Efficient All-Direction Eddy Current Correction for DTI Using Orthogonal Basis Sets

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Introduction

Magnetic resonance diffusion tensor imaging (DTI) typically requires at least six diffusion weighted images and one base image to calculate the diffusion tensors. In practice, more directions are often acquired to improve the reliability of tensor computation. For example, the DTI protocol of Biomedical Informatics Research Network (BIRN) is based on 30 diffusion weighting directions. One of the imaging artifacts specific to DTI is the direction-dependent geometric distortions from the eddy current induced fields. These distortions cause mis-registration among images with different diffusion weighting directions, resulting in computational inaccuracies of the diffusion tensors throughout the entire image.

It was proposed recently that the geometric distortions from the main field inhomogeneity and gradient eddy currents in DTI images can be corrected under a unified framework [1]. Distortion-free field maps for the base image and each diffusion direction were acquired by a pulse sequence combining phase encoding steps and EPI readout trains. The eddy current induced gradients were computed from the difference images between the base field map and the diffusion weighted field maps. Although acquiring one phase map for each diffusion weighting direction can directly measure the eddy current induced gradients, it is not optimal in time for a diffusion scheme with large number of diffusion directions. The three physical gradient coils largely produce their own characteristic residue fields within a given setting of the magnet, coils, and gradient pre-emphasis. It can thus be hypothesized that the final residual field is the superposition of the fields generated by individual gradients followed by the law of electromagnetic induction. Horsfield [2] proposed a method to map eddy current induced fields with 3 orthogonal gradient pulses. The pixel shifts in a series of diffusion weighted images were used to assess the strengths of the residual fields with an assumption of single time constant decay. However, the iterative downhill simplex method for field estimation is highly computation-intensive and needs 24 hours or more to determine the characteristic fields. In this study, we propose an efficient and accurate method to estimate eddy current induced gradient fields for any directions by measuring 3 orthogonal diffusion weighting directions.

Methods

The sequence development and data acquisition were conducted on a 4T GE Signa Horizon LX system. The pulse sequence was written based on an EPI readout train with the addition of sinusoidal phase encoding in the beginning, generating distortion-free images sampled at progressing echo times [1]. The phantom images were acquired using this sequence and used to calibrate the eddy current induced gradients after high order shimming.

In a perfect system, measuring one eddy current induced field in X, Y, Z directions with a full gradient magnitude should be sufficient to find the residual field under any diffusion weighting gradient pairs by linear superposition. In practice, however, there could be cross-talks among various shim coils, possible non-linear behavior of the eddy currents, and measurement uncertainties that will require more than one measurement along each direction. In this study, we first acquired the phase maps of a DTI dataset with 3 orthogonal diffusion directions and 3 gradient combinations, as shown in Table 1 b1 to b6. The eddy current induced gradients of the later 3 directions (b4 to b6) can be estimated from those of 3 orthogonal directions (b1 to b3). To better characterize the eddy current behavior and evaluate the accuracy of the one measurement method, we acquired the phase maps at various amplitudes of the diffusion gradients along different diffusion directions to directly measure the eddy current induced fields (Figure 1). The least square fitting was conducted to find the relationship between the eddy current induced gradients and the diffusion weighting gradients. Subsequently, the fitted equations were used to predict the eddy current induced gradients under b4 to b6 conditions. The predicted values were compared with the one measurement method with the directly measured values as a standard.

$$\begin{array}{c} \mathbf{X} \\ \mathbf{Y} \\ \mathbf{Z} \end{array} \left[\begin{array}{c} 0 \\ 0 \\ 0 \end{array} \; \overbrace{\begin{array}{ccccc} 1 & 0.8 & 0.6 & 0.4 & 0.2 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}}^{\textbf{X ON}} \; \overbrace{\begin{array}{ccccc} 0 & 0 & 0 & 0 & 0 \\ 1 & 0.8 & 0.6 & 0.4 & 0.2 \\ 0 & 0 & 0 & 0 & 0 \end{array}}^{\textbf{Y ON}} \; \overbrace{\begin{array}{ccccc} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0.8 & 0.6 & 0.4 & 0.2 \end{array}}^{\textbf{Z ON}} \right]$$

Figure 1: Diffusion scheme for direct characteristic field measurement generated by 3 orthogonal diffusion gradients.

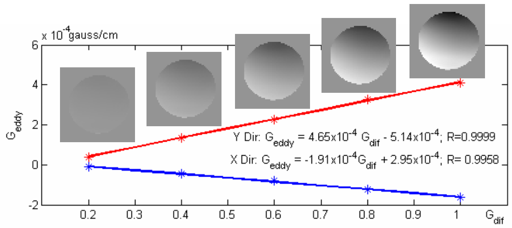

Figure 2: Representative eddy current induced gradients when Gy is on. The induced gradients (due to mutual induction and cross talk) in X, Y directions are shown in blue and red respectively. The gray images are the eddy current induced fields at different gradient amplitudes. A high linearity between the diffusion gradients and the induced characteristic gradient suggests that measuring two points could be enough for accurate prediction of the induced characteristic gradient under any diffusion gradient.

Results

The direct measurement of induced characteristic gradients at different diffusion weighting shows high linearity as in Figure 2. This linearity allows us to easily find the eddy current induced gradients in any diffusion gradient pairs by measuring at two different diffusion amplitudes. In comparison, a one-point measurement is not sufficient due to the non-zero zero-crossings of the eddy-current induced gradient field. Table 1 shows the results of induced gradients in frequency and phase directions with the estimated values from one measurement and from fitted equations. The prediction by fitted equations has much smaller percentage errors, and should help improve the accuracy for the distortion correction procedure.

Table 1: Eddy current induced gradients (unit of induced gradients in frequency and phase directions: 10^{-4} gauss/cm)

DWI	Gx	Gy	Gz	Freq	Phase	Freq	Phase	Freq (%error)	Phase (%error)	Freq	Phase	Freq (%error)	Phase (%error)
b1	1	0	0	1.02	-0.65	Estimated induced gradients from b1,b2 and b3. Percentage errors are computed by referencing the direct measurements.				Estimated induced gradients from the fitted equations. Percentage errors are computed by referencing the direct measurements.			
b2	0	1	0	-1.72	4.32								
b3	0	0	1	-0.27	0.10								
b4	0.7	0.7	0	-0.45	2.38	-0.49	2.56	8.9%	7.6%	-0.43	2.28	4.4%	4.2%
b5	0	0.7	0.7	-1.19	2.91	-1.39	3.09	16.8%	6.2%	-1.13	2.81	5.0%	3.3%
b6	0.7	0	0.7	0.60	-0.41	0.52	-0.38	13.3%	7.3%	0.53	-0.39	11.7%	4.9%

Discussions and Conclusions

It was found that the eddy current induced gradients have stable temporal and spatial characteristics as a function of the corresponding diffusion gradients. This fact makes it possible to determine the induced gradients by acquiring a very limited number of phase maps, specifically, two measurements along each of three orthogonal directions, to determine the induced gradients in any diffusion weighting directions. It is anticipated that this efficient and effective correction method will find broad applications in DTI imaging experiments where many directions are acquired.

References and Acknowledgment: 1. Chen B, Guo H., Song AW. NeuroImage 2006;30:121-129. 2. Horsfield M. MRI 1999;17(9):1335-1345. This work was supported by NIH grants RR 21382 and NS 50329.