3D EPI Phase Maps for Real Time EPI Distortion Correction

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Target Audience: This work will be of interest for all applications that use EPI (Cartesian and spiral; single and multiple shots) for image acquisition.

Purpose: The long readout of single-shot EPI makes diffusion weighted imaging (DWI) or functional MRI (fMRI) susceptible to magnetic field inhomogeneity. If not corrected during image reconstruction, field inhomogeneity can produce nonlinear geometric distortions, primarily along the phase-encoding direction. Several methods have been proposed to correct effects of EPI distortions, including B0 field mapping and image registration. The field map scheme[1] requires an additional scan or pulses in which the B0 field inhomogeneity can be computed, while the image registration method[2] requires registering the distorted EPI images to a corresponding undistorted T2W structural image (having similar contrast to the b0) acquired from an additional scan[2]. In the present work, we combine aspects of each correction technique in a novel approach to compute, report and correct the B0 field inhomogeneity in real time for each DWI volume using low resolution 3D-EPI phase images.
In this study, we measure the distortion effects present in the four acquired non-diffusion weighted images, $b0_{(1,2,3,4)}$, and assess the ability of the proposed shim correction scheme to correct them. This is done both quantitatively and qualitatively by comparing differences in the first $b0_1$ image (which is uncorrected for B0 inhomogeneity, as correction can only be applied after one acquisition) and the subsequent $b0_{(2\text{-}4)}$.

Methods: The twice-refocused, two-dimensional diffusion pulse sequence[3] was modified to acquire two 3D EPI pulses with different echo times and low resolution immediately following the acquisition of each DWI volume. The difference in echo times (2.4 ms) was chosen to have fat and water in phase. The field maps are reconstructed on-line by a complex division of EPI images. For each DWI volume, the B0 field inhomogeneity is computed in terms of first order shim gradients (G_x, G_y and G_z). The diffusion sequence was further modified to receive these parameters at the end of the EPI acquisition and to update in real time the current of the shim coils in x, y and z directions simultaneously.
All scans are performed on a Siemens Allegra 3T scanner (Siemens Healthcare, Erlangen, Germany). Three healthy subjects (29:32 years) were scanned twice with the standard and the modified diffusion sequence. For all scans the acquisition parameters for the two EPI pulses were the same except for the TE: TR = 14 ms, TE_1 = 6.6 ms, TE_2 = 9 ms, 8 x 8 x 8mm^3, matrix size 32 x 32 x 28, FOV 256 x 256 x 224 mm^3, bandwidth 3906 Hz/px, flip angle 2 degrees. The acquisition parameters for the modified diffusion sequence were: TR = 10400 ms, TE = 86 ms, 70 slices, matrix size 112 x 112, in-plane FOV 224 x 224 mm^2, slice thickness 2 mm, 30 non-collinear diffusion gradient directions, diffusion weighting = 1000 s mm^{-2}, four b=0 scans. Each b0 was registered to the T1 image using linear registration FLIRT in FSL (FMRIB Software Library; http://www.fmrib.ox.ac.uk/fsl) with 12 degrees of freedom (DOF) and mutual information cost function. For each subject, the image distortion parameters such as translation, rotation, scaling and shearing (total of 12 DOF) were calculated between each pair of b0s using AFNI-3dAllineate. Additionally, FSL-fast was used to perform tissue segmentation on T1 maps and to create white matter (WM) masks. WM outlines were overlayed on acquired b0 images from various acquisition and processing schemes for relative distortion comparison[2].

RESULTS: Figure 1 shows the relative distortion of the various acquisitions and processing methods tested here by overlaying T1 WM outlines (blue overlay, and righthand image) on the b0 images. Locations of particularly large mismatch are highlighted with arrows. Several areas of mismatch are apparent in all standard WM_$b0_{(1\text{-}4)}$_Stand scans and the non-corrected WM_$b0_1$_B0NoCo scan, particularly in the superior and inferior regions, with far fewer in the corrected WM_$b0_{2\text{-}4}$_BoCo. Quantitative comparisons of image distortions are given in Figure 2, showing values of affine warping parameters among all b0s for the same subject. Both root mean square (RMS) and maximum magnitudes of parameters are shown. Parameters among all maps in the standard sequence are approximately homogeneous. However, in the shim correction cases, parameter values differ by orders of magnitude in rotation and in shear between cases of to-$b0_1$ and non-to-$b0_1$ transforms. The results of the other subject are similar.

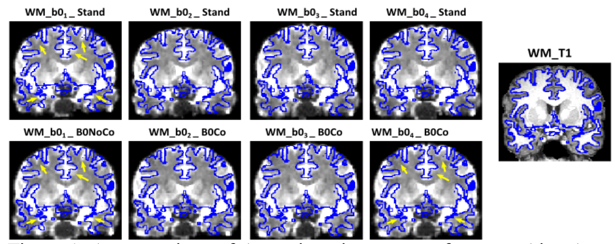

Figure 1: A comparison of the registration process for one subject between the four b0 (1-4) images and the T1 image with the standard sequence ([1]row) and the modified sequence ([2]row) using FLIRT in FSL. The T1 WM outlines (blue overlay) were overlaid on each registered b0 (underlay). Arrows highlight particular areas of sizable distortion. For clarity of the images the arrows are not shown for all images.

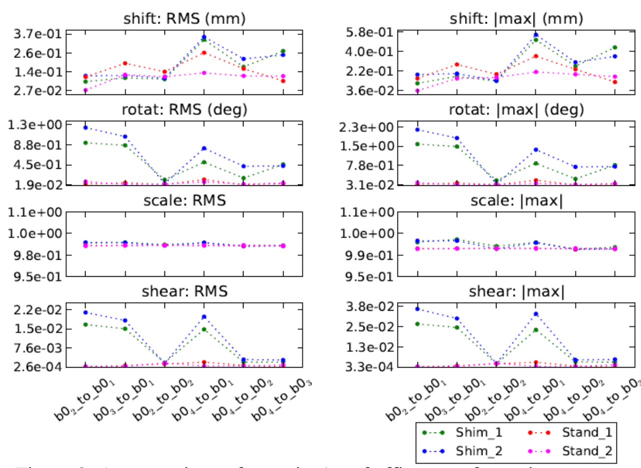

Figure 2: A comparison of magnitudes of affine transformation parameters among the four $b0_{(1\text{-}4)}$ images of each acquisition scheme. Standard acquisition parameters tend to be homogeneous, while shim-corrected $b0_{(2\text{-}4)}$ show order of magnitude differences in warping to the uncorrected $b0_1$.

Discussion: Figure 1 shows that shim-corrected b0 images show stronger alignment to the anatomical T1 images with fewer distortions than the non-shim corrected acquisitions. Figure 2 shows that this is largely due to reduction of shear distortion introduced by the EPI sequence.

Conclusion: The presented 3D-EPI phase image method has the capability to reduce susceptibility artifacts in real time for diffusion imaging. Because it is independent of the acquired images themselves, similar levels of correction observed in the b0 images are expected for the DW images themselves. This is done without the need for acquiring extra scans or complicated retrospective alignment methods that may introduce further artifacts when applied to the DWIs themselves. Furthermore, the proposed technique can be implemented for different image modalities that use EPI for image acquisition, such as fMRI.

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