Multi-Shot DWI with Iterative Phase and Field Inhomogeneity Corrections

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INTRODUCTION: Diffusion Tensor Imaging (DTI) is an emerging and important tool for the examination of the health of brain white matter and also offers the potential to track connectivity in between brain regions. There are several desirable, though often competing, characteristics of DTI, including high spatial resolution, high signal-to-noise ratio (SNR), reasonable acquisition times, and minimal image distortions. For example, high SNR might dictate imaging at higher magnetic fields and reasonable imaging times might dictate the use of longer readouts, but these factors often result in increased image distortions due to magnetic field inhomogeneity. Even with the use of multishot approaches with phase correction, such as SNAILS (1), there are still susceptibility related distortions at lower slices in the brain and these are more dramatic at higher field strengths. In this work, we examine an image reconstruction approach that corrects for both shot-to-shot phase variations due to bulk patient motion in conjunction with the large DTI gradients and magnetic field inhomogeneity.

METHODS: The pulse sequence used was a twice refocused spin echo sequence with a variable density spiral acquisition similar to SNAILS (1). We then reconstructed a low resolution image for each shot and used the phase of these images as an estimate of the phase accrued due to bulk motion between shots (1). We also acquired a field map by using the TE shift method (3). The final diffusion weighted images were then reconstructed using an iterative approach based on the non-uniform fast Fourier transform (NUFFT) and a time-segmented approximation of the off-resonance phase accumulation (4). The reconstruction, in general can be expressed, in matrix form, as the inversion of the discretized signal equation:

$$\mathbf{y} = \mathbf{A}\,\mathbf{x}, \qquad [1]$$

where **x** is the image as a column vector, **y** is the **k**-space data, also as a column vector, and **A** is the "system" matrix that accounts for all operations that must be used to go from image space to the acquired data. Here, the matrix **A** not only encompasses the gridding and Fourier transform operations (e.g. the **k**-space trajectory and NUFFT), but also for the field inhomogeneities (4).

To accommodate the shot-to-shot phase variations, we have adopted the approach taken in (2) to explicitly model the phase variations in the signal equation. Here, the acquired data signal for the i^{th} shot is expressed as:

$$\mathbf{y}_i = \mathbf{A}_i\,\mathrm{diag}(\mathbf{p}_i)\,\mathbf{x}, \qquad [2]$$

where $\mathbf{p}_i$ is the (columnized) phase map of the i^{th} shot as derived from the fully sampled part of $\mathbf{y}_i$, and $\mathbf{A}_i$ represents the signal equation for the **k**-space trajectory of the i^{th} shot as well as the field inhomogeneity. The acquired data are concatenated into one column vector (**y**) and the new system matrix (**A**) is derived by vertically concatenating the $[\mathbf{A}_i\ \mathbf{p}_i]$ matrices. This expression is then solved using an iterative conjugate gradient reconstruction method.

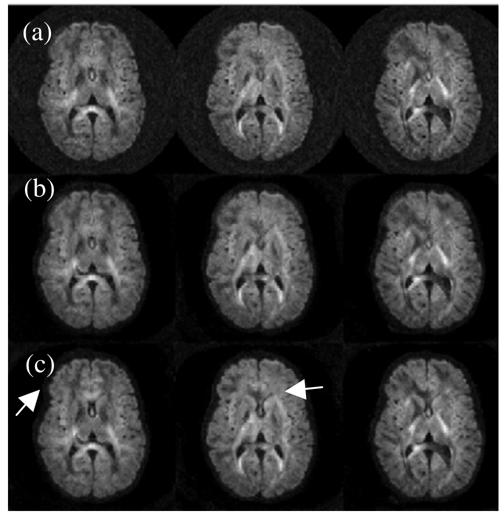

Figure 1. Diffusion weighted images reconstructed with (a) SNAILS algorithm, (b) iterative SNAILS algorithm and (c) iterative reconstruction with field map correction.

Diffusion-weighted images were collected using a SNAILS related sequence on a 3.0T GE scanner. The sequence used 4 interleaves, a TR of 5.0 s and a TE of 80 ms to acquire images of a 22cm field of view at a resolution of 128 x 128. Slice thickness was 4mm and b ~ 800 s/mm^2. Four averages were made for each of the six diffusion-weighting directions as well as the b=0 volume for a total scan time of 8 minutes. Also, higher order shimming was used to minimize errors due to magnetic field inhomogeneity; this improved the image quality of the conventional non-field corrected reconstruction.

RESULTS and DISCUSSION: Figure 1 shows diffusion weighted images from a slice just above the sinuses. The iterative reconstruction without field map correction (b), gives a better image than (a), the standard SNAILS reconstruction and both do a very good job of removing phase accrued between shots. However, there is still a significant amount of blurring in the frontal lobes. While both sets of iteratively reconstructed images appear similar in the rear areas of the brain, the frontal areas are distorted due to the proximity to the sinuses above the eyes and the associated field inhomogeneities. The field map corrected images (c) show increased structure and less blurring than their counterparts in (b), and therefore will provide for more accurate calculations of the diffusion tensors and functional anisotropy (FA) maps. Improvement of the tensor accuracy in the frontal lobes is very important because it will lead to superior connectivity mapping and better diagnosis of white matter disease.

The improvement in (FA) maps can be seen in Fig.2. With the field map corrected reconstruction, shown in (b), greater anisotropy can be seen in the left anterior part of the brain as well as in the frontal regions of the corpus callosum.

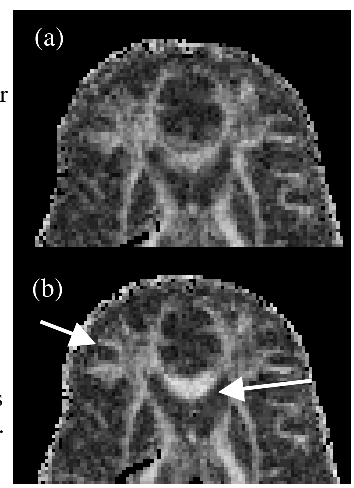

Figure 2. FA maps, both without field map correction (a) and with field map correction (b).

Future work will include updating the $\mathbf{p}_i$ with regularization, based on the same cost function as the **x** and $\mathbf{y}_i$ updates, during each iteration of the reconstruction. This formulation will be better able to correct for errors in the phase calculations and therefore will lead to more accurate corrections of motion variation between shots.

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