Correction of Gradient Error Distortions in Echo-Planar Imaging

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Introduction

In Echo-planar imaging (EPI), factors related to the gradient field errors, such as eddy current effects due to the switching of readout (RO) gradients, cannot be measured with conventional field-mapping. Although methods using a multireference scan (phase map) to reduce the distortion induced by gradient error have been reported and are theoretically useful [1], they are often limited in applications like fMRI for the longer scan times. We propose a simple and general approach to correcting the distortion due to RO field gradient errors based on the statistical properties of EPI images. The proposed method can correct the linear eddy-current-induced field gradient error along the RO direction even in high-resolution EPI (such as 128×128-pixel imaging) by online processing.

Theory and Methods

To correct the linear phase error at spatial point (*x*, *y*) and time point (*k, l*) and reconstruct the ideal EPI image, we have to estimate the phase error gradient along RO direction. But we cannot easily estimate this phase error by averaging the first-order phase error differences of all adjacent RO lines, Since the PE field gradients between adjacent RO lines make all RO lines are acquired under different phase condition, and the low S/N of some RO lines (suppressed by the PE field gradient) always reduces the accuracy of the result. We remove the influence of the PE field gradient from the calculation of estimation by

$$\rho_x = \sum_{l=1}^{N-1} S'_{x,l} \tag{1}$$

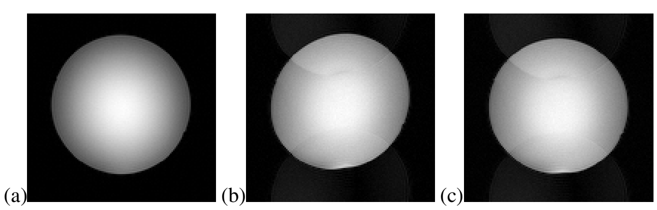
where S' is the spatial space (inverse Fourier transform) of a RO k-space line. Here we assume that the center line in the k-space is RO line number *N/2*, in which spins are refocused by PE field gradients. In Eq (1), the PE-gradient-induced phase variation of each spin in a RO line $S'_{x,N/2+l}$ is canceled by the symmetric RO line $S'_{x,N/2-l}$. So if B0 is homogeneous, the phase error in ρ_x is caused by RO gradient only. Base on an autocorrelation-based algorithm [2], the linear phase error gradient or in other words the first-order phase error caused by field gradient error can be shown as

$$G = phase[\sum_{x=0}^{M-2} \rho_x conj(\rho_{x+1})]/(N/2) \tag{2}$$

where *conj* denotes complex conjugation. If G_l denotes the accumulated first-order phase error at RO line number *l*, then during the calculation using Eq. (1)(2), the difference between $G_{N/2-l}$ and $G_{N/2}$ is canceled by the difference between $G_{N/2+l}$ and $G_{N/2}$, since $G_{N/2-l} = G_{N/2} - lG$ and $G_{N/2+1} = G_{N/2} + lG$. Thus the G in Eq. (2) is the linear phase error gradient (the first-order phase error) caused by each RO field gradient. Once *G* is calculated, the accumulated first-order phase error of each RO line *Gl* can be used to correct the gradient-error-induced distortion easily using prior method [2]. We tested this method in gradient-echo EPI experiments performed on a 3-T whole-body scanner (Siemens Trio). To enhance the distortion, we used a 128×128 matrix size to image a standard phantom as well as the head of a normal volunteer. Scans were taken with a slice thickness of 5 mm, a field of view (FOV) of 230×230 mm, an echo time (TE) of 50 ms, and a bandwidth 1862 kHz to obtain 128 RO lines. Then the ideal EPI image was created from this k-space using the proposed method.

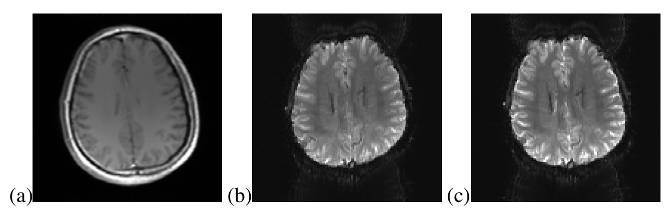
Results and Discussion

The proposed algorithm was first examined on a standard phantom with a one channel coil. Fig. 1(a) shows the GRE image. The renewed accurate phase correction (MR-system-provided) was used to create an EPI image shown in Fig. 1(b). In this image, the ramp-sampling-induced expansion along the RO direction is gone and the ghost is almost gone but the shearing is not corrected. By using the MR-system-provided phase-correction algorithm and our proposed algorithm, we reconstructed the ideal EPI image shown in Fig. 1(c). The results obtained when the experiment was repeated with a multichannel coil using a human brain instead of a phantom show that the proposed algorithm also corrects the RO-field-gradient-error-induced distortion in images of a human brain (Fig. 2). When a multichannel coil is used in experiments, the RO-field-gradient-induced phase errors estimated respectively from each k-space (acquired from each channel) are therefore all very different. All of these estimated phase errors have to be averaged to provide a final estimated phase error that can be used in the proposed phase correction of the data of all channels. In echo-planar images of the human brain, not only field inhomogeneity but also susceptibility-related field variation influences the estimation of RO-field-gradient-induced phase error. Fortunately, a human brain is symmetric, during the phase error estimation, the susceptibility-related phase variation can be canceled if the brain's axis of symmetry is set at the center line along the PE direction (RO gradient symmetrical axis).



(a) (b) (c)

Fig.1 Phantom GRE image (a), and original EPI (b), corrected EPI (c)



(a) (b) (c)

Fig.2 Human brain GRE image (a), and original EPI (b), corrected EPI (c)

References

1. Magn Reson Med 1999; 41:1206–1213. 2. IEEE Trans Med Imaging 1987; 6:32–36.