Updating Shim Dynamically During Diffusion Tensor Imaging Acquisition

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Target Audience: This work is of interest to researchers and clinicians who use single-shot Echo Planar Imaging (EPI) in several applications such as Diffusion Tensor Imaging (DTI), Functional MRI (fMRI), and Dynamic Susceptibility Contrast MRI (DSC-MRI).

Purpose: Single-shot Echo Planar Imaging (EPI) is the first choice for diffusion tensor imaging, due to its ability to acquire a 2D image in less than 100 ms. However, standard EPI incurs significant spatial and intensity distortions[1] due to B0 field inhomogeneity. Temporal changes in B0 may arise from breathing, air-tissue susceptibility differences, poor shimming, or subject motion during long DTI acquisitions. We present a first implementation of real time TR-by-TR measurement and correction of B0 homogeneity changes (frequency/0th order and linear/1st order shim) in DTI with simultaneous real time motion correction.

Methods: The navigated diffusion sequence[2] is modified to acquire an additional 3D EPI navigator with a different echo time immediately after the first navigator. A field map is created online by complex division of the images from the two navigators. The required linear gradients (G_x, G_y and G_z) (first order shim) and frequency shift (zero-order shim) for each volume (separate navigator and DTI volumes) are calculated using a least squares fit to the 3D field map. The motion correction mechanism (PACE[3]: Prospective Acquisition CorrEction) is also activated using the first of each pair of navigators to correct for motion and adjust for frequency shift. The calculated shims (separately for navigators and DTI) and motion parameters are used to correct simultaneously for B0 distortions (by adjusting the shim currents) and motion after the second navigator. All scans were performed on a Siemens Allegra 3T scanner (Siemens Healthcare, Erlangen, Germany). A water phantom was scanned to validate shimming accuracy. The static shim, initially prepared by the scanner before the DTI acquisition, was manually adapted as follows: a baseline scan was acquired with the initial shim settings, after which the shims were adjusted by (1) 10 µT/m (X direction), (2) 10 µT/m (X and Y), and (3) 10 µT/m (X, Y, and Z), and (4) 10 µT/m (X, Y and Z) with a 10 Hz frequency offset. Two adult subjects were scanned with the modified DTI sequence with (1) a base scan with no subject motion (NoMo_base), (2) with no motion and with real time shim and motion correction (NoMo_PACE-Shim), (3) subject motion with no correction (Mo_base_NoCo) and (4) subject motion with real time motion and shim correction (Mo_PACE-Shim). Subjects were instructed to move six times during each motion scan (at acquisitions 4, 10, 16, 23, 19 and 33). For all scans, navigator parameters were: TR 14 ms, TE_1 6.6 ms, TE_2 9 ms, 8x8x8 mm^3, matrix 32x32x28, FOV 256x256x224 mm^3, bandwidth 3906 Hz/px, flip angle 2 degrees. Parameters for the modified navigated diffusion sequence were the same for the water phantom and the human scans, except for number of slices and TR. For the human scans: TR 10400 ms, TE 86 ms, 70 slices, matrix 112x112, in-plane FOV 224x224 mm^2, slice thickness 2 mm, 30 non-collinear diffusion gradient directions, b-value 1000 s/mm^2, four b=0 scans. For water phantom scans: TR 3800 ms, 20 slices. DTI data processing, T1 segmentation and registration were performed using FSL tools (FMRIB Software Library; http://www.fmrib.ox.ac.uk/fsl) and Freesurfer (http://surfer.nmr.mgh.harvard.edu/). NoMo_base and Mo_base scans were corrected for motion retrospectively using FLIRT with mutual information cost function and 12 degrees of freedom. To evaluate the similarity between pairs of scans, the Dice coefficient (S) was calculated using Freesurfer.

Results: The first row of Figure 1 shows the difference in the normalized signal intensity of the water phantom, in a representative slice, between the base scan and scans where the static shim was distorted manually either as an individual change in Gx or simultaneous changes in Gxy, Gxyz or Gxyzf. The second row of Figure 1 shows the same difference following real time shim correction. Figure 2 shows the absolute magnitude of motion parameters (translation and rotation) and the accompanying changes in the linear B0 gradients for one subject (Mo_PACE-Shim). The performance of the modified DTI sequence for different motion and correction scenarios is illustrated in Figure 3 by comparing the whole brain white matter generated from the Freesurfer segmentation of T1 (blue) with the white matter from the thresholded FA maps (0.2<FA<1) (red). For global comparison, the Dice coefficients of the spatial overlap between the T1 white matter and the thresholded FA white matter for the different scenarios are $S_{NoMo\_base\_retro} = 0.93$, $S_{NoMo\_PACE\text{-}Shim} = 0.98$, $S_{Mo\_base\_retro} = 0.94$, and $S_{Mo\_PACE\text{-}Shim} = 0.97$.

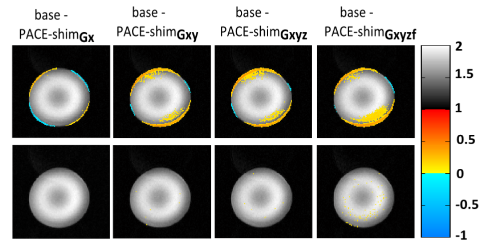

Figure 1: Difference in normalized signal intensity between base scan and scans where static shim was adjusted manually before shim correction (first row: change in Gx only, or simultaneous changes in xy, xyz or xyzf) and after shim correction (second row).

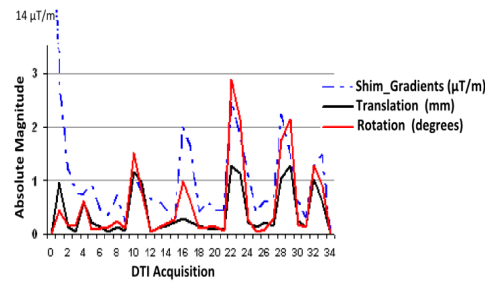

Figure 2: Abs. magnitude of motion parameters and linear B0 gradients for one subject (Mo_PACE-Shim).

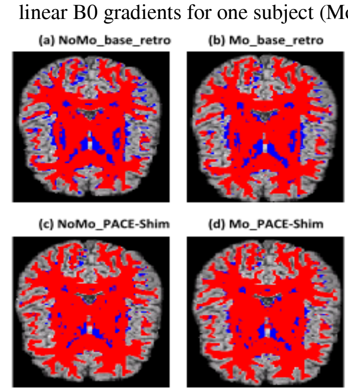

Figure 3: Comparisons between modified DTI and standard sequence. Whole brain white matter from T1 shown in blue, and white matter from thresholded FA map (0.2<FA<1) in red.

Discussion: The modified sequence performed well following manual shim changes (Fig. 1). Results concur with an fMRI study[4] in which subject motion altered B0 homogeneity (Fig. 2). Retrospective correction reduces FA in NoMo_base_retro and Mo_base_retro scans, shown in Fig. 3 a, b as more blue areas are evident on white matter difference maps. Simultaneous real time shim/motion correction results in excellent overlap, even when subjects move ($S_{Mo\_PACE\text{-}Shim} = 0.97$; Fig. 3 d).

Conclusion: The static shim, calculated by the scanner before acquisition, may change from one diffusion TR to another, or from one DTI scan to another, for various reasons amongst which subject position/orientation changes. The proposed method measures and corrects B0 homogeneity changes and associated distortions in real time. The sequence is being adapted to adjust shim over selected regions of the DTI and slice-by-slice.

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