Shearing Distortion Correction for EPI at 7T MRI

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***Abstract*—In Echo Planar Imaging (EPI), the Readout (RO) train-induced background gradients under B0 homogeneity at 3T-MRI always causes linear geometric distortions. We have reported a simple method for correcting such kinds of linear geometric distortions at 3T-MRI. In this paper, we developed our previous work to 7T-MRI, without any reference measurements of field errors. The proposed method estimated the background gradient in the RO direction in the EPI acquisition window from the phase autocorrelation, which was calculated from the one-dimensional inverse-Fourier-transformed k-space. Our method was implemented on a 7T-MRI whole-body scanner equipped with a gradient insert system, which enables high resolution EPI acquisition with a demand for the distortion correction.**

***Index Terms*—fMRI, distortion, neuroscience**

I. Introduction

In recent years, echo planar imaging (EPI) is the most commonly used rapid acquisition technique in functional MRI and diffusion-weighted imaging. Correction of EPI distortions due to the static field inhomogeneity are well known as a severe problem for functional magnetic resonance imaging (fMRI) studies [1]-[4]; many works focus on the inhomogeneity mapping. And the conventional field mapping methods that are based on double-echo gradient-echo or offset spin-echo imaging are usually used for distortion correction. However, a field mapping method cannot determine the dynamic off-resonance effect in EPI, such as eddy current effects arising from the fast switching of the readout (RO) gradients. Some researchers reported theoretically useful methods employing a multi-reference scan (phase map) to reduce the distortion induced by gradient error [5]–[7], but phase map methods are not applicable for fMRI studies easily. Field mapping methods and multi-reference scan methods have a disadvantage, they require a long scan time. The point spread function (PSF)-based method [8] and parallel imaging method [9] were reported to reduce the RO number in an EPI RO train, but an additional PSF mapping scan is required. The potential applications of high-resolution EPI have been increased by new rapid technology such parallel imaging; however, high resolutions aggravate the distortions induced by gradient error, thereby increasing the number of repeated scans required for corrections based on field maps or phase maps. A k-space energy spectrum analysis algorithm based on the quantification of the spatially dependent echo-shifting effect was developed [10] to overcome the limitations of conventional field mapping methods. This k-space energy spectrum method can measure the susceptibility field gradients and correct the EPI distortion without the need for extra field mapping scans. First-order systematic errors can be corrected by a statistical approach [11] using autocorrelation. Based on this concept, a simple post-processing approach was proposed to eliminate a particular type of distortion that is caused by the RO train-induced linear background gradients under B0 homogeneity. This particular distortion is caused by first-order phase errors, and hence, phase errors of zero-order or of other orders are not considered in this paper. The experimental results demonstrated the existence of background gradients caused by the RO train under B0 homogeneity. The shearing distortion caused by such a background gradient can be corrected by our approach without the need for pre-scanning.

II. Theory

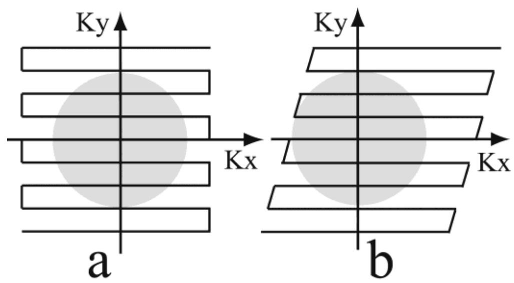

Figure 1. Standard trajectories in a k-space for EPI sampling. (a) Trajectory without field errors and gradient errors. (b) Trajectory with a linear gradient error in x direction. The shaded area represents the region with a strong signal.

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As shown in Fig. 1(b), the additional gradients in the RO direction due to eddy currents, susceptibility effects, amplifier slew-rate distortion, or poor shim result in linear errors in the phase of spins in the RO direction always cause the EPI sampling trajectory drift in k-space [12]. This trajectory drift in k-space produces image shear and also increases ghosting since the echoes pair up instead of being evenly spaced, as observed in the case of minimal ghosting. Without pre-scanning, the first-order phase error has to be calculated and eliminated before image reconstruction. It is easy to understand that the shift in the kx direction in k-space should correspond to the shift in the echo center within the centerline theoretically; however, an actual echo center also can be shifted by sampling timing and gradient errors in PE direction, that is why shift of the echo center in a k-space cannot provide a detailed first-order phase error. A statistical approach has been proposed to calculate the background first-order phase error for EPI with entire k-space acquired [1]. According to the basic idea of this algorithm, the autocorrelation between adjacent pixels on the x-ky space line is performed in the RO direction:

$$\rho_{ky0} = \sum_{x=0}^{M-2} S'_{x,ky0} conj(S'_{x+1,ky0}) \tag{1}$$

where *conj* denotes complex conjugation, M is pixel number in RO direction, $ky0$ is the number of the echo center RO line and S' is the inverse Fourier transform (FT) of an RO k-space line. The background gradient of a single RO line in the RO direction can be obtained by:

$$\varphi_{ky0} = phase[\rho_{ky0}] \tag{2}$$

The center/off-center field of view (FOV) does not cause the echo-center shift in k-space, or phase gradient in image domain, so these calculations are independent to FOV set, because the phase difference in the equations are not related to pixel locations in image domain.

Some systematic errors can be estimated by calculating the ensemble average of the autocorrelation functions for the entire space, but the small phase error induced by an RO gradient in the echo-planar image cannot be estimated, because the phase error in an RO line will add to all the subsequent RO lines in k-space. But during EPI scanning, each RO sampling does the same thing, therefore in other words, there is a constant RO train-induced background gradient is considerable, so the first-order phase error in the RO line number ky may be shown by:

$$\varphi_{ky} = \varphi \times (ky + N/2) \tag{3}$$

This equation is based on the assumption of a constant background gradient φ, the first-order phase error caused by the background gradient of a single RO line in the RO direction. This assumption holds true or approximately true since the data of each adjacent odd/even RO line pair in the k-space are acquired by performing the same RO gradient and phase encoding (PE) gradient repeatedly under the same condition. Many researchers mentioned that the differences in odd/even RO gradients may cause N/2 ghosting, but this kind of errors would not be conserved and added to the subsequent RO lines. Although φ may not be caused only by the simple RO gradients or eddy currents, but it can be considered as a constant background gradient errors. Because the difference in PE gradients between the adjacent RO lines cause all of the RO lines to be acquired under different phase conditions, this means the spins situation in different RO lines are very different, so φ cannot be easily estimated by averaging the first-order phase-error differences in all adjacent RO lines.

Furthermore, the accuracy of the calculation results always be reduced by the low signal-to-noise ratio (S/N) of some RO lines (suppressed by the PE gradient). This problem can be solved by eliminating the influence of the PE gradient on the estimation calculation. So, what we need to do is to find the zero phase-encode RO line, which is usually the center RO line but sometime can be shifted. It is easy to find zero phase-encode RO line, because it has the strongest signal from others. In this RO line, the phase variations induced by the PE gradient are canceled by the preparation PE gradient.

Using equation (1-3), the accumulated first-order phase error in each RO line can be calculated, and the first-order phase error in each RO line can be easily corrected. The correction is performed in x-ky space, which is one-dimensional (1-D) Fourier transformed (FT) from k-space.:

$$C'_{x,ky} = S'_{x,ky} \exp(i(x \times (ky + N/2) \times \varphi)) \tag{4}$$

After the first-order phase error correction, the nonshearing echo-planar image can be reconstructed with the 1-D inverse FT in the PE direction simply:

$$I_{x,y} = \sum_{ky=-N/2}^{N/2} C'_{x,ky} \exp(2\pi i((ky + N/2) \times y / N)) \tag{5}$$

III. Methods and Results

Our previous work [1] demonstrated the existence of background gradient caused by an RO train under B0 homogeneity using a field map, gradient-echo, and gradient-echo EPI sequences at 1.5T MRI and 3T MRI. In the EPI scans, varying PE direction, echo spacing, and bandwidth were used at the same echo time (TE), repetition time (TR), FOV, flip angle and matrix size. In this paper, the feasibility of our shearing distortion correction method was tested by phantom experiments on a 7T whole-body scanner (Siemens) equipped with a gradient insert system with a maximum strength of 200 mT/m. After B0 shimming, a filed map at a representative slice position was acquired to assess B0 homogeneity. A standard gradient-echo EPI sequence was used to obtain k-space data sets. Fig. 2 represents the effect of our distortion correction for a gradient-echo EPI image (left, uncorrected; right, corrected). Imaging parameters were as follows: TR = 2 sec, TE = 30 ms, FOV = 88 mm, matrix = 128×128, thickness = 1 mm, and pixel bandwidth = 3000 Hz. In addition, we performed phantom experiments using a whole-body gradient system (70 mT/m). A cylindrical phantom was imaged with the gradient-echo EPI using an 8-channel head coil. Imaging parameters were as follows: TR = 2 sec, TE = 53 ms, FOV = 180 mm, matrix = 180×180, thickness = 3 mm, pixel bandwidth = 1736 Hz. Fig. 3 compares uncorrected (left) and corrected (right) images.

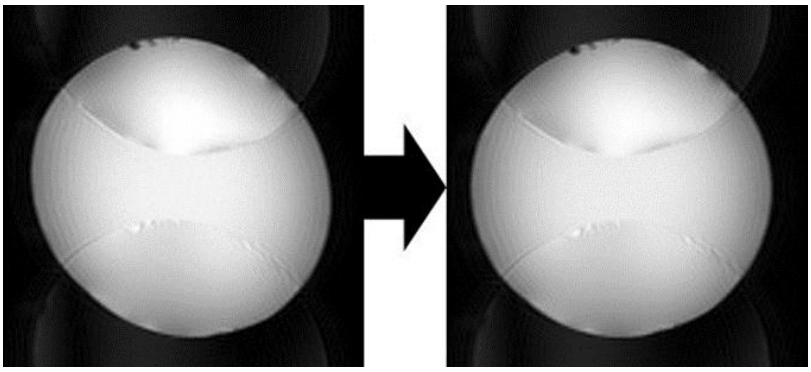

Figure 2. Distortion correction of an EPI image obtained with a gradient insert system

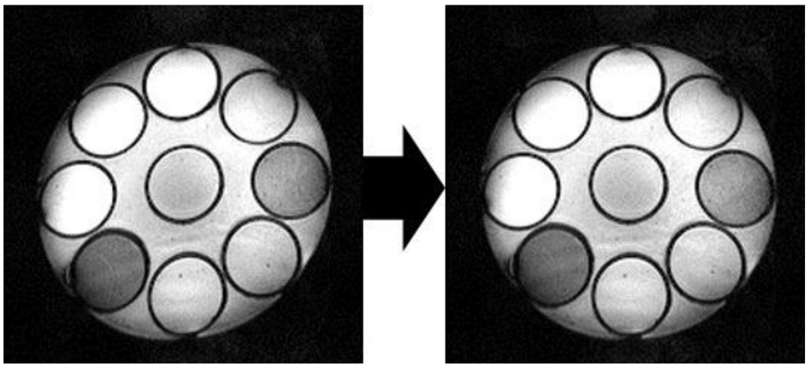

Figure 3. Distortion correction of an EPI image obtained with a whole-body gradient system

IV. SUMMARY

Based on the basic idea of previous work [1], we investigated the existence of linear geometric distortions due to RO train-induced background gradients under B0 homogeneity at 7T-MRI. Using the proposed simple method, shearing distortion caused by background gradient errors could be corrected successfully. This method does not necessitate pre-scanning and that it can be easily combined with other phase-correction methods. So the proposed method is applicable for fMRI studies easily over conventional methods [13, 14, 15]. Another advantage of our method is that it can be implemented as a post processing step in the image reconstruction flow, hence, a penalty of signal loss is avoidable.

There are two cases that illustrate the risks of our method: (1) the use of surface coils and (2) shifting the FOV off the center in the RO or PE direction. But for normal fMRI studies, surface coils and off center FOV are not used regularly.

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