Navigator-free, high-resolution prostate diffusion imaging: Multi-Shot EPI with Multi-Scale Low-Rank Reconstruction

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Synopsis

Keywords: Diffusion Reconstruction, Prostate

Motivation: Prostate DWI is an important contrast for the diagnosis of prostate cancer.

Goal(s): The aim is to achieve prostate DW images and ADC maps with less-geometric-distortion, high-resolution and high signal-to-noise ratio (SNR).

Approach: A novel multi-scale low-rank reconstruction approach is introduced to improve multi-shot EPI diffusion-weighted imaging of the prostate. It addresses the ability to jointly reconstruct images over all b-value/diffusion directions at multiple different spatial scales without loss of contrast/structure information.

Results: Applied to healthy volunteers using different resolution protocols, the method demonstrates significant improvements in image resolution and SNR compared to a state-of-the-art reference method in a clinically acceptable scan time.

Impact: This multi-scale, low-rank reconstruction approach for prostate DWI can significantly improve the quality of diagnostic images, benefiting clinicians and patients by enabling more accurate prostate cancer diagnoses within short scan times.

Introduction

Prostate Diffusion-weighted imaging (DWI) with ADC mapping is essential for the diagnosis of prostate cancer[1]. Single-shot EPI (ssh-EPI), while clinically prevalent, suffers from geometric distortions, near tissues-air interfaces, and limited image resolution by T_2^* decay[2]. Multi-shot EPI (msh-EPI) can potentially offer better resolution and less distortion. However, as a typical challenge, shot-to-shot phase variations induced by physiological motion[3] have to be corrected properly, which is particularly difficult in low-SNR prostate DWI. In the past, researchers have used locally low-rank[4,5] (LLR) or structured low-rank (SLR)[6,7] methods for navigator-free, phase-corrected DW msh-EPI, mainly in brain imaging. In this study, we propose to use the multi-scale low-rank[8,9] concept, applied across diffusion-directions/b-values[10] to improve the image quality of prostate DWI, achieving both high-resolution and high-SNR.

Methods

The multi-scale low-rank modelling, typically applied to dynamic imaging, models the image into spatial scales as $\mathbf{x}_j = \sum_{n=1}^{N} \mathbf{x}_{j,n}$, where $\mathbf{x}_{j,n}$ represents one image at timeframe j at the n-th scale. It integrates global low-rank ($n = N$), sparse modeling ($n = 1$), and various local low-rank scales ($1 < n < N$)[9]. For msh-EPI DWI in prostate imaging, factors like motion, susceptibility changes, and eddy currents can cause spatial mismatch between scan partitions. In this study, we treat data from each diffusion direction of each b-value as having a distinct temporal spatial-state (frame). The joint reconstruction across all b-values/diffusion directions (J frames) is thus formulated as:

$$\{\hat{\mathbf{x}_{1,\dots,J}}\} = \underset{\mathbf{x}_{1,\dots,J}}{\operatorname{argmin}} \sum_{j=1}^{J} \left\| A\left(\sum_{n=1}^{N} \mathbf{x}_{j,n}\right) - \mathbf{y} \right\|_2^2 + \sum_{n=1}^{N} \sum_{b=1}^{B_n} \lambda_n \left\| R_{b,n} \{x_{1,\dots,J,n}\} \right\|_{s'}$$

For each b-value/diffusion direction image frame $\mathbf{x}_j$, the system matrix A is a block-diagonal matrix containing each frame-specific system matrix A_j describing multiplication of the k-space sampling mask (M), the Fourier transform (F), the coil-sensitivity maps (S) and the phase map of each shot (P). $\mathbf{y}$ contains the measured k-space data across all diffusion-directions/b-values, while $R_{b,n}$ extracts the b-th spatial block at the n-th scale (each scale has B_n blocks) and combines blocks of all frames to form the Casorati matrix. By minimizing the nuclear norm (as a constraint on the rank of $R_{b,n}$) at each scale n, the correlation of each scale is enforced, sharing the across-frame redundant information. This guides the reconstruction with compact representations of different low-rank/sparse structures using varying low-rank block sizes. This could especially enhance SNR in high b-value images while keeping frame-specific spatial/contrast information.

Prostate DWI experiments were performed on 7 healthy volunteers at a 3T Scanner (Philips) using 16-channel anterior and 12-channel posterior coils. Measurements were taken in low- (1.6×1.6×3mm^3, matrix-size:192×188) and medium-resolution (1.3×1.3×3mm^3, matrix-size:240×236) with fat-suppressed 3-shot DW EPI. One subject was additionally scanned with high-resolution (1.0×1.0×3mm^3, matrix-size:256×240) using 4-shot EPI, and another with ssh-EPI (1.6×1.6×3mm^3) for comparison. All multi-shot EPI scans had four b-values (b=0,150,500,1000 s/mm^2) with varying numbers of diffusion directions (1,1,2,4 for each b-value), producing =8 frames. Each frame was repeated 3 times (NSA=3) with TE=59/TR=4000ms. ssh-EPI had 3 diffusion directions per b-value (b=0,150,500,1000 s/mm^2), NSA=1,1,2,4, and TE=83/TR=4000ms, matching the 5-minute scan time of low-/medium-resolution msh-EPI; the 4-shot scan took 6:15 mins. SPAIR was used for fat-suppression for all datasets.

For reconstruction, 20 iterations of ADMM with automatic regularization-parameter selection was used with $N = 5$ scales (1×1,4×4,16×16,64×64,full-matrix-size). Shot-to-shot phase estimation was performed using a modified IRLS-MUSSELS method (with 8-outer/8-inner iterations), assuming consistent magnitudes but varying phases between images for each b-value (similar to ref.[11]). The estimated phases were simply used to construct P. With estimated initial phase maps, each of the 8 frames was individually reconstructed using IRLS-MUSSELS[7] as the reference method (phase-initialized MUSSELS). Coil sensitivities are estimated from b=0 s/mm^2 images using ESPIRiT[12]. The reconstruction pipeline is shown in Fig.1.

Results

Fig.2 shows one dataset reconstructed with the multi-scale low-rank concept over 8 frames highlighting low-rank information at different scales. Fig.3 shows a subject's prostate at different resolutions compared to the reference method. Fig.4 shows the high-resolution (1 mm^2) b=1000 s/mm^2 images of four diffusion directions reconstructed with original/phase-initialized MUSSELS and the proposed algorithm, demonstrating the denoising capability of the proposed method. Fig.5 shows a comparison between ssh-EPI and msh-EPI (with two different reconstructions), highlighting the reduced geometric distortion with msh-EPI, and improved denoising especially using multi-scale low-rank for ADC mapping.

Discussion and conclusion

In this study, we employed a multi-scale low-rank method for msh-EPI prostate DWI reconstruction across b-values and directions, effectively using across-frame redundant information to guide the reconstruction. The technique yielded high-SNR DW images and ADC maps within a clinically feasible five-minute scan. Although there is minimal diffusion anisotropy in the prostate[13], there are noticeable temporal-spatial changes that are captured by the proposed algorithm (see different frames in Fig.2-4). Future applications may include regions with more severe macroscopic motion, such as liver or breast DWI, or high-resolution SNR-starved brain DTI.

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Figures

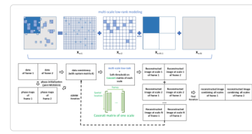

Figure 1. Multi-scale low-rank modelling scheme and reconstruction pipeline, showing the example with only two frames. For each b-value, the modified MUSSELS is used to estimate the phase of each shot, forming the system matrix A. Then, an ADMM solver is used to reconstruct the images at different scales. The low-rank nature of each scale was reinforced by minimizing the nuclear norm of each Casorati matrix constructed along the "frame" direction (different diffusion-directions/b-value). In the final iteration, images from all scales are combined to produce the final images.

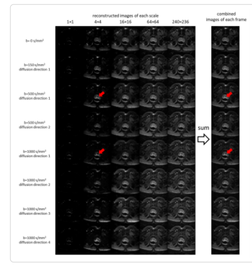

Figure 2. Multi-scale low-rank reconstruction of a subject's prostate using 8 frames from 4 b-values and multiple diffusion directions (1.6 mm^2). All images are individually normalized for better visualization. Multi-scale low-rank efficiently extracts sparse information (1×1) and captures different low-rank structures across scales. For example, a distinct direction-specific structure (direction 1 for b=500 and b=1000 s/mm^2) is clearly captured only at the scale 4×4 (red arrows). The final output images are the sum of all decomposed images from all scales of each frame.

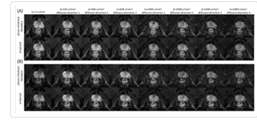

Figure 3. Multi-scale low-rank reconstruction of a subject's prostate with 8 frames at two (A) 1.6 mm (B) 1.3 mm resolution, comparing with the frame-by-frame reconstructed phase-initialized MUSSELS (prostate zoom in). For both scans, diffusion direction-specific structures can be well captured by the proposed algorithm, while the MUSSELS results are dramatically impaired by noise.

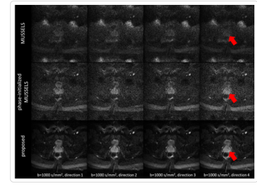

Figure 4. Multi-scale low-rank reconstruction of a high-resolution (1 mm) prostate DWI dataset with 8 frames, showing only 4 different diffusion directions b=1000 s/mm^2 images, comparing with original and phase-initialized MUSSELS reconstruction. With joint phase initialization, the image quality can be slightly improved from the original MUSSELS but there is still too much noise present. The proposed method can significantly improve the image quality and remove the noise (red arrows).

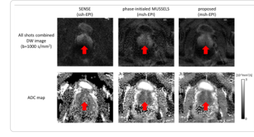

Figure 5. Four diffusion directions combined b=1000 s/mm^2 prostate DWI (in-plane 1.6 mm) with associated ADC maps, from ssh-EPI and msh-EPI using different reconstructions. Ssh-EPI produced DW images with strong geometric distortions, which can be mitigated by msh-EPI (red arrows). With the same scan time, the MUSSELS result shows lower SNR than ssh-EPI. For the same msh-EPI data, the proposed method can significantly improve the SNR by jointly reconstructing b-values. The same effects can also be seen in the ADC maps.