A Combined Distortion Corrected Protocol for Diffusion Weighted Tractography and fMRI

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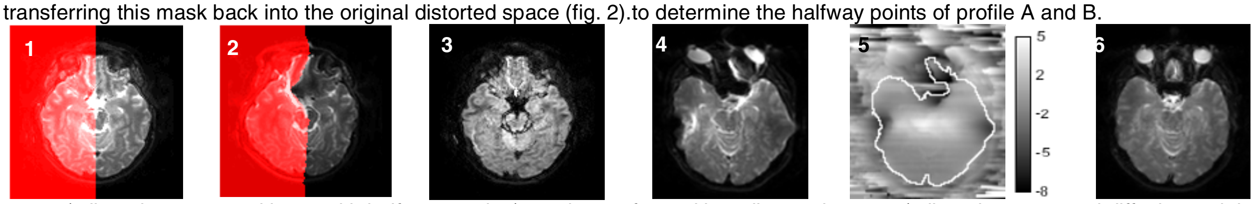
Introduction Although Echo Planar Imaging (EPI) has become the method of default for diffusion weighted imaging (DWI) and fMRI, this spatial encoding scheme suffers from substantial geometric distortion when applied to regions subject to large magnetic susceptibility variations such as the temporal lobes. The low bandwidth in the phase-encode direction results in mis-mapping of signal in both spin-echo (SE) and gradient-echo (GE) EPI and additionally a loss of signal in GE EPI due to intravoxel dephasing. One previously suggested method to correct for distortion in SE-EPI arising from susceptibility differences is to acquire a pair of images with opposite direction k-space traversal and opposite resultant distortion, thereby allowing derivation of a distortion corrected image from the distorted pair [1]. This is performed by co-localisation of signal from matching 1-D profiles in the phase-encoding direction and repositioning that signal at the mean of the 2 profiles. We present a protocol for combined, distortion corrected DW-EPI and SE-EPI fMRI that includes a number of novel features to allow successful routine application of distortion correction procedure including: 1) a registration algorithm to ensure image pairs are aligned in the frequency-encode direction to subvoxel accuracy 2) an algorithm for reducing correction artefacts due to large signal voids in diffusion weighted images 3) an fMRI protocol with a dual k-space traversal pre-scan and single direction k-space traversal dynamic for optimum distortion correction with minimum repetition time.

Methods *data acquisition* All imaging was performed on a 3T Philips Achieva scanner using an 8 element SENSE head coil with a sense factor of 2.5 and phase-encoding in the L-R orientation. DWI was performed using a SE-EPI sequence with TE = 54 ms, TR = 11884 ms, G = 62 mTm^{-1}, 112 × 112 matrix, reconstructed resolution 1.875 mm, slice thickness 2.1 mm, 60 slices, 61 diffusion sensitisation directions at b = 1200 smm^{-2} (Δ, δ = 28.5, 13.5 ms), and 1 b = 0 image. Two sets of images with identical diffusion gradient directions but with opposite direction k space traversal (defined as A & B) were acquired for each diffusion gradient and slice. Total imaging time was 2 × 14 min. For fMRI a 30 slice SE-EPI sequence with TE = 75ms, TR = 3200ms, 112 × 112 matrix, reconstructed resolution 1.875 mm, and slice thickness 4.2 mm was used. The fMRI acquisition consisted of a 10 dynamic pre-scan with interleaved reversed direction phase encoding and the subject at rest, followed by the main dynamic sequence of 160 timepoints with a single phase encoding direction over which the fMRI task was performed. To test ability to detect activation in susceptibility-prone brain regions a word categorisation task involving semantic understanding and known to produce temporal lobe activation was used [2].

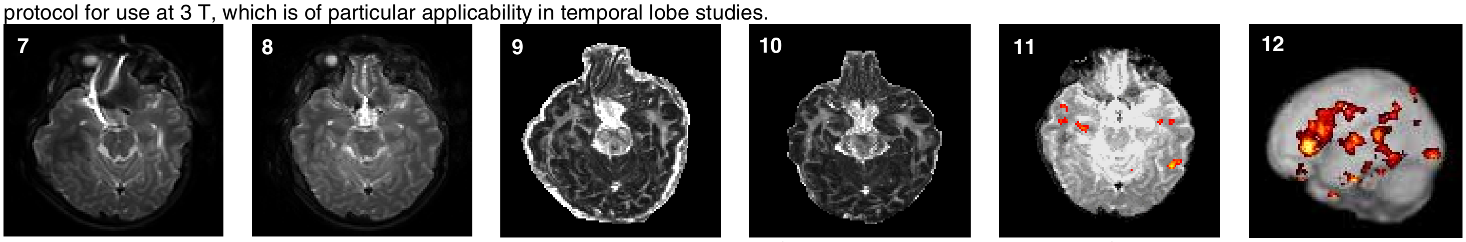
Image processing and distortion correction Geometric and intensity distortion corrections were performed using an algorithm based on the method of Bowtell *et al* [1]. For the correction technique to work it is vital that image pairs are well aligned in the frequency encode direction, as any misregistration in this direction will be severely detrimental to the quality of the restored image. Conventional image registration techniques are not satisfactory as images show opposite distortions. Instead, an in-house registration algorithm was written to register image pairs to subvoxel accuracy in the frequency encode direction using the standard deviation of signal intensity of the resultant distortion corrected images as the cost function for the registration process. Correct co-localisation of corresponding signal in profile pairs is of critical importance to the accuracy of the distortion correction. Error from mis-matching is most noticeable when a signal void is present in the middle of a profile as is often the case for diffusion weighted images (e.g. fig. 3). While in theory the correction is improved by limiting the integration to shorter lengths of matching profile [3], determining the exact position of corresponding borders in each distorted pair is a very difficult task. Improved correction in the diffusion weighted images was obtained by splitting each profile in half and correcting the 2 half-image pairs separately. This was accomplished by a defining a mask of the midway point in the corrected b = 0 image (Fig. 1) and then transferring this mask back into the original distorted space (fig. 2).to determine the halfway points of profile A and B.



***Figures** 1) distortion corrected b = 0 with halfway mask 2) mask transformed into distorted space 3) distortion corrected diffusion weighted image 4) distorted SE-fMRI image 5) map of pixel shift required to correct fMRI image 6) corrected fMRI image.*

For the fMRI data the closest matching image pair (particularly in respect to vascular and CSF inflow effects) from the dual phase-encode pre-scans was manually chosen and corrected for distortion as above. A matrix of pixel shift required to correct the images was also derived. Each dynamic from the fMRI experiment was then registered to the chosen uncorrected pre-scan dynamic using a 12 parameter rigid registration (FLIRT, FSL, FMRIB Analysis Group, Oxford). Distortion in the registered fMRI series was then corrected by signal mapping according to the pixel shift maps.

Results and discussion The reverse phase encoding/k-space traversal technique effectively corrects in-plane geometric distortions caused by magnetic susceptibility effects in both DWI (figs. 7-10) and SE-fMRI (figs.11-12). We have previously demonstrated that this method also removes eddy current-induced distortions in DWI [4]. We show that SE-EPI fMRI at 3 T is sensitive enough to detect activation in the temporal and frontal lobes from a word categorisation task, implying that the benefits of effective distortion correction, which requires SE-EPI, are not aversely offset by the lower sensitivity of SE-fMRI when compared with GE-fMRI. In summary, our results allow us to define a sensitive and distortion-free combined DWI-fMRI protocol for use at 3 T, which is of particular applicability in temporal lobe studies.



***Figures** 7) b = 0 image before correction 8) distortion corrected b = 0 image 9) Generalized fractional anisotropy (GFA) map from uncorrected images 10) GFA map from corrected images 11) Individual fMRI image with significant activation overlaid (cluster analysis p= 0.05) 12) Group analysis for 12 subjects showing frontal and temporal lobe activation.*

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References (1) Bowtell, R.W., et al. Proc. of the 2nd Annual Meeting of ISMRM. 1994. San Francisco, (2) Devlin, J.T., et al., Neuroimage 2000, 11: p. 589-600., (3) Morgan, P.S., et al., J Magn Reson Imaging, 2004. 19(4): p. 499-507. (4) Embleton, K. & Parker, G. J. M. BC-ISMRM 2005 Oxford.