Robustness of echo planar imaging (EPI) distortion correction in diffusion tensor imaging using forward/reverse phase encode directional b=0 scans

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Introduction

Most diffusion tensor imaging (DTI) pulse sequences use echo planar imaging (EPI) readout. However, the low bandwidth in the phase encode (PE) direction leads to spatial distortions due to magnetic field inhomogeneities that can be described as a voxel shift in the PE direction [1]. Since EPI images with forward (for.)/reverse (rev.) PE directions provide voxel shifts in opposite directions, several approaches have been proposed to calculate voxel-wise displacement maps using the two [2,3]. Recently, Holland et al. presented a fast, highly computationally efficient unwarping method using for. and rev. PE direction EPI scans [4]. In this study, we propose a single DTI scan that implements two PE directions scans with b = 0 at the beginning from which the following DTI scans are unwarped. We test the reproducibility (repro.) and robustness of the unwarping technique from the voxel-wise FA comparison.

Methods

Unwarping: Forward/reverse PE direction b=0 scans were used to calculate a displacement map using the method of Holland et al. [4]. The displacement map is determined by iteratively minimizing a cost function that reflects the consistency of the unwarped images with forward and revesred PE directions and the smoothness of the deformation [4].

MR imaging: A healthy subject was scanned using a DTI imaging sequence under IRB approval, as shown in Fig1. A single b=0 scan with reversed PE direction is inserted after the first b=0 scan, leading to an increase of scan time by a single TR (7.8 s), much less than that required by field mapping [1] or point spread function mapping [5]. To evaluate the performance of the unwarping method, 3 scans were performed. Scan1: forward PE direction was set to Anterior (A) to Posterior (P), and reverse PE was set to P to A. Scan2: scan1 was repeated with the identical parameter settings. Scan3: forward PE direction was set to P to A, and reverse PE was set to A to P. The following MR imaging protocols for DTI scans were used: isotropic 2mm resolution, TR/TE=7800/92 ms, 51 slices, 9 scans with b=0, and 71 scans with b=1000 s / mm^2.

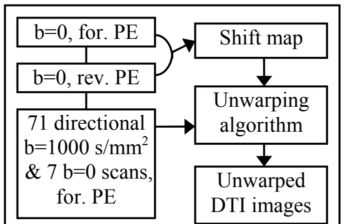

Fig 1. Sequence diagram and work flow of the unwarping process

Data analysis: The displacement map is calculated from forward/reverse PE directional EPI images with b=0. Time series DTI images were unwarped using the calculated displacement map. Both warped and unwarped FA maps were calculated with head motion correction. For voxel-wise FA comparison, b=0 images of each scan and FA maps were coregistered to anatomical T1-MPRAGE images.

Statistical analysis: Voxel-wise FA values in whole brain are compared, and correlation coefficients (R^2) is calculated between scans (see Fig2). The comparison of warped scan 1 and 2, indicates the baseline reproducibility of DTI analysis. The comparison of warped scan 2 and 3 indicates the error due to EPI distortion. The comparison of unwarped scan 1 and 2 indicates the reproducibility of the unwarping method. The comparison of unwarped scan 2 and 3 indicates the robustness of the unwarping.method.

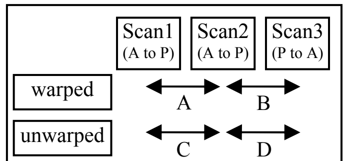

Fig 2. Diagram of comparison
A: repro. of FA in DTI analysis
B: error of FA in warped image
C: precision of unwarping
D: robustness of unwarping

Results & Discussion

Figure 3 demonstrates the qualitative results of unwarping on b=0 images and FA maps in DTI analysis. Severe image distortion is observed in the frontal lobe of the warped images, which is corrected after unwarping in both b=0 image and FA map (fig 3, yellow arrows). Note that unwarped b=0 images from scan 2 and 3 look consistent, indicating the quality of the performance of the unwarping (fig 3, blue arrows and circles). Table 1 shows the correlation of voxel-wise FA values betweens scans. The proposed unwarping method shows the high reproducibility over two separate scans (C: R^2=0.94), which is consistent to the baseline of DTI analysis with unwarped images (A: R^2=0.94). The unwarping method also shows the high robustness (B: R^2=0.81) while warped FA maps between scan 2 and 3 presents low R^2 (0.52) due to image distortion.

images	r^2 between FA	
	scan1 vs 2	scan2 vs 3
warped	0.94 (A)	0.52 (B)
unwarped	0.94 (C)	0.81 (D)

Tab 1. correlation coefficient of voxel-wise FA

However, we found residual warping in FA maps from the comparison of scan 2 and 3 that is not observed in b=0 images (fig 3, red / blue arrows and circles). This residual warping might be induced the eddy current artifact associated with the diffusion weighting gradients. This bias can be minimized when a displacement is calculated from for./rev. PE acquisition in every diffusion-weighted image, as demonstrated in the recent study [6].

The proposed DTI sequence does not require additional pre-scanning to correct EPI distortion, and a minimal time (<8s) is added in total running time. The unwarping method as applied to DTI shows accurate, reproducible and robust performance. Future work will examine time-efficient methods for incorporating eddy current corrections.

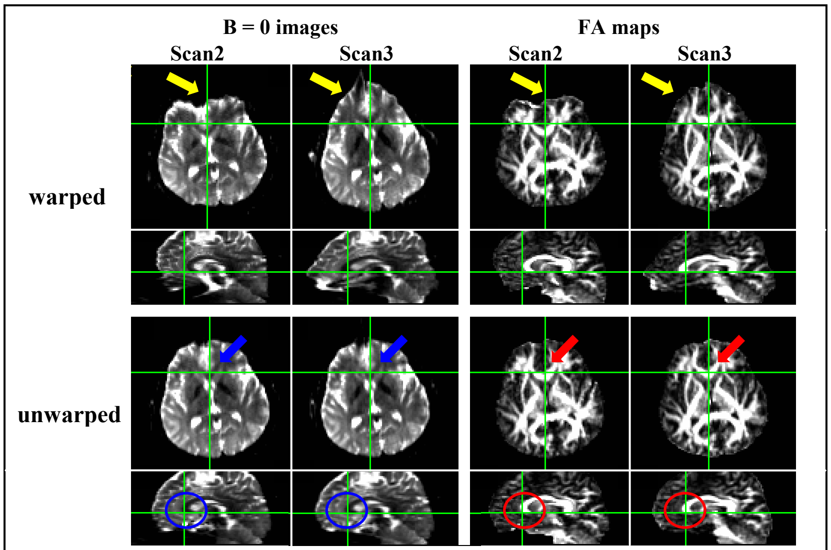

Fig 3. Qualitative comparison of unwarping method using two different PE directional scans

Acknowledgements

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Reference

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