Dynamically unwarped diffusion imaging removes direction-dependent eddy current effects and unveils hidden fiber structures

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INTRODUCTION

A major problem for high b-value diffusion tensor imaging (DTI) is eddy current (EC) artifacts. The leading EC-reduction method is a 12 degree of freedom (DOF) affine coregistration between some combination of diffusion directions and b=0 images or anatomical priors [4]. However, this only attenuates diffusion direction-dependent EC artifact. Other methods that more completely remove EC artifacts typically rely on calibration mapping for every direction in a time-consuming (separate) acquisition. These methods are technically demanding (field camera or advanced image-based field mapping) and do not necessarily capture the same ECs observed in the separate DTI data. We have in the past presented a combined acquisition and unwarping method [1] relying on a recent algorithm [2] that is superior to other methods in 3 ways: it 1) doesn't require additional time in typical use, 2) removes static field inhomogeneity warping and 3) is insensitive to drift in head position over time (see also [3]). We now present a pilot study at two sites, using a modified Stejskal-Tanner DTI sequence in 8 subjects at 3T and 7T, and show this method ***removes eddy current artifacts***, ***reduces tensor fit error*** and unveils structures ***only visible with dynamic unwarping***.

METHODS

8 healthy controls were scanned in IRB-approved protocols (5 at 3T site, 3 at 7T site) with a 71-direction 2mm isotropic whole-brain DTI sequence (b=1000sec/mm^2) with every direction repeated with a forward and reverse-phase encoding as described in [1]. Due to the repeats, this acquisition is equivalent to two averages of a single 71-direction DTI scan. b=0 weighted images were interspersed every 20 volumes. At 7T only, subjects were scanned in using GRAPPA factor 2 to reduce severe image warping artifact. The images were split into 3 pipelines: 1) warped, and 2) statically and 3) dynamically unwarped using the method of Holland et al[2]. Static unwarping relied on the unwarping maps created from the most recently-acquired b=0 unwarping map. These maps were coregistered to the intervening b=1000 images and used to unwarp the b=1000 images (reverse images were unwarped by inverting polarity of the shiftmap). This implementation of static unwarping produces the best possible unwarping that will approximately follow the head over time, but does not remove direction-dependent EC effects. For dynamic unwarping, every pair of forward and reverse images with matched weighting was unwarped together. The warped and static unwarped pipelines were corrected with a canonical EC+motion correction while the dynamic was corrected using 6 DOF rigid-body motion correction [4].

Using our previously-acquired pilot data [1], we developed an optimal motion correction pipeline for dynamic unwarping data that differed substantially from non-dynamically unwarped data. Specifically, a first-pass coregistration of all images to the averaged, coregistered b=0 images was followed by averaging of all b=1000 images. This was followed by a second-pass coregistration of all images to the averaged b=1000 image with correlation ratio as the cost function. The b=1000 images were averaged and used as the base in a third and final pass with correlation ratio. In all cases, diffusion direction vector files were corrected with the motion parameters [4].

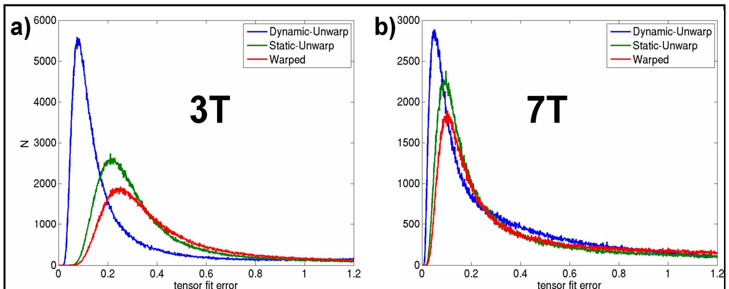

Figure 1: histograms of Chi^2 FOD tensor fit error, for 3 processing pipelines, for data acquired at a) 3T and b) 7T (with GRAPPA=2).

Whole brain histograms of tensor fiber orientation distribution (FOD) Chi^2 fit error were created across subjects, separated by field strength and correction pipeline. Finally, representative comparison images are shown.

RESULTS

Figure 1 shows the tensor fit error distributions. Dynamic unwarping resulted in reduced fit error, but the effect was smaller at 7T, likely due to the use of GRAPPA at 7T resulting in smaller EC effects. Figure 2 shows selected colorized FA maps in brainstem and around the anterior commissure (AC), a known interhemispheric fiber pathway that in DTI is only seen in higher resolution data. The AC is only visible when the data is dynamically unwarped. The affine matrices suggest that the EC-induced local shifts are approx 1mm, which is approximately the size of the AC, demonstrating that EC artifacts reduce the effective resolution.

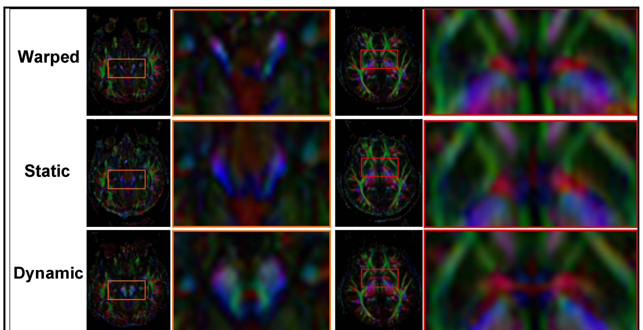

Fig 2: colorized FA maps with selected blow-ups of brainstem and anterior commissure at 3T.

DISCUSSION

In this study, we showed that dynamic unwarping using reversed phase-encodes can produce improved diffusion images over the best possible static unwarping. In a follow-up study, we intend to examine the effect of dynamic unwarping with and without GRAPPA on the fit distributions, diffusivities and probabilistic tractography characteristics. This previously published method has potential to remove static and dynamic field effects and increase the effective resolution of DTI images.

REFERENCES

1) Beall et al, E-poster #4566, ISMRM Montreal 2011, 2) Holland et al, NeuroImage 2010; 50:p175-183, 3) Embleton, Hum Brain Mapp 2010, 31:1570, 4) Sakaie et al, NeuroImage 2007; 34:p169-176.