Correction of Eddy Current Induced Artefacts in MR Diffusion Tensor Imaging using Iterative Cross-Correlation.

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Introduction:
Geometric distortions of echo-planar images produced by strong eddy currents present in the diffusion tensor imaging (DTI) experiment are a major confound to the accurate quantification of diffusion coefficients and measures of diffusion anisotropy based upon them. Here we investigate how the method of iterative cross-correlation (ICC) of baseline and diffusion-weighted images (DWIs) can be extended to correct high b-value DWIs without the need for extrapolation of distortion parameters determined from low b-value images. The ICC algorithm works by correcting the distorted image through a combination of a change of scale (M'), a shear distortion (S') and a translation (T') applied to each phase encode column of the distorted image.

Monte Carlo Simulations:
Monte Carlo simulations were undertaken to determine how accurately the ICC algorithm corrected distorted DWIs as a function of the b-value and SNR using (i) a synthetic brain image, and (ii) a synthetic water phantom image. These two cases were chosen to indicate the maximum value of b at which distorted and baseline images can be directly compared using normal brain images (i) and water phantom images (ii). The synthetic diffusion-weighted brain image was based on a 181 x 217 T2-weighted image obtained from the Montreal Simulated Brain Database (http://www.bic.mni.mcgill.ca). Regions of grey matter, white matter and CSF were each assigned a characteristic diffusion tensor with diffusion properties close to those measured in living tissue.

The simulations showed that the maximum value of the trace of the b-matrix, Tr(b), at which distorted DWIs of human brain can be accurately corrected by direct comparison with the undistorted baseline image is approximately 500 s mm^-2. Conversely, in the water phantom simulations, the distorted DWIs could be corrected at values of Tr(b) up to 2000 s mm^-2. Given these results we investigated whether ICC distortion parameters determined from separate calibrations of water phantom images would be effective in correcting geometric distortions observed in the DWIs collected as part of a human volunteer DTI study.

Methods:
Both human volunteer and water phantom images were obtained using a single-shot DW-EPI sequence implemented on an Elscint 2T Prestige scanner (Haifa, Israel) equipped with a 15 mT m^-1 actively shielded gradient set. Image acquisition parameters were as follows: 10 (volunteer) or 15 (phantom) non-oblique axial slices, 6 mm slice thickness, 226 x 128 image matrix, 44 x 22 cm field of view. TR of 1 s per slice, TE of 103 ms. Diffusion sensitization was achieved by inserting two symmetric trapezoidal gradient pulses of duration δ = 40 ms, separation Δ = 43 ms and rise time 5 ms placed around the 180° pulse in the required gradient channel. Diffusion sensitizing gradients were applied sequentially along the directions:

G0 = G0(0, 0, 0), \( G^1 = G_0(1/2, 0, 1/2), \)
G2 = G0(1/2, 0, 1/2), \( G^3 = G_0(0, 1/2, 1/2), \)
G4 = G0(1/2, 1/2, 0), \( G^5 = G_0(1/2, 1/2, 0), \)
G6 = G0(1/2, 1/2, 0), \( G^6 = G_0(0, 1/2, 1/2), \)
(1)

following the uniform diffusion gradient direction sampling scheme of Basser and Pierpaoli. In each diffusion gradient direction we acquired 10 DWIs with a peak diffusion gradient strength of 11 mT m^-1, giving Tr(b) ~ 682.77 ± 7.07 (SD) s mm^-2 for \( G^1 \) to \( G^6 \). A total of 60 DWIs per slice position was collected, plus 10 baseline images with no diffusion sensitization. The total scan time was approximately 15 minutes. The magnitude MR images were transferred from the scanner to a workstation for processing. Within each slice the set of 10 images for each of the seven diffusion gradient directions was separately re-aligned, and then averaged to give seven high signal-to-noise images. The six elements of D and the baseline T2 signal intensity were estimated in each voxel by multivariate regression.

Results:
Figure 1 shows the variation in M', S' and T' estimated by the ICC algorithm for water phantom images as a function of slice position for the first two diffusion gradient directions \( G^1 \) and \( G^2 \). The dependence of M', S' and T' on slice position is seen to be almost linear (as it is with \( G^3 \) to \( G^6 \)) which allows M', S' and T' to be determined for new non-oblique slices positions by interpolation. An example of the use of this method on human data is shown in figure 2. It can be seen that there is a significant reduction in the misalignment artefacts in the corrected images (d-f) compared with the uncorrected images (a-c).

![Figure 1: Variation in magnification factor M', translation T' and shear S' versus slice position for DWIs \( G^1 \) (square) and \( G^2 \) (circle) for a water phantom. Dot-dashed lines indicate best-fit lines to the data.](image1)

![Figure 2: Maps of the off-diagonal diffusion tensor elements \( D_{xy} \), \( D_{xz} \), \( D_{yz} \) for a volunteer before (a-c) and after (d-f) correction.](image2)

Conclusion:
This work suggests that distorted DWIs acquired at high values of b may be corrected using the ICC algorithm without collecting low b-value images. This should not only improve the accuracy of the algorithm, but also allow the implementation of simplified methods for measuring the diffusion tensor D based on collecting the minimum number of DWIs.

References:

Acknowledgements: The work was undertaken at the SHEFC Brain Imaging Research Centre for Scotland.