Correcting High Order Eddy Currents for Diffusion Weighted Imaging with Arbitrary Scan Plane and Diffusion Direction

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INTRODUCTION

Eddy currents can cause diffusion gradient direction dependent image distortion in diffusion weighted (DWI) and diffusion tensor imaging (DTI), resulting in image misregistration and subsequent analysis inaccuracies. The majority of these eddy currents are high order eddy currents (HOEC) because linear and B0 eddy currents are typically well compensated by system level preemphasis [1] and/or linear gradient correction [2]. The HOEC relates to factors such as gradient coil alignment, and is difficult to remove completely in general. However, its effect on DWI can be reduced or corrected by several means: 1) Use the eddy current balanced dual spin echo (DSE) [3] to replace the single spin echo (SSE, also called Stejkal-Tanner) sequence [4]. However, this approach significantly prolongs echo time, leading to much reduced signal-to-noise ratio (SNR), which is essential in body and high resolution brain imaging. 2) Use image registration [5] to spatially align the already distorted images. However, it is often challenging for the underlying mathematical model to encompass all kinds of distortions from HOEC, especially those of 3rd order and higher. It is also difficult to recover from the blurring and/or SNR loss using registration. 3) Use HOEC correction at the pulse sequence and image reconstruction stages [6] to reduce image distortion. The advantage of this method is that it does not assume a particular mathematical distortion model because it is based upon a system level HOEC calibration. It also retains the high SNR of SSE and has the capability of reducing blurring because of its prospective, dynamic nature in compensation. In this paper, we extend HOEC correction to arbitrary scan planes with arbitrary diffusion gradient directions.

PROPOSED METHODS

Denote **R** as the rotation matrix that transforms logical to physical coordinates. Denote $\mathbf{g}_L$ as the length-3 diffusion gradient amplitude vector in logical axes for a given b-value and diffusion gradient direction, and $\mathbf{E}(t)$ as the $N \times 3$ eddy current coefficient matrix at time *t*, where e_{ij} is the coefficient of eddy current contribution from the *i*th axis, $i = X, Y, Z$, to the *j*th spatial polynomial basis function in physical coordinates, $j = 1, 2, \dots, N$. $\mathbf{E}(t)$ is calculated based on sequence gradient shape and timing. Detailed form of $\mathbf{E}(t)$ is omitted here for limited space. We also denote square matrix **F** as the matrix that transforms polynomial bases from logical to physical coordinates. For polynomials of up to *p*th order, the size of **F** is $(p+1)(p+2)(p+3)/6$ and **F** is a function of **R**. For example, for *p* = 2:

$$\mathbf{F} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r_{11} & r_{12} & r_{13} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r_{21} & r_{22} & r_{23} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r_{31} & r_{32} & r_{33} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_{11}^2 & r_{12}^2 & r_{13}^2 & 2r_{11}r_{12} & 2r_{11}r_{13} & 2r_{12}r_{13} \\ 0 & 0 & 0 & 0 & r_{21}^2 & r_{22}^2 & r_{23}^2 & 2r_{21}r_{22} & 2r_{21}r_{23} & 2r_{22}r_{23} \\ 0 & 0 & 0 & 0 & r_{31}^2 & r_{32}^2 & r_{33}^2 & 2r_{31}r_{32} & 2r_{31}r_{33} & 2r_{32}r_{33} \\ 0 & 0 & 0 & 0 & r_{11}r_{21} & r_{12}r_{22} & r_{13}r_{23} & r_{11}r_{22}+r_{12}r_{21} & r_{11}r_{23}+r_{13}r_{21} & r_{12}r_{23}+r_{13}r_{22} \\ 0 & 0 & 0 & 0 & r_{11}r_{31} & r_{13}r_{32} & r_{13}r_{33} & r_{11}r_{32}+r_{12}r_{31} & r_{11}r_{33}+r_{13}r_{31} & r_{12}r_{33}+r_{13}r_{32} \\ 0 & 0 & 0 & 0 & r_{21}r_{31} & r_{22}r_{32} & r_{23}r_{33} & r_{21}r_{32}+r_{22}r_{31} & r_{21}r_{33}+r_{23}r_{31} & r_{22}r_{33}+r_{23}r_{32} \end{bmatrix},$$

where r_{ij} is the element of **R**. It can be shown that the coefficients of HOEC bases in logical axes $c(t) = \mathbf{F}^{\mathrm{T}}\mathbf{E}(t)\mathbf{R}\mathbf{g}_L$. Polynomial bases and $c(t)$ are then used to determine the per-slice, per-echo gradient and frequency compensation in pulse sequence as well as the distortion correction field map in image reconstruction.

RESULTS

Brain DTI images were acquired on a 3T GE scanner using SSE without and with HOEC correction, and DSE. The scan plane was single oblique (tilted axials with tilting angle being about 25 degrees). Twelve diffusion directions were used; images from two representative directions (not aligned with X, Y, or Z axes) are shown in Fig. 1. The remaining parameters were: b value = 1000 s/mm^2, NEX = 1, parallel imaging acceleration factor = 2. For comparison, T2 image is plotted in the top row. The same window width and level is used for all images. As can be seen, the DSE images have significantly lower SNR than the SSE images. For the first direction, the SSE image appears sheared due to a large quasi-linear eddy current along the readout for this particular slice. The shape of the SSE image with HOEC correction is comparable to T2 while having significantly higher SNR than DSE. For the second direction, the SSE image appears stretched and slightly shifted in the vertical (phase encoding) direction due to a quasi-linear eddy current along phase encoding and slice directions for this slice. Again SSE with HOEC correction reduces the distortion to minimum while providing higher SNR than DSE.

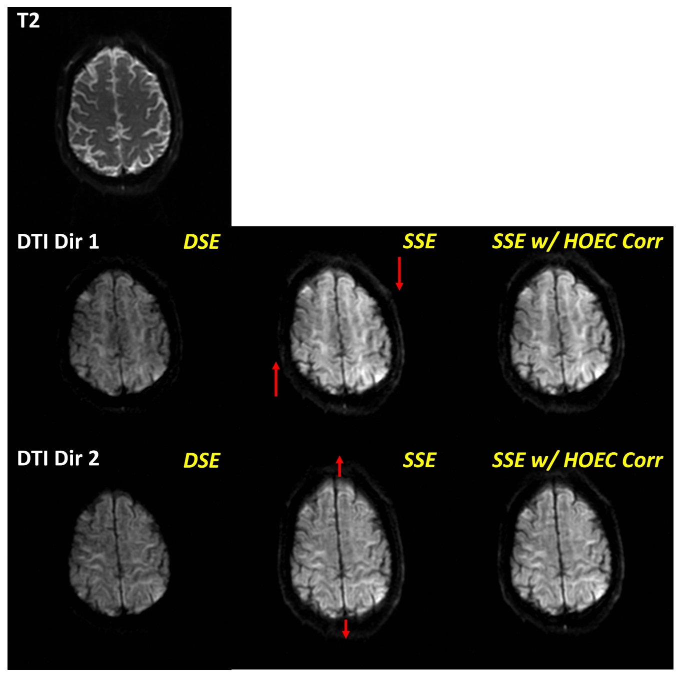

Fig. 1. Brain DTI images at 3T acquired in single oblique scan plane showing comparison of SSE, SSE with HOEC correction, and DSE images. SSE with HOEC correction generates images with significantly reduced distortion over SSE alone while providing higher SNR than DSE.

CONCLUSION

The proposed HOEC correction is an effective way to mitigate eddy current generated image distortion in DWI and DTI. SSE with HOEC correction can produce images with significant SNR advantage over DSE images due to the shorter echo time while maintaining similar, minimum distortion levels. The SNR gain is essential in applications such as liver diffusion or high resolution brain diffusion. HOEC correction can be extended to arbitrary scan plane with arbitrary diffusion direction through the application of gradient and polynomial basis rotation matrices.

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