New algorithm of correction for eddy current-induced distortion of DWI

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Introduction: Diffusion-weighted imaging (DWI) uses diffusion-sensitized gradients to encode the Brownian movement of water molecules. These diffusion gradients usually incur residual eddy currents which crosstalk with the imaging gradients and lead to gross geometry distortions. Haselgrove and Moore (1) proposed a retrospective method by coregistering the distorted DWI images to the undistorted images (the null images). Under the linear model, parameters were determined column-wise by an algorithm based on normalized cross-correlation (NCC). Their algorithm has two drawbacks. One is that the contrasts of the DWI images and the null images are usually different and additional scans are required. Another one is that the algorithm is limited to a linear model. The first drawback can be avoided by, as proposed by Bodammer et al (2), using two DWI images acquired with opposite diffusion gradients. This opposite-gradient method follows the fact that, theoretically, opposite diffusion gradients result in opposite distortions. Thus NCC is adequate to be used in correcting the distortions of the image pair since they have the same contrast. However, the second shortcoming of Haselgrove and Moore's algorighm still exist. In the present study, we propose a generalized algorithm for this problem.

Theory: Assuming the deformation fields $d(x,y,z)$ can be modeled with a parameter set $\mathbf{P}$. Suppose that the inverse deformation field d^{-1} exists and the deformation is small such that $d^{-1}=-d$. The relationship between the two distorted DWI images (f_1, f_2) and the undistorted image (f) can be written as

$$f(x,y,z)=f_1\left(x,y+d^{-1}(x,y,z),z\right)\approx f_1(x,y,z)+\frac{\partial f_1}{\partial y}d^{-1}(x,y,z)\ . \qquad (1)$$
$$f(x,y,z)=f_2\left(x,y-d^{-1}(x,y,z),z\right)\approx f_2(x,y,z)-\frac{\partial f_2}{\partial y}d^{-1}(x,y,z)$$

From Eq. (1), we have

$$f_2(x,y,z)-f_1(x,y,z)=\left(\frac{\partial f_1}{\partial y}+\frac{\partial f_2}{\partial y}\right)d^{-1}(x,y,z)\cdot \qquad (2)$$

Reformulate Eq. (2) in matrix form,

$$[\mathbf{f}_2-\mathbf{f}_1]=diag\left(\frac{\partial \mathbf{f}_1}{\partial y}+\frac{\partial \mathbf{f}_2}{\partial y}\right)\mathbf{AP}+\boldsymbol{\varepsilon}\cdot$$

The least square estimation for $\mathbf{P}$ is

$$\hat{\mathbf{P}}=\left(\mathbf{A}^T\mathbf{A}\right)^{-1}\mathbf{A}^T diag\left(\frac{\partial \mathbf{f}_1}{\partial y}+\frac{\partial \mathbf{f}_2}{\partial y}\right)^{-1}[\mathbf{f}_2-\mathbf{f}_1]\cdot$$

The estimate $\hat{\mathbf{P}}$ can be effectively computed by numerical iterative algorithm. In the present study, the correlation coefficient between the image pair serves as the metric of correction.

Materials and methods: For demonstration purpose, a DSI dataset of 203 points in the q-space was corrected with the proposed algorithm. Scanning parameters of the DSI dataset were: TR / TE = 9100 / 142 ms, FOV / slice thickness = 370 / 2.9 mm, matrix size = 128^2, max b-value = 6000 s/mm^2. The deformation field was parameterized with a second-order model.

Results: One selected DWI image pair is presented. Fig. 1 displays (a) the distorted image and (b) the corrected image, where the white contour is generated from the null image. Fig. 2 shows (a) the difference of distorted image pair and (b) the difference of the corrected image pair. Evidently, the mis-registration of the distorted image pair is greatly reduced. Similar result is illustrated in Fig. 3, where the correlation coefficient between the corrected image pair (vertical axis) is improved with iteration steps (horizontal axis).

Discussion: Providing two DWI images acquired with opposite diffusion gradients, the proposed algorithm could effectively remove the eddy-current induced distortions. The opposite-gradient method is suitable to correct for diffusion spectrum imaging (DSI) or q-ball imaging (QBI) datasets where symmetric points about the origin in the q-space are usually acquired. Though it has been shown that the linear model is effective for the deformation field, at least for moderate b-values (~1000 s/mm^2) (1,2), rare evidences are presented for high b-value DWI images (e.g. DSI or QBI). The proposed algorithm is applicable for model of arbitrary order and therefore is superior to Haselgrove and Moore's algorithm.

References: 1.Haselgrove JC, Moore JR. Magn Reson Med 1996;36(6):960-964.
2.Bodammer N, Kaufmann J, Kanowski M, Tempelmann C. Magn Reson Med 2004;51(1):188-193.

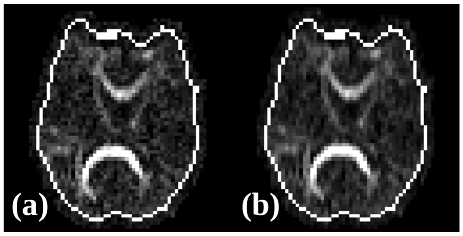

Fig. 1

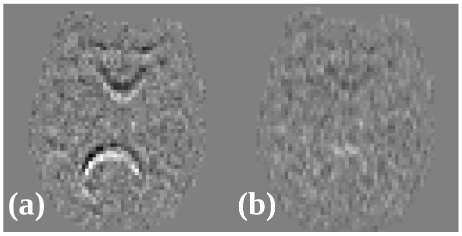

Fig. 2

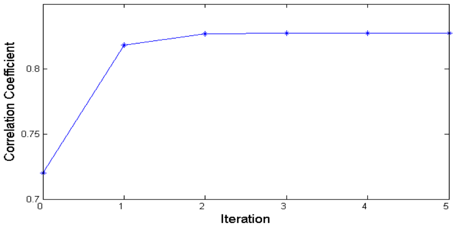

Fig. 3