Correction of Image Shift and Distortion in Diffusion-Weighted Echo Planar Imaging

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INTRODUCTION

Diffusion-weighted echo planar imaging (DW-EPI) is a useful tool for early detection of cerebral ischemia. Since diffusion can be anisotropic in brain tissues, "trace"-weighted images are commonly used to minimize the dependence of image contrast on diffusion gradient orientations *(1)*. To obtain a trace-weighted image, three individual images are acquired with the diffusion-weighting gradient being applied along three orthogonal directions, respectively, followed by a pixel-by-pixel geometric average. Even in a well-calibrated MRI scanner, the three diffusion-weighting gradients can exhibit different eddy current characteristics (time constant, amplitude, and spatial distribution), causing inconsistent image shift and distortion among the individual images *(2,3)*. These problems can introduce misregistration in the trace image, and lead to inaccuracy in clinical diagnosis. We have developed a method to address the image misregistration problems.

METHODS

Unlike the technique reported earlier *(3)*, our new method does not require *a priori* knowledge of the system's eddy current characteristics. Instead, a system calibration is carried out to characterize the net effects of the residual eddy currents. This is accomplished by performing a total of 12 single-shot DW-EPI "reference" scans in which the EPI phase-encoding gradient is turned off. The diffusion-weighting gradient is applied along the x, y, and z-axes (x, y, and z are the physical gradient axes), respectively. For each diffusion gradient orientation, the readout gradient is respectively played out along the x, y, and z-axes. In addition to these 3x3 combinations, three more reference scans are also performed with no diffusion-weighting gradient and with the readout gradient along x, y, and z-axes, respectively. The 12 data sets can be represented in a matrix form:

$$R=\begin{bmatrix} R_{xx}(m,n) & R_{yx}(m,n) & R_{zx}(m,n) & R_{0x}(m,n) \\ R_{xy}(m,n) & R_{yy}(m,n) & R_{zy}(m,n) & R_{0y}(m,n) \\ R_{xz}(m,n) & R_{yz}(m,n) & R_{zz}(m,n) & R_{0z}(m,n) \end{bmatrix}, \quad [1]$$

where $Rpq(m,n)$ is a non-phase-encoded echo signal acquired with the diffusion-weighting gradient applied along the p-axis (p can be x, y, z, or null) and the readout along the q-axis (q can be x, y, or z), m is the readout sample index for a given echo and n is the echo index in the EPI echo train.

After acquiring the reference scans, a 1D Fourier transform is performed on each matrix element $Rpq(m,n)$ with respect to m. From the Fourier transformed data, a linear phase fitting is carried out to obtain a constant phase $\phi_{0,pq}(n)$ and a linear phase $\phi_{1,pq}(n)$ for each echo n. The phases from the last column in Eq. [1] are subtracted from the phases of the first three columns to remove the phase errors not directly related to the diffusion gradients. After the phase subtraction, four spatial components of the eddy currents induced by each diffusion-weighting gradient are calculated at the center of k-space. These components include a spatially constant term b_0, and three linear terms g_x, g_y, and g_z. The b_0 term can cause image shift, and the linear gradient terms can produce image shear, compression/dilation, and intensity loss depending on their relationships with the imaging gradient axes *(2)*.

To compensate for the b_0 term, the receiver phase is dynamically adjusted for each echo in the echo train according to: $\theta_{receiver} = \theta_0 + nf(b_0)$, where θ_0 is the initial receiver phase, n is the echo index, and $f(b_0)$ is a pre-determined function of b_0. To compensate for the linear gradient errors g_x, g_y, and g_z, an offset is applied to the readout, phase-encoding, and slice-selection gradient axis, respectively, during the echo train acquisition. When the diffusion-weighting gradient in the actual acquisition is different from the one used in calibration, the compensation parameters are calculated from a model based on b_0, g_x, g_y, g_z, the rotation matrix, as well as the diffusion-weighting gradient amplitudes.

The technique was implemented on a number of 1.5T GE Signa Lx scanners equipped with EchoSpeed or HiSpeed gradient systems. To improve the accuracy of the phase error calculations, a small spherical phantom with a diameter of ~5cm was used in the calibration. After the calibration, eddy current errors arising from the diffusion gradients were evaluated and the results were stored in a system calibration file. In the actual DW-EPI acquisition, a modified pulse sequence was used to (i) read the calibration file, (ii) convert the errors in the calibration file to the b_0 and gradient compensation terms, and (iii) apply the compensation by dynamically adjusting the receiver phase, and readout and phase-encoding gradient amplitudes. Since gradient errors in the slice-selection direction do not cause image misregistration *(2)*, we did not implement correction in the slice direction.

RESULTS AND DISCUSSION

The technique has been tested on a number of phantoms. A representative result is shown in Fig. 1 where image compression due to eddy current gradients in the phase-encoding direction is noticeably reduced. Similar improvement is also observed in terms of image shift and shear.

We have developed a new method to reduce image shift and distortion in DW-EPI. This method has been shown effective on phantoms in several protocols. Since the method does not require operator input nor *a priori* knowledge of the residual eddy currents, we expect the method to be more useful than a previously reported technique *(3)*.

REFERENCES

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2. X. Zhou, *et al.*, *Proc. ISMRM,* p. 1722 (1997).
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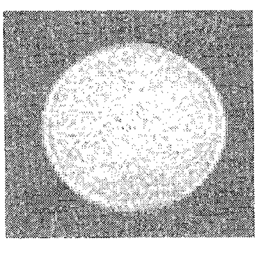
(a)



(b)

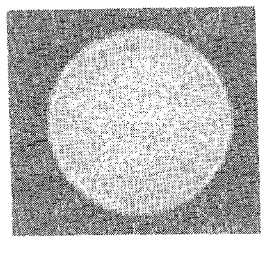


Fig. 1 DW-EPI images before (a) and after (b) the correction.