Improved multi-shot EPI ghost correction for high gradient strength diffusion MRI using Structured Low-Rank Modeling k-space reconstruction

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Synopsis

Multi-shot EPI diffusion MRI acquired using high diffusion-encoding gradient strengths suffers from severe ghosting artifacts, which can bias and confound the estimation of diffusion microstructural MRI measures at high b-values. In this work, we show that conventional EPI ghost correction techniques fail short in ghosting reduction when high diffusion-encoding gradient strengths ~250mT/m are used, and that advanced reconstruction algorithms based on structured low-rank matrix modeling can substantially reduce ghosting without introducing additional artifacts.

Introduction

Multi-shot EPI diffusion MRI is an appealing alternative to conventional single-shot EPI dMRI as it is less vulnerable to geometric distortions and eddy-current artifacts due to the shortened echo train length. Unfortunately, reconstruction of multi-shot EPI images still suffers from odd/even line inconsistency, an intrinsic feature to all EPI sequences (i.e., Nyquist ghosting). These effects are exacerbated when using high gradient strength MR scanners as the strong gradients amplify eddy current distortions and static field inhomogeneities.

To address this problem, we explore the use of advanced reconstruction algorithms based on Structured-Low Rank Matrix (SLM) modeling, which have shown excellent results for 2D single and multi-shot EPI dMRI with lower diffusion gradient strengths. We demonstrate that SLM modeling can provide high quality, artifact-free 3D multi-shot EPI dMRI with diffusion gradient strengths up to 250 mT/m.

Method

Ghosting is a pervasive artifact in EPI, which is produced by the mismatches between k-space data acquired with gradients with different polarities and multiple shots. Conventionally, EPI ghosting is corrected with phase information from k-space data acquired from navigator scans. While robust and computationally cheap, ghost correction methods based on navigators often make modeling errors. The assumptions made in correcting for k-space line mismatches are excessively simplistic, especially in the regime of high gradient strengths.

Alternatively, it has been shown that ghost correction in EPI reconstruction can be cast as an undersampled k-space reconstruction problem, where the k-space data of different shots and polarities are treated separately. As the k-space data for each shot and polarity is highly undersampled, accurate reconstruction requires prior knowledge to compensate for the lack of measured data (ill-posed problem). Structured Low-rank Matrix (SLM) methods exploit the fact that k-space data are linearly predictable, and hence it can be embedded into a structured Hankel matrix, which can be shown to be a low-rank matrix. Hence, missing k-space lines can be recovered by applying low-rank matrix recovery techniques.

We investigate whether SLM methods can reduce ghosting artifacts in ex-vivo whole human brain diffusion MRI data acquired with high diffusion-encoding gradient. Similar to the work of, we formulate the reconstruction problem as a SENSE-type optimization algorithm, where the data fidelity term is complemented with a regularizer based on SLM. This regularization term enforces low-rank characteristics on a Hankel matrix that comprises of the k-space data from all shots and odd/even polarities. The proposed method can be considered within the LORAKS framework, and we refer to it as the LORAKS-based method from now on. Coil sensitivities are estimated from a GRE acquisition with the popular SPIRiT algorithm. We compare this approach with the standard linear phase correction (LPC) method based on 1D navigators, and with a SENSE-based reconstruction with no additional prior information.

Results

Reconstructed images using the combined shots are shown in Fig.1. The LPC and SENSE-based reconstructions were insufficient to correct for the ghosting artifacts seen with high diffusion-encoding gradient strengths. On the other hand, LORAKS enabled substantial ghost reduction, which is best seen on the intensity-amplified images.
Discussion
Our results show that EPI ghosting in images acquired at high diffusion-encoding gradient strengths requires more complex approaches than conventional 1D navigators, and that SLM-based recovery algorithms can substantially reduce the level of ghosting. We foresee an even better quality reconstruction with more advanced SLM-algorithms i.e., exploiting linear predictability of k-space data over channels, introducing calibration data into the reconstruction problem, or incorporating q-space regularizers, aiming at a joint reconstruction from the k-q space, directly.

Conclusions
3D multi-shot diffusion MRI acquired using high diffusion-encoding gradients requires far more advanced reconstruction algorithms than conventional approaches to producing ghosting-free DWI images. In this preliminary work, we have shown that structured low-rank matrix-based recovery algorithms substantially reduce ghosting effects, enabling distortion-free, diffusion MRI in ex vivo samples that often require higher b-values to achieve sufficient diffusion weighting. We believe SLM-based algorithms could be indispensable for high quality, multi-shot diffusion MRI reconstruction in Connectome like MR scanners.

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References

Figures
Two representative sagittal slices reconstructed with linear phase correction, SENSE, and LORAKS-based reconstruction. Note the marked ghosting reduction obtained with LORAKS-based k-space reconstruction.