Correcting High Order Eddy Current Induced Distortion for Diffusion Weighted Echo Planar Imaging

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INTRODUCTION

It is well known that diffusion weighted echo planar imaging (DW-EPI) often suffers from direction dependent distortions due to diffusion gradient generated eddy currents. These distortions, if not corrected, can lead to misregistration among DW images of different directions and inaccuracies in any post processing operations involving DW image combination. Dual spin echo DW-EPI [1] has been proposed to provide certain level of inherent eddy current cancellation, but at a significant cost on echo time and signal-to-noise ratio. Conventional distortion correction methods have focused on correcting the linear and B_0 eddy currents, either by preemphasis [2] or explicitly modifying gradient waveforms and receive frequency [3]. However, untreated eddy currents of high spatial order due to gradient coil leakage field, or simply high order eddy currents (HOEC), can also be significant with the increase of gradient amplitude and slew rate in modern MR scanners. Because of the high spatial order, distortions generated by these eddy currents are not only diffusion direction dependent, but also slice dependent. In this paper, we propose two complementary methods to correct the HOEC induced distortions: The first method extends the method in [3] to modify gradient and frequency waveform amplitudes on a slice-by-slice basis in the pulse sequence, and the second method corrects the distorted images by image domain post processing. Body diffusion results show that the proposed methods are capable of significantly reducing HOEC induced distortions.

PROPOSED METHODS

We use a gradient echo based sequence to map the HOEC. A large eddy current generating trapezoidal gradient is followed by a series of conventional gradient echo data acquisitions, each making an image of a chosen slice at a particular time point. By repeating the sequence with different donor axes and polarities of the eddy current generating gradient, evaluating the phase difference between images of the same axis but opposite polarities, and fitting the data spatially using high order polynomials and temporally using an exponential model, we generate a series of (α_{mn}, τ_{mn}) where α_{mn} is the weight and τ_{mn} is the time constant (for notational simplicity, we assume single exponential) of the *n*th spatial basis function $B_n(x, y, z)$ with diffusion donor axis *m*, *m* = *X*, *Y*, or *Z* axis.

Method 1: We extend the method in [3] to compensate for certain HOEC terms by adjusting readout, phase encoding gradients, and receiver frequency on a per-slice basis in the pulse sequence. For simplicity, axial scan plane with readout along physical *X* direction is assumed. Following the derivation in [3], the correction coefficient $c_n(t)$ for the *n*th basis function at time *t* after the second diffusion gradient is $c_n(t) = \sum_{m=X,Y,Z} G_m \beta_{mn} \alpha_{mn} \tau_{mn} e^{-t/\tau_{mn}}$, where G_m is the diffusion gradient component on *X*, *Y*, or *Z* axis, and β_{mn} is a sequence related constant. Noting that basis functions z^p, xz^p, yz^p $(p \geq 0)$ are constant or linear functions of *X* and *Y* gradients at any given slice location *z*, we can obtain the effective gradient or B_0 field compensation coefficient by multiplying $c_n(t)$ with z^p for that slice. The per-slice per-echo correction coefficients are included in the pulse sequence to correct the above-mentioned HOEC terms (referred to as Type I terms). We found Type I terms are often the dominant terms, and method 1 alone often provides sufficient distortion correction.

Method 2: The remaining terms (referred to as Type II terms), or all the terms, can be corrected using a field map based post-processing method. This method does distortion correction in image domain on a per-slice basis. For simplicity, we drop the *z* dependency in the notation. Denote the eddy current field at echo time (center of k-space) as $f(x, y)$, then the corrected image has the form: $I_{corr}(x, y) = I(x, y + f(x, y))(1 + \partial f(x, y)/\partial y)$, where $I(x, y)$ and $I_{corr}(x, y)$ are distorted and corrected images, respectively.

The two methods are complementary to each other: In addition to correcting distortion, Method 1 is also capable of reducing image blurring and ghosting due to the exponential decay of eddy currents across the echo train. Correction on the pulse sequence side also opens the opportunity of reducing signal loss due to slice dephasing (not discussed due to limited space). Method 2 can correct all HOEC terms, but has to approximate the exponential decay of HOEC by a constant (corresponding to k-space center) and cannot regain lost signal. The two methods can be combined to provide synergistic advantages.

RESULTS AND DISCUSSION

Single spin-echo body DW-EPI images with and without HOEC compensation were acquired at 3T using the whole body coil with diffusion directions on *X*, *Y*, and *Z*. T2 weighted images without diffusion are also acquired as a reference. The remaining relevant parameters were: TE = 54 ms, TR = 7s, 24 slices, scan plane = axial, HOEC correction = method 1 (results from method 2 are not shown for limited space). The top row of Fig. 1 shows a slice 14 cm off isocenter in superior direction: The image with diffusion gradient on *X* shows very significant shear distortion from the T2 reference due to a significant *xz* term. The image with diffusion on *Y* shows large image dilation and intensity drop due to a significant *yz* term. Both cases were well corrected using the proposed method. The bottom row shows another slice with less distortion because the slice is closer to isocenter, and the proposed method again makes the DW images spatially register with the T2 image. In summary, the proposed methods are capable of compensating HOEC induced distortions for DW-EPI, making single spin echo DW-EPI more practical. This can significantly benefit applications (e.g., whole body diffusion imaging) where single spin echo DW-EPI is desired to increase signal-to-noise ratio.

REFERENCES

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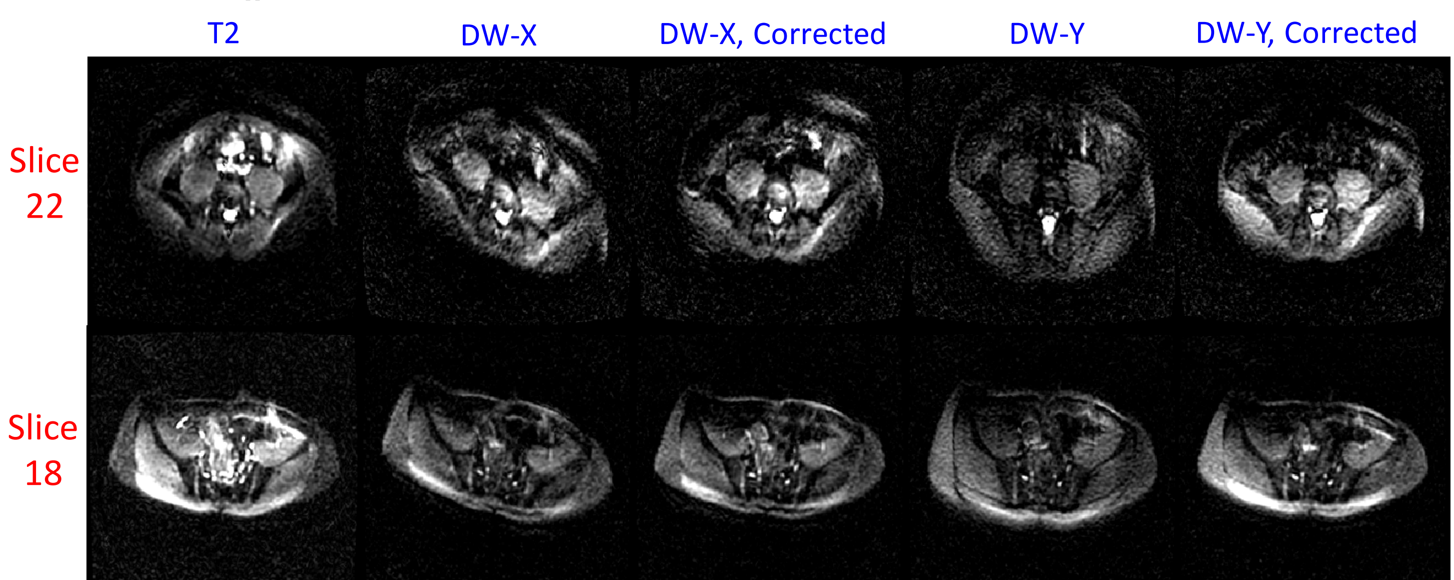

Fig. 1. Axial T_2 and DW images at slice 22 (top row, 14 cm off isocenter in superior direction) and slice 18 (bottom row, 9 cm off isocenter in superior) from a body DW-EPI scan. From left to right: T_2 reference, DW on X, DW on X with HOEC correction, DW on Y, DW on Y with correction (DW on Z not shown as the distortion is insignificant). The two slices have different levels of distortion due to the HOEC; these distortions are well corrected by the proposed method.