Correction of Eddy-Current Induced Phase Error in Diffusion-Weighted Imaging

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Introduction: The theoretical basis for measuring the spatial derivative of diffusivity of water diffusion in tissues has been established based on a newly derived theoretical relationship between the diffusion gradient and the image signal acquired with a diffusion-weighted spin-echo pulse sequence [1]. The diffusion gradient is linearly related to the phase difference of the signal with and without diffusion-encoding gradients (DEG). Since anatomical regions with different diffusion magnitudes may present large diffusion gradients at their interfaces, measuring the diffusion gradients provides a means of delineating the interfaces. However, the large phase error caused by the eddy current when the DEG are applied makes it difficult to delineate these interfaces. In this paper, we present a method to measure the eddy current and correct the phase error introduced on diffusion-weighted phase images.

Method and Materials: DEG induce a time-varying eddy current (EC) as

$$\vec{B}_{EC}(t) = [\varepsilon_0(t) + G_x(t)x + G_y(t)y + G_z(t)z]\hat{B}_0 \qquad (1)$$

where $\hat{B}_0$ represents the unit vector of the main field [2]. When a spatially symmetric uniform phantom is placed at the center of the magnet with all phase- and frequency-encoding gradients turned off, assuming that the slice-selection is the y-axis, the signal acquired at time t with the DEG in an arbitrary direction is given by

$$S_{on}(y_0,t) = S_0 \exp[i\phi_{on}(y_0,t)] \quad (2a), \qquad \phi_{on}(y_0,t) = -\gamma\int_0^t [\varepsilon_0(t') + G_y(t')]dt' + \Phi_{off}(y_0,t) \quad (2b)$$

where $\Phi_{off}(y_0,t)$ represents the cumulated phase with the DEG turned off. Thus the phase difference between with and without the DEG turned on is

$$\Delta\phi_{on}(y_0,t) = \phi_0(t) + y_0\varphi_y(t) \quad (3)$$

where $\phi_0(t) = -\gamma\int_0^t \varepsilon_0(t')dt'$ and $\varphi_y(t) = -\gamma\int_0^t G_y(t')dt'$. Based on the measurements at two slice positions y_1 and y_2, the following can be obtained:

$$\phi_0(t) = [y_2\Delta\phi_{on}(y_1,t) - y_1\Delta\phi_{on}(y_2,t)]/(y_2 - y_1) \qquad (4a), \qquad \varphi_y(t) = [\Delta\phi_{on}(y_1,t) - \Delta\phi_{on}(y_2,t)]/(y_1 - y_2) \quad (4b)$$

Optimal estimations for $\phi_0(t)$ and $\varphi_y(t)$ can be obtained by a polynomial or exponential curve fitting of the measured $\phi_0(t)$ and $\varphi_y(t)$, respectively. With these estimations, both $\varepsilon_0(t)$ and $G_y(t)$ can be computed for each time point in the acquisition window, and similarly, $G_x(t)$ and $G_z(t)$. The effect due to $\vec{B}_{EC}(t)$ in Eq. (1) can potentially be removed in image reconstruction.

A spin echo pulse sequence was developed on GE 3T EXCITE scanner to include DEG and an option to turn off the phase- and frequency-encoding gradients. A dimethyl silicone, gadolinium-enhanced spherical phantom was used. Two slices with equal distance (11.5 mm) from the center of the magnet were selected on each of the three axes with FOV = 200mm, matrix size 128x128, TE/TR=100/1000ms, slice thickness 3mm, b=86 (s/mm^2), and d=1.73 (s·radian/mm). Similar to the b-factor, the new parameter d characterizes the diffusion gradient effect [1]. In the absence of phase-, frequency-, and diffusion-encoding gradients, the signal magnitudes of the six slices were used to align the center of the phantom to the center of the magnet (the relative signal difference for the two slices in each axis was less then 1%).

Results and Discussion: Fig. 1 shows the measured eddy current terms in the acquisition window with the DEG in the superior/inferior direction. Fig.2 shows the phase images of the two slices without DEG (left column), their corresponding phase images with the DEG (middle column), and the EC corrected phase images (right column). Only the cumulated effect due to the spatially invariant EC term was corrected in the right column in Fig. 2. The EC term caused an overall phase shift as illustrated in Fig. 3. For the selected ROI (yellow box) in Fig. 2, the phase values are 1.09 ± 0.14 (mean ± sd), -2.21 ± 0.13, and 0.80 ± 0.13 rad, respectively for the top panel, and are 0.70 ± 0.13, -2.68 ± 0.15, and 0.32 ± 0.15 rad, respectively for the bottom panel.

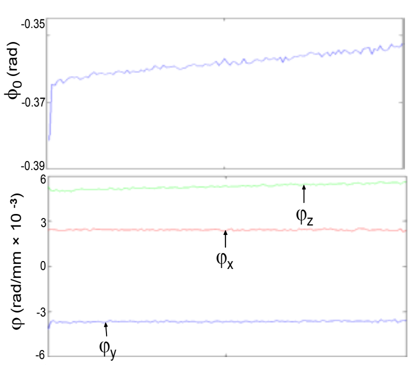

Fig. 1 Measured $\phi_0(t)$, $\varphi_x(t)$, $\varphi_y(t)$, and $\varphi_z(t)$.

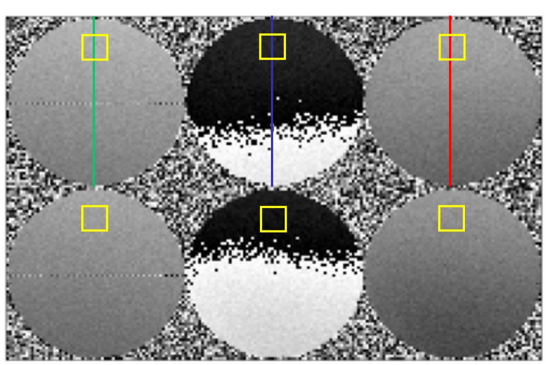

Fig. 2 Phase images: Left, without DEG; Middle, with the DEG; and Right, after EC correction.

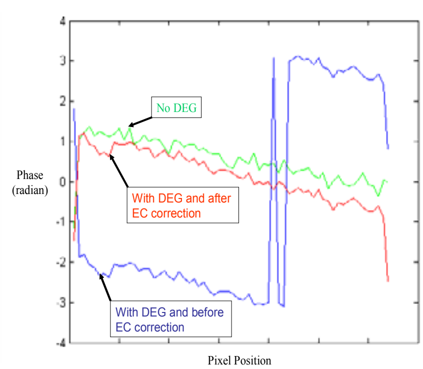

Fig. 3 Plots of phase values of the three colored lines in Fig. 2.

References: 1. Huang J, Theory of Delineating Tissue Interfaces with Diffusion Gradient-Weighted MRI. Abstract submitted to ISMRM Annual Meeting, 2006. 2. Jezzard P, *et al*, Magn Reson Med **39**: 801-812, 1998.