Higher order correction of eddy current distortion in diffusion weighted echo planar images.

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Target Audience: The method presented in this work is relevant to those interested in accurate correction of eddy-currents distortions in diffusion MRI when distortions are large.

Purpose: It is well known that eddy currents induce distortions in the diffusion weighted EPI images typically used for diffusion tensor imaging (DTI) and high angular resolution diffusion imaging (HARDI). To correct the distortions, one must find and a correction displacement map. To a very good approximation, the distortions involve displacements in the phase-encoding direction only, and the displacement field can be expressed as a sum of polynomials. Until recently, a linear (affine) model for the displacement field for eddy current correction has been used by most diffusion MRI processing software packages, with the sole exception TORTOISE [1], which uses the quadratic model proposed by [2]. Unfortunately, the linear model is frequently inadequate, and in some instances even a quadratic model may be insufficient. In a general cubic model, there are six possible quadratic terms 10 possible cubic terms. For an eddy current distortion correction, one of the quadratic terms and three of the cubic terms are excluded by the requirement that the z-component of the eddy current field, and hence the displacement field, obeys the Laplace equation. When higher order corrections improve the distortion correction, it is important that only the physically realizable terms should be used.

Theory: To an excellent approximation the image reconstructed without distortion correction and the true object are related by:

$$f_{lmn} = g\left(l\Delta x, m\Delta y + \delta y, n\Delta z\right) \qquad (1)$$

f_{lmn} is the value in pixel *lmn* of the distorted image,

$g\left(l\Delta x, m\Delta y + \delta y, n\Delta z\right)$ is the true object at coordinates $x = l\Delta x$, $x = m\Delta y + \delta y$, and $z = n\Delta z$,

Δx is the pixel size in the frequency-encode direction,

Δy is the pixel size in the phase-encode direction,

Δz is slice thickness, and

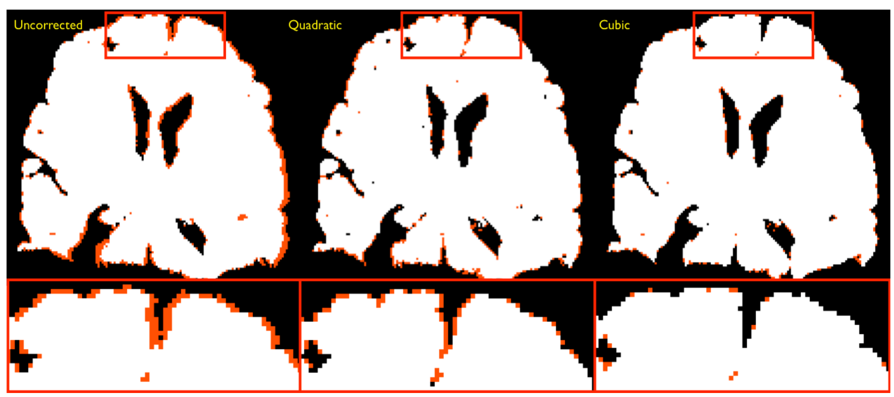
δy is the eddy-current induced distortion, which is proportional component parallel to the main field of the magnet of the magnetic field generated by the eddy currents.

Since eddy-current field component obeys the Laplace equation, so does δy. Up to third order we may write:

$$\delta y = a_0 + a_{10}z + a_{11}x + a_{12}y + a_{20}\left(z^2 - \left(x^2 + y^2\right)\right)/2) + a_{21}x^2 + a_{22}y^2 + a_{23}xy + a_{23}xz + a_{23}yz + a_{30}z\left(x^2 - y^2\right)$$
$$+ a_{31}x\left(4z^2 - \left(x^2 + y^2\right)\right) + a_{32}y\left(4z^2 - \left(x^2 + y^2\right)\right) + a_{33}xyz + a_{34}x\left(x^2 - 3y^2\right) + a_{35}y\left(x^2 - 3y^2\right) + a_{36}z\left(2z^2 - 3\left(x^2 + y^2\right)\right)$$

The fitting procedure involves finding the values for the a_{ij} that best corrects the distortion using Equation 1. This step can involve either optimizing a goodness of fit parameter such as mutual information, or by independently measuring the eddy current field.

Examples: To determine the effectiveness of the registration algorithm on real data, a set of DWI volumes of a fixed human brain acquired on a Bruker 4.7T imaging system with considerable eddy current distortions was corrected using either quadratic or cubic basis functions. The performance of these is most evident when rapidly browsing the image volumes, where remarkable differences in registration of both the sample edges and internal features were seen between fitting approaches. This outcome is approximated in the accompanying figure by showing the regions of overlap (white) and mismatch (orange) between adjacent volumes in the data set following no fitting (left), quadratic fitting (middle) or cubic fitting (right). Following quadratic fitting, misregistration was on the order of several voxels in many areas, while cubic fitting resulted in much lower mismatched voxels. We also analyzed the advantages of using higher-order terms for about 10 data sets of the “connectome” data [3] and found that quadratic basis functions were always necessary, while cubic terms improve the quality of the correction process in about 30% of the cases.



Conclusions: Including physically-based cubic terms for correction did not cause any instabilities in registrations and provided significant improvements when simpler basis functions could not provide a good alignment.

References: 1) Pierpaoli C. et al., ISMRM, 2010; **2)** Rohde G. et. al., MRM, 2004; **3)** www.humanconnectomeproject.org