Evaluation of a new method to correct the effects of motion-induced B_0-field variation during fMRI

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INTRODUCTION Inhomogeneous B_0-fields generate distortion in MR images, particularly those acquired using EPI (1). This distortion can be corrected using information provided by a field map (2-4) that is often generated from phase images acquired at two (or more) echo times (TE) (3,4). The dominant source of field inhomogeneity in many MRI experiments is the variation of magnetic susceptibility across the tissues of the human body. In fMRI, head movement changes the susceptibility-induced field distribution leading to changes in distortion, which can induce signal variation and a consequent reduction in BOLD contrast-to-noise ratio (4). In the presence of significant motion (or other sources of variability such as respiration induced resonant offsets that may be similar in magnitude to the frequency changes due to head rotation), the resulting field changes mean that image distortion-correction based on a field map acquired prior or subsequent to an fMRI experiment is sub-optimal. In previous work, this problem was addressed by acquiring data at two echo times during the fMRI experiment, thus providing a contemporaneous measurement of field and BOLD signal variation (4). Here we describe a method for measuring the field variation in fMRI experiments that is based on monitoring phase variation in conventional EPI data acquired at a single TE.

METHODS The phase map measured in a gradient-echo echo planar image depends on the evolution under the local magnetic field during, TE, but additional contributions to the accrued phase may arise due to the maximum signal not being centred in k-space, intrinsic T_2^* decay and imperfections in the excitation phase. The method proposed here relies on separating the two contributions (intrinsic effects and frequency offsets) and assumes that the intrinsic phase accumulation is constant during the fMRI time series. The local frequency offset can be calculated as

$$\omega_n(\mathbf{r})=(\phi_n(\mathbf{r},t_2)-\phi_n(\mathbf{r},t_1))/(t_2-t_1) \qquad [1],$$

where $\phi_0(\mathbf{r},t_2)$ and $\phi_0(\mathbf{r},t_1)$ are phase images acquired at echo times t_2 and t_1. The intrinsic phase is given by

$$\phi_{ACQ}(\mathbf{r})=\phi_0(\mathbf{r},t_2)-\omega_0(\mathbf{r})*t_2/(t_2-t_1) \qquad [2].$$

This value should be independent of the object, and therefore does not have strong spatial dependences, allowing it to be well fit with a second order polynomial, $\phi_{ACQfit}(\mathbf{r})$. Once this is calculated, the instantaneous frequency offset during an fMRI experiment with TE=t_2, is given by

$$\omega_n(\mathbf{r})=(\phi_n(\mathbf{r},t_2)-\phi_{ACQfit}(\mathbf{r}))/t_2 \qquad [3].$$

A simple error analysis of the frequency maps as obtained by [Eq.1] and [Eq.3] shows that the noise in the new method will be reduced by a factor of

$$\frac{(t_2-t_1)\sqrt{\exp(2t_2R_2)}}{t_2\sqrt{\exp(2t_2R_2)+\exp(2t_1R_2)}} \qquad [4].$$

To compare the result of image distortion correction using single [Eq. 3] and double echo [Eq. 1] data, experiments were performed on a 3 T scanner. Phantom studies were carried out to compare the signal-to-noise ratio (SNR) of frequency offsets measured using the two methods and to test whether $\phi_{ACQ}(\mathbf{r})$ remained invariant with motion of the phantom. 10 repeted masurements were made for each phantom position, so that the variance of field maps could be evaluated. The phantom consisted of a plastic sphere filled with agar gel containing an off-centre, glass sphere filled with agar gel (doped with Gd-DTPA. In experiments on human subjects, the first aim was to observe the change in field offset associated with head rotations about different axes. Subjects were asked to make small head rotations about the lateral and anterior-posterior axes. Between movements they remained still while two image volumes (64x64x52 matrix) with a resolution of 4x4x4 mm^3 were acquired with echo times of 25 and 37 ms. The EPI acquisition employed had a bandwidth of 60 Hz per point in the phase encoding direction. In order to evaluate the possibility of using the proposed approach in fMRI, double-echo fMRI time series (100 volumes) were processed using two different approaches: (i) data from the two echoes were used to produce a field map via Eq.[1] (ii) $\phi_{ACQ}(\mathbf{r})$ was estimated from an average over the double-echo data and field maps were then calculated from data acquired at the longer TE via Eq. [3]. Once each image of the time course was undistorted using the corresponding field map, motion correction and normalisation were applied. Finally, the standard deviation of each pixel intensity over time was evaluated. This evaluation was carried out for images obtained using the post-processing methodologies described earlier and a similar one in which no undistortion was applied. Phase unwrapping, motion correction and undistortion were implemented using the FSL software.

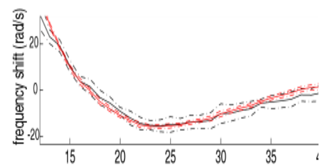

Fig. 1 Calculated field variation along one line of the image (standard deviation shown using dashed lines) (**grey**) using proposed method (**black**) using conventional double-echo method.

Fig. 2 Change in frequency map (Hz) due to a rotation of 1.7 degrees about the lateral axis.

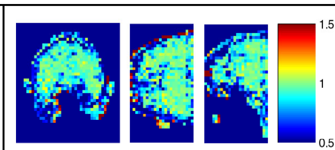

Fig. 3 Image representing the ratio $(\sigma/<S>)_{ii}/(\sigma/<S>)_i$, the average and standard deviation are calculated in the time course dimension. The index (i) stands for the conventional method, and (ii) for the method proposed

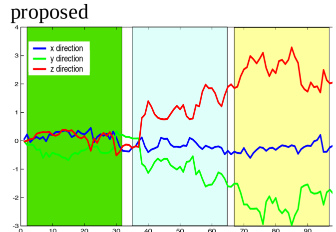

Fig. 4 Translation motion correction parameters for 100 volumes, the color coding (green, cyan and yellow) represents the subsets with different movement characteristics.

RESULTS The results of the phantom experiments (Fig.1) show that the field values measured using the two methods are in good agreement, but the standard deviation of the measurement made using the proposed method is significantly smaller (on average, the standard deviation was reduced by 48%).

Figure 2 shows the field change induced by rotation about the lateral axis, which is in good agreement with previous experimental (1) and numerical studies (5).

The comparison of the weighted standard deviation, $\sigma/<S>$, of images acquired in a double echo experiment and then corrected using the two different methods, shows that the new method yields a 10% reduction of the weighted standard deviation in regions just above the sphenoid sinus, whilst in the middle of the head the improvement is approximately 3%. When comparing the proposed methodology with the result of post-processing using only motion correction, the standard deviation of the signal just above the sphenoid sinus is reduced by 14%.

Also interesting are the consequences of dividing one of the 100 volume samples up into three groups of 30 data volumes, corresponding to periods of different ranges of subject movements (see Fig. 4). These show a period of lower amplitude movement (green), and increased movement later in the time course (cyan and yellow). The evaluation of the ratio between the standard $(\sigma/<S>)_{ii}/(\sigma/<S>)_i$ was calculated in a region over the nasal sinus, and found to vary from 0.95 (green), 0.93 (cyan) and 0.92 (yellow). These results show a tendency for the performance of the proposed method to be improved compared to the conventional method as the amount of subject movement increases. One reason for this effect might be that the conventional method relies on the subject remaining still during acquisition of every double echo image pair, whilst the new method proposed only relies on such an assumption for the initial volumes used to calculate the intrinsic phase.

CONCLUSIONS AND FUTURE WORK In the functional studies, the reduction in the noise was not as significant as in the phantom experiments (if it would be of the same order of magnitude it would mean all the noise was motion related which is obviously not true). Comparison of the standard deviations of the pixels time courses measured with and without distortion can be misleading because the interpolation involved in the undistortion process (4). But, as we compare two different methodologies with the same inherent smoothing, the proposed method proves to be more reliable in regions where time varying distortions are relevant. Furthermore, as scanner field strengths increase, distortion becomes an increasingly serious problem, the associated reduction in T_2^* makes double echo EPI acquisition less practical. The ultimate test will be the usage of the method in the processing of functional data, which is presently being carried out.

References (1) Jezzard *et al*, Human Brain Mapping, **8**, 80-85 (1999). (2)Bowtell *et al*, Soc. Magn.Res. Abstr. **2**:411. (3)Jezzard et al, *Magn. Res. Med.*, **34**, 65-73. (4) Hutton *et al*, NeuroImage **16**, 217-240(2002). (5) Marques *et al*, Conc. Magn. Reson. b *(submitted)*