount of oversampling in the k-space center, our proposed method provide more accurate estimation of the object function than that derived from VDS technique.

THEORY: MRI signals in k-space obtained from N shots is given by

\[ K_j = F_j (I e^{i \phi}) \quad j = 1, \ldots, N, \]

where the index describes the shot \( j \) of a multishot acquisition; \( I \) denotes the motion free image to be reconstructed; \( \phi \) is the motion-induced phase error for shot \( j \); \( F_j \) is an operator which maps the object function and the phase map of \( j \) to the measured k-space data \( K_j \). This nonlinear equation can be solved by IRGN method using the proposed new model which estimates the image \( I \) and phase map \( \phi \) at the same time.

\[ I, \phi = \arg \min \sum_j \| F_j (I e^{i \phi}) - K_j \|_2^2 + \alpha \| I - I_0 \|_2^2 \quad j = 1, \ldots, N \]

In this work, we only consider the linear component of the motion-induced phase error. Thus the regularization of IRGN by penalizing high frequencies to enforce the smoothness of the phase map can be directly applied here.

METHODS: To validate the proposed concept, only numerical simulations were performed due to limited imaging sequence access. Firstly, an unaliased diffusion weighted image is acquired by using the iterative phase correction [3], which was used as a reference image. Secondly, k-space data was sampled by 2 interleaved spiral trajectories, each consisting of a variable density spiral using a modified version of Hargreaves’ code [6]. Thirdly, random linear phase error was added to both of the two shots. Lastly, the motion-free image and phase map were estimated using the proposed method.

The reference DW image was obtained on a GE 3T HD MRI scanner (GE Healthcare, Milwaukee, WI) with an eight-channel RF coil and a gradient system. A spin-echo spiral imaging pulse sequence was used with the following parameters: repetition time = 5s, echo time = 56ms, FOV = 24cm, matrix size = 96*96, slice thickness = 2.5mm.

RESULTS AND DISCUSSION: Representative results are shown in Fig. 1. In this case, there is a global phase difference of \( \pi \) between 2 shots, which we consider as the most severe situation. Compared to the reference image (Fig. 1a1), the image (Fig. 1a2) after adding a linear phase error suffers from aliasing artifacts as well as signal loss. The image (Fig. 1b2) obtained by the proposed method provides a much improved estimation of the object function, while the image (Fig. 1b1) derived from the direct phase correction using the self-navigator data has unsuppressed noise in the background and still has some residual artifacts as pointed by the arrows.

It is noteworthy that even in case of using regular spiral trajectory, which means the center of the k-space is not oversampled, our method still to some extend works and removes most of the motion-induced artifacts, but leads to image with increasing noise. Therefore, minor oversampling in the k-space can improve the performance of this method. The long readout window required by the traditional VDS DWI might be alleviated.

CONCLUSION: A new method which jointly estimates object function and motion-induced phase errors in muti-shot spiral DWI is proposed, and is validated by the simulation results. Our proof-of-concept work demonstrates that this method can estimate the desired artifact-free image more accurately than self-navigator based technique when navigator information is limited. Thus, it has potential utilization in high resolution diffusion weighted imaging with multi-shot technique when the readout window is critical. Further work will be performed to apply this method to reconstruct images from \textit{in vivo} data with real motion-induced phase errors.

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REFERENCES: