Evaluation of EPI Geometric Distortion Correction using Phase Labeling for Additional Coordinate Encoding (PLACE)

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Introduction: Echo-planar imaging (EPI), due to its high sensitivity to main magnetic field (B_0) inhomogeneities, is vulnerable to geometrical distortions. This poses a major problem in imaging brain in particular, as it involves tissue types of varying susceptibility. Furthermore, these unwanted signal intensity changes in EPI may introduce mislocalized or even missing activations in fMRI studies, which can lead to misinterpretation of results. Field map (FM) based correction methodology was proposed over a decade ago [1] and is widely used; However it requires additional scan time, has poor performance when the slice prescription is different from that of the functional scans, and is inadequate to correct time varying distortions like respiration and subject motion [2]. More recently, a modified EPI sequence called 'Phase Labeling for Additional Coordinate Encoding' (PLACE) has been proposed, that requires no additional scans [3]. In this method, geometric distortions are corrected by computing and accounting for non-linearities in the (ideally linear) phase ramp between adjacent volumes acquired with the different phase-encoding (PE) shifts. Qualitative improvement of activation in the frontal cerebral hemispheres with PLACE has been previously reported [4], but is yet to be quantitatively tested. In this study, we aim to (a) evaluate the technique relative to ground truth functional activation (finger tapping task) by inducing artificial distortions using additional shims; (b) compare the results quantitatively with FM based correction method in SPM5 (Wellcome Trust Centre for Neuroimaging, London) [5] and (c) validate the findings with a cognitive task (associated with self-reference) that has been consistently proven to activate susceptibility prone frontal brain areas [6].

Methods: Three normal subjects were imaged using a 3T Siemens MAGNETOM Trio, a TIM System (Siemens Medical Solutions, Erlangen, Germany). A 3D high resolution T1-weighted structural scan was acquired using an MP-RAGE sequence with voxel size = 1.3x1x1.3 mm, flip angle (FA) = 7°, TE=3.39 ms, TI=1100 ms, and TR=2530 ms. Functional BOLD measurements were obtained using a single-shot, gradient echo EPI sequence with TR=2000 ms, TE=30 ms, FA=90°. Thirty-two interleaved 4 mm thick slices were acquired (AC-PC orientation) with inter-slice gap of 0.8 mm and an in-plane resolution of 4x4 mm^2. To enable PLACE correction alternate EPI volumes were acquired with a shift of two PE blip steps in k-space (alternating between a shift of -1 and 1 blip steps). Magnitude and phase images were collected using a FM sequence with the same number of slices, voxel size and slice orientation as that of the EPI sequence with TR=500 ms, TE1=2.83 ms, TE2=5.29 ms, FA=55°. Subjects performed a simple finger-tapping task (alternating left and right hand) in runs lasting 6 minutes each. Shim value in the X direction was adjusted to exaggerate the effects of geometric distortion in EPI, specifically in the motor cortex. Subjects were also presented with a self-reference task (series of trait adjectives) during which they were required to make judgment about themselves. Scans lasted ~4 minutes each. Data analysis was carried out in SPM5. Both PLACE corrected and original EPI time-series were realigned using a least squares approach and a six parameter rigid body spatial transformation. FM correction was carried out in the original EPI series for comparison with the PLACE corrected data set using the fieldmap toolbox (SPM5). After realignment and unwarping, images were spatially smoothed with a Gaussian kernel with FWHM of 8 mm. Canonical hemodynamic response function was used as the basis function and L>R, R>L and self-reference>valence contrasts were estimated. A surface representation of the SPM activation maps was constructed from the structural volume using the FREESURFER software package [7]. Prior to projecting the t-maps on the surface, mean of the functional volumes were co-registered to the structural scans using SPM5.

Results: For the finger tapping task, the global maximum (motor areas) of the activation maps for both L>R and R>L contrasts overlapped for both PLACE corrected and uncorrected data sets on all the subjects. When X shim was applied, PLACE correction was successful in bringing the shifted activation maps in the motor area (Fig. 1b) back to the correct location (Fig. 1c). The result of PLACE correction was similar to that of original series without shim (Fig. 1a) and field map correction (Fig. 1d). For the cognitive task (self-reference), orbito-frontal activation was improved after PLACE correction and mislocalized activations were restored (Fig. 2b). As seen with results from finger-tapping task, all other activations from regions without susceptibility were left in tact before and after PLACE correction.

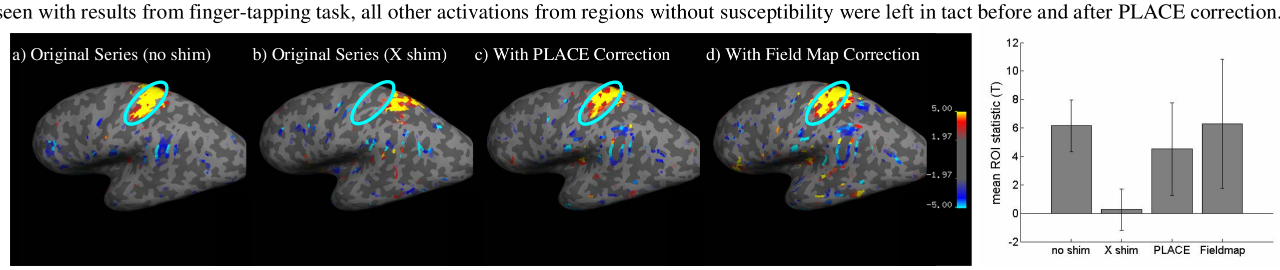

Figure 1: a) Activation in the left motor area (R>L) from a single subject (no shim). b) Activation is shifted away from the region-of-interest (ROI), shown in blue oval, with X shim and is brought back to its original location with PLACE (c) and FM correction (d). The right panel shows the mean ROI statistic for the four cases.

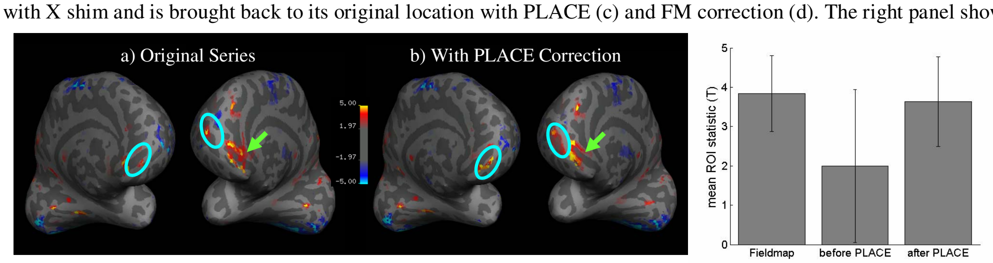

Figure 2: Shift in orbito-frontal activations (self-reference>valence) before (a) and after PLACE correction (b) during a cognitive task. Mislocalized activations were also corrected with PLACE (green arrow). The graph shows the mean ROI statistics with FM as the reference.

Conclusions: We have demonstrated that PLACE can correct for displacements in brain activations even in extreme cases of field inhomogeneity. In addition, correction for susceptibility based distortion in the orbito-frontal areas were validated and quantitatively assessed. Results of PLACE correction were comparable to that of FM correction, but PLACE has the advantage that it does not require additional post processing steps as corrected images are generated real-time during acquisition. Our evaluations suggest that among existing methods, PLACE would be a better candidate for EPI distortion correction in fMRI studies providing real-time corrections.

References: [1] Jezzard P, Balaban RS, MRM 1995; 34:65-73. [2] Hutton C, Bork A, et al, NeuroImage 2002; 16:217-240. [3] Xiang QS, Ye FQ, MRM 2007; 57(4):731-41. [4] Vogler M et al, HBM meeting 2008. [5] Andersson JLR, Hutton C, et al, NeuroImage 2001; 13:903-919. [6] Kelly WM, J. Cogn. NeuroSci 2002; 14:5, 785-794. [7] Dale A.M., et al. Neuroimage, 9 (2):179-194, 1999.