Non-Linear Motion Correction for Diffusion Imaging Using a Self-Navigated Cartesian-Based Sequence

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Synopsis:
Multi-shot techniques can be used to obtain high-resolution diffusion-weighted images. However, the images become very sensitive to patient motion, resulting in severe artefacts. In order to obtain reliable information about the orientation of white-matter fibres, it is essential to compensate for these motion-induced phase errors, in general requiring non-linear corrections. The refocusing reconstruction method has been shown to correct for non-linear errors but to date has only been applied to spiral trajectories. We show here that this method is also effective when using IEPI-based self-navigated sequences with the significant advantage of not requiring any re-gridding to the Cartesian grid.

Introduction:
A multi-shot approach is required to obtain high resolution diffusion-weighted images (DWI). Since diffusion pulse sequences are inherently very sensitive to motion, any movement of the subject during the application of the diffusion gradients will result in considerable phase errors between segments of K-space acquired over different shots. These phase errors can, however, be successfully corrected by separately acquiring a low spatial resolution image for each interleave (2D navigator echoes) as shown by Butts [1].

Several methods have been suggested to perform these corrections, amongst which are the linear methods proposed by Atkinson [2] and the refocusing reconstruction approach introduced by Miller [3]. The latter method has to date only been applied to spiral trajectories. We have adapted this method to an IEPI based sequence, which has the advantage of already using a Cartesian grid. This means that the re-gridding step of the refocusing method can be eliminated and its implementation further simplified. Here we used a self-navigated pulse sequence termed Echo Planar Imaging with Keyhole (EPIK) which was first introduced by Zaitsev for fMRI [4].

Methods:
Data were acquired on a 3.0 T Varian Inova scanner. To minimise eddy currents, a doubly-refocused spin-echo sequence was used [5]. Each set of images contained 9 contiguous slices (2.5 mm thickness). The other acquisition parameters were: TE= 106 ms, TR= 1.6 s, bandwidth of 200 kHz. The field of view was set to 240×240 mm^2, with a matrix size of 128×128, which resulted in a final, true, resolution of 1.875×1.875 mm^2 in-plane. The K-space was covered over four shots and the keyhole covered a fraction of one-sixteenth of the K-space. Each dataset consisted of one non-DW and nineteen DWI (b-value 650 s/mm^2). The gradients were uniformly distributed over a sphere in b-space, using the optimized scheme proposed by Jones [6]. In order to obtain enough SNR, eight datasets were acquired. This took approx. 54 minutes. Acquiring several datasets is essential also to be able to satisfactorily correct for the motion-induced phase errors. Two methods were implemented to perform the phase corrections: the linear method proposed by Atkinson [2] and the refocusing method introduced by Miller [3]. To minimize motion artefacts due to pulsatile flow, peripheral gating was used such that triggering occurred on every cardiac cycle, with three slices being excited per cycle. The refocusing method requires the absence of abrupt phase discontinuities between adjacent lines of K-space. By synchronising the acquisition with the cardiac cycle so that, for a given image, all interleaves were acquired at roughly the same cardiac phase, a smooth modulation of the K-space phase could be ensured [3].

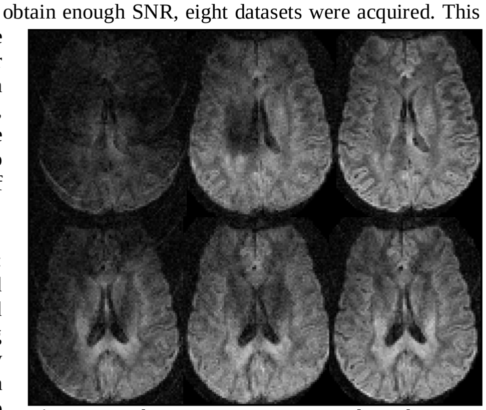

Figure 1: The two rows correspond to the same slice imaged with diffusion-weighting along two different directions. From left to right: uncorrected images, corrected using the linear method, and the refocusing reconstruction method.

Results and Discussion:
Figure 1 shows the DWI obtained for a given slice: without corrections (left), using the linear method (middle) and the refocusing reconstruction method (right). Each row corresponds to weighting along different directions. The uncorrected images display severe artefacts that are corrected to a great extent with the linear method. The medial areas tend, however, to display some residual attenuation. By using the refocusing method, this attenuation is also removed, producing high-resolution images, which display no visible artefacts. The non-linear method has the further advantage of sharpening the images.

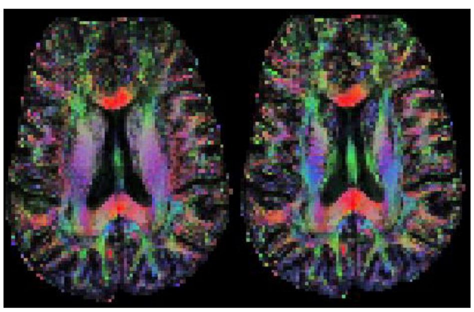

Figure 2: Colour-coded maps depicting the directions of the main eigenvectors: red corresponds to R/L, green to A/P and blue to S/I. The intensity is given by the fractional anisotropy. The map on the left was obtained using the images corrected with the linear method whereas the refocusing method was used on the right.

The effective removal of all motion-related phase errors is essential if the data are to be used to extract reliable information on the orientation of white-matter fibres. This is further illustrated in Fig. 2, which uses a colour-coded map [7] to display the principal eigenvectors computed for the images obtained using the two methods. The vectors were computed using the simple partial volume model suggested by Behrens [8]. On the map corresponding to the linear method (left), it can be seen that an extensive portion of the white matter in medial areas shows a preferential Inferior/Superior orientation that is known to be artefactual. This effect is no longer visible in the images reconstructed with the refocusing approach (right).

The rigid-body motion assumption is only approximately valid during a small fraction of the cardiac cycle [9]. Consequently, unless all but this quiet phase of the cardiac cycle are avoided, a rigid body assumption will not be met and non-linear phase errors will persist on the images when the linear approach is used. The refocusing method does not appear to be so limiting and works well provided that the peak of systole is avoided. As a further benefit, it also presents the advantage of not requiring such a lengthening of the acquisition time [3].

Conclusion:
We have shown that the refocusing reconstruction method first developed for spiral imaging can successfully be implemented for use with the DW-EPIK sequence. Furthermore, since the EPIK sequence already uses the Cartesian grid, the re-gridding step – required when using spiral acquisitions – becomes superfluous. This fact significantly simplifies the implementation of the refocusing method, making it very straightforward. When compared to the previously introduced linear methods, the refocusing method performs significantly better, as also enables correction for higher order phase errors. This results in a more reliable mapping of fibre orientation, vital if fibre-tracking is to be performed.

References
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