Dynamic Distortion Correction of SE EPI data using Phase Maps from Simultaneously-Acquired GE-EPI data

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Introduction:
EPI acquisitions are highly susceptible to image distortions due to the presence of B_0-field inhomogeneities. A variety of methods for correcting these distortions have been developed, many relying on the use of field maps calculated from the phase of gradient echo (GE) images acquired at different echo times. A powerful approach for correcting dynamically varying distortions in GE-based fMRI time series involves exploiting the phase of the EPI data in conjunction with a reference field map generated at the start or end of an fMRI series. The reference map is acquired using the same GE-EPI sequence with two different echo times [1-3]. This approach ensures field inhomogeneities are measured in the same space as the distorted images and can be monitored at the same rate as the fMRI data acquisition. Unfortunately it has not been possible to use this approach for (spin echo) SE-EPI data because phase variations due to field inhomogeneities are refocused by the 180^0 RF pulse. Here, however, we show that this dynamic distortion correction can be applied to SE-data by modifying the SE-EPI sequence to acquire a GE-image before the 180^o RF pulse and then using the phase of the GE-EPI data to monitor variation in field inhomogeneity. Since the GE and SE images are simultaneously acquired with an identical imaging readout they show the same distortion. By exploiting parallel imaging, the GE-EPI sequence can be incorporated without significantly increasing the echo time of the SE data. To assess the effectiveness of this technique we compared the spatial correspondence of distortion-corrected 7T EP-images with conventional scans, for both a phantom and human subjects. An auditory fMRI experiment was also performed to test the method in an area that is prone to significant distortion, since air-tissue interfaces strongly perturb the field in the temporal lobes.

Theory: The phase of a GE image acquired at echo time, TE, in the presence of field offset ΔB is given by: $\phi = \phi_0 + \gamma.\Delta B.TE$, where ϕ_0 is a time-invariant phase term that depends only on sequence-specific imaging parameters [2]. Measurement of ϕ thus allows calculation of ΔB on an image-by-image basis provided ϕ_0 is known. ϕ_0 can be calculated from initial phase measurements made at two different echo times. In this work we corrected the image distortion by using the simulated phase evolution rewinding distortion correction method (SPHERE) [4]. This was facilitated by the use of simple Cartesian sampling for all EPI acquisitions.

Methods: Scanning was performed on a 7T Philips Achieva System with a 16-channel array coil. A dual GE-SE-EPI sequence was implemented with a GE echo time (TE) of 21ms and a SE-EPI TE of 58 ms, producing GE-SE pairs with 2mm isotropic resolution and a bandwidth of 35.6 Hz/pixel. ϕ_0 maps were generated from averages of 10 GE-EPI acquisitions acquired with echo times differing by 2 ms. Field maps produced from subsequent GE acquisitions were smoothed by removing the high spatial frequencies from a discrete cosine transformation of the field map so as to reduce noise and edge effects. 3D polynomial fitting was also tested, but did not adequately model the rapid ΔB variation around the sinuses in the human data, despite modelling to 7^{th} order. Distortion correction was applied to individual GE and SE images in the time-series using SPHERE and the measured ΔB. The performance of the method was initially assessed on a phantom and then further tested on three human subjects. An auditory fMRI study was also performed using "sparse" imaging, in which the 20-slice GE-SE-EPI volume acquisition took 2 s while the TR was 10 s. Sound stimuli comprising broadband noise modulated at 10 Hz at ~ 80 dB were presented for a 20 s period commencing ~ 5 s prior to the readout following a 20 s baseline period over 10 cycles. To assess the effects of motion-induced distortions, the fMRI paradigm was performed twice and in the second run, the subject was asked to undergo small movements so as to induce B_o variations. fMRI analysis was carried out using FEAT (FSL**,** Oxford**,** UK). Data were motion corrected, but no spatial smoothing was applied.

Results: The technique provided robust correction of geometric distortion of GE- and SE-EPI data acquired from the phantom and subjects (Figs. 1 and 2). Figure 3 shows the activation maps from the auditory fMRI experiment performed with small subject movements. Both the distorted (top row) and undistorted maps are shown (overlaid on their corresponding mean EPI image). Table 1 details the cluster size and maximum z-score of activation in the left auditory cortex for data without (*uncorr*) and with (*corr*) dynamic distortion correction. Cluster size and maximum z-score tend to increase, suggestive of an improvement in data quality when using the dynamically varying correction. Figure 3 also shows an example slice from these data with the SE- cluster overlaid on the anatomical image. Improved spatial localization of the cluster to grey matter is seen.

Discussion: We have shown that dynamic distortion correction can successfully be applied to SE-EPI data using a dual GE-SE EPI acquisition. Anatomical outlines of the brain (Fig. 2) show better alignment with the EP-images after distortion correction. A banding-like artefact can be seen in the lower slices close to the sinuses, due to the large signal drop-out in this region. This may be overcome using conjugate phase reconstruction [5]. Dynamic distortion correction proved successful at reducing absolute distortions, and provided small improvements in functional power (cluster size and maximum z-score) for auditory fMRI. This will now be tested in a larger study. The mean ΔB field inhomogeneity in the functional ROI in Herschel's gyrus was found to be ~23 Hz, leading to a sub-pixel shift in this region. SE-EPI is thought to provide improved spatial localisation of activation, but is susceptible to distortions. Using the technique described here, distortions in SE fMRI data can be corrected to provide improved alignment to anatomical data, which is particularly advantageous for flat mapping of activation patterns. The dual GE-SE-EPI scheme does increase the minimum echo time that can be achieved in the SE acquisition, dependent on the matrix size used, but the accessible echo times fall in a good range for fMRI, as highlighted by our auditory fMRI study.

References: [1] Jezzard & Balaban, MRM, 34 , 1995 [2] Lamberton et al. JMRM, 26, 2007 [3] Hahn et al, Neuroimage, 44, 2009 [4] Kadah & Hu, MRM, 38 1997 [5] Schomberg, IEEE Trans. Med. Imag., 18, 1999

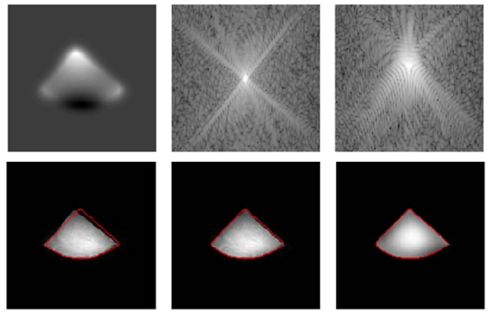

Figure 1 Phantom data. Top row (left to right): 3D polynomial fitted B_0 map, k-space data, corrected k-space data. Bottom row: Distorted SE-EPI, distortion-corrected SE-EPI, structural scan. The red line shows the outline of the structural scan.

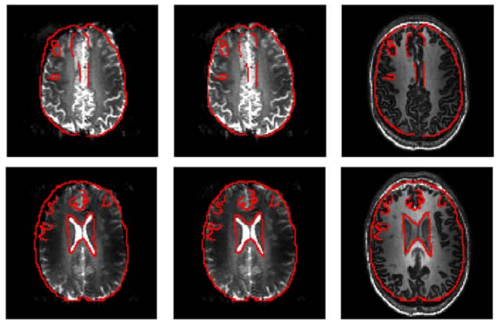

Figure 2 Left: Distorted SE-EPI. Middle: undistorted SE-EPI. Right: MPRAGE image, grey matter nulled. An outline of anatomical features is displayed in red. High (top row) and low plane (bottom row) shown.

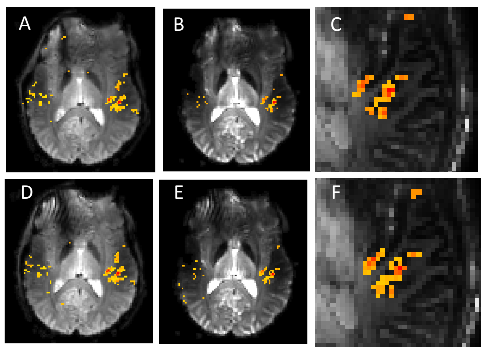

Figure 3 Top row: Distorted GE and SE EPI data and SE fMRI activation overlaid on MPRAGE; Bottom row: corresponding data after distortion correction.

	No movement		Movement	
	Max z	Cluster (k)	Max z	Cluster (k)
GE *uncorr*	8.2	325	7.8	185
GE *corr*	8.3	365	7.9	263
SE *uncorr*	7.1	192	6.7	143
SE *corr*	7.6	217	7.0	146

Table 1: Maximum z-score and cluster sizes for GE- and SE- functional data sets.