Prospective correction of both motion and B0 distortions in fMRI and DTI

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Target Audience: This work is of interest to researchers and clinicians who use Echo Planar Imaging (EPI) in applications.

Purpose: Single-shot Echo Planar Imaging (EPI) is the sequence of choice for diffusion tensor imaging (DTI) and functional MRI (fMRI) due to its ability to acquire a 2D image in less than 100 ms. DTI and fMRI require scanning a volume of the brain repeatedly and subject motion as well as magnetic field inhomogeneity may occur. While a large number of methods have been proposed to correct for subject motion in both fMRI and DTI, few have corrected field inhomogeneities, especially in DTI. In fMRI the conventional methods for B0 distortion correction acquire a field map, which enables off-line distortion correction during post-processing. Although several alternative methods have been proposed, the majority fail when subject movement occurs. In this study, we present the first implementation of imaging navigators for TR-by-TR simultaneous correction of both subject motion, frequency drift and linear shim in both fMRI and DTI acquisitions. Each navigator provides a field map that can be used for 3D distortion correction at every TR.

Methods: The standard twice-refocused, two-dimensional diffusion pulse sequence and the 2D single-shot BOLD EPI sequence were modified to acquire two 3D EPI navigators with different echo times and a very low spatial resolution immediately following each fMRI/DTI measurement. The difference in echo times (2.4 ms) was selected so fat and water would be in phase at 3T. A very small flip angle of 2º minimizes the impact of signal saturation. After each fMRI/DTI measurement, 3D field maps are reconstructed on-line by a complex division of EPI images, and the B0 field inhomogeneity is computed over the whole FOV in terms of first-order (Gx, Gy and Gz) shim gradients. The sequence then updates, in real time, simultaneously the current of the x, y, and z shim coils. In the modified sequences (vNavDTI, vNavBOLD), Prospective Acquisition CorrEction (PACE) for motion is implemented using the first of each navigator pair. The standard Siemens BOLD sequence also uses PACE for motion correction as a part of the BOLD protocol.

All scans were performed on an Allegra 3T scanner (Siemens Healthcare, Erlangen, Germany) according to approved protocols. A water phantom was first scanned to validate shimming accuracy. The static shim initially prepared by the scanner before the DTI/fMRI acquisition was manually changed as follows: a baseline scan was acquired with the initial shim settings, after which the shims were adjusted by (1) ~ 16 µT/m (Y direction), (2) ~ 16 µT/m (X and Y), and (3) ~ 16 µT/m (X, Y, and Z).

In two adult subjects we acquired (1) high resolution T1 images and resting BOLD data using (2) the standard BOLD and (3) vNavBOLD sequences. DTI data were also acquired using (4) the standard DTI and (5) vNavDTI sequences. Each subject was instructed to move several times during scans 2 to 5 and the patterns of motion were almost identical. For vNavBOLD/vNavDTI navigator parameters were: TR/TE_1/TE_2 14/6.6/9ms, 8x8x8mm^3, matrix 32x32x28, bandwidth 3906Hz/px. Time for navigator implementation with all calculations is 550 ms. BOLD and vNavBOLD parameters were: TR/TE 3100/30ms, 33 slices, matrix 64x64, 4mm slices, 151 measurements, flip angle 77º. DTI and vNavDTI parameters were: TR/TE 10400/86 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 scans 2 and 3, fMRI images were aligned using FLIRT in FSL (http://www.fmrib.ox.ac.uk/fsl) with 12 DOF to determine the transformation matrix for each measurement. Rotation, translation, scales, and skews (shears) were extracted using the avscale tool in FSL. Images of DTI scan 4 were also corrected for motion using FLIRT. Stability of the mean fMRI signal intensity over the 151 measurements was assessed in two different gray matter ROIs for each acquisition. In vNavBOLD, B0 distortion correction starts after the first measurement. 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/). DTI parameters were extracted using Diffusion Toolkit. To evaluate the similarity between pairs of scans in DTI, the Dice coefficient (S) was calculated using Freesurfer.

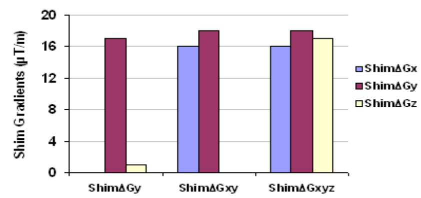

Figure 1: Changes in shim parameters as estimated by vNavDTI following the manual distortion of the static shim.

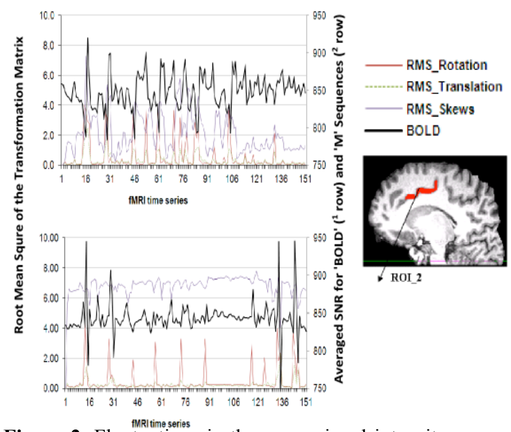

Figure 2: Fluctuations in the mean signal intensity across the fMRI time series in a gray matter ROI for the standard BOLD (top row) and vNavBOLD (bottom row) sequences. The root mean square (RMS) motion (rotation and translation) and distortion (skews or shears) parameters, as calculated using FLIRT, are also shown. The shear values were scaled by a factor of 100 on the plots.

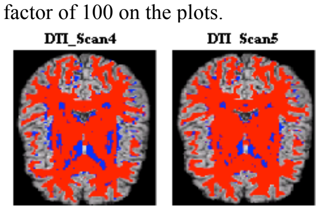

Figure 3: Comparison of overlap of whole brain white matter from T1 (blue) and white matter from thresholded FA map (0.2<FA<1) (red) for standard DTI (left) and vNavDTI (right) acquisitions.

Results: Figure 1 shows the difference between the three shim parameters following the manual distortion of the static shim. Figure 2 shows the fluctuations in the mean signal intensity in one ROI in gray matter across the fMRI time series for BOLD (top) and vNavBOLD (bottom), as well as motion (rotation and translation) and distortion (skews or shears) parameters. Figure 3 compares 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 scans 4 and 5. For global comparison, the Dice coefficients of the spatial overlap between the T1 white matter and the thresholded FA white matter for the two different scenarios are $S_{DTI\_Scan4} = 0.94$ and $S_{DTI\_Scan5} = 0.97$. Results of one subject are presented; results of the other subject are similar.

Discussion: The modified sequences are able to accurately measure the shim parameters following manual distortion (Fig. 1). The manual shim distortions were corrected perfectly. The long readout of EPI makes the fMRI signal susceptible to magnetic field inhomogeneity. Subject motion changes the initial static shim, which prospective motion correction alone (Fig. 2, top row) fails to recover, resulting in a less stable signal. By contrast, vNavBOLD, which also employs PACE for prospective motion correction, but in addition enables B0 correction, results in a more stable fMRI signal (Fig. 2, bottom row). Retrospective correction reduces FA in DTI scan 4 (left column, Fig. 3), as demonstrated by more blue areas evident on white matter difference maps. Simultaneous real time shim/motion correction results in excellent overlap, even when subjects move ($S_{DTI\_Scan5} = 0.97$; right column, Fig. 3).

Conclusion: In contrast to linear navigators or navigator echoes, sophisticated imaging navigators allow simultaneous correction for both subject motion and B0 distortion following the acquisition of each fMRI/DTI measurement, resulting in more stable fMRI time series and more accurate evaluation of DTI parameters. The proposed method overcomes most of the obstacles of current methods for B0 correction in both fMRI and DTI. The sequence is being adapted to measure and adjust shim over selected regions of the DTI/fMRI 'Slab-by-Slab'.