Estimation of Eddy Current Induced Phase Error in EPI

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Introduction

There are a number of sources of distortion in echo-planar images such as static field inhomogeneity, susceptibility effects, eddy currents, amplifier slew rate distortion, and Maxwell effects. 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. The multireference scan (phase map) methods have been reported to reduce the distortion induced by gradient error, but they are often limited in applications like fMRI for the longer scan times. Last year, we described a simple method of correcting distortions due to linear RO gradient errors (mainly those induced by eddy currents) in echo-planar images without using reference measurements of field errors when the main field(B_0) is perfect and no echo time shifting along phase encoding(PE) direction [1]. In fMRI studies, the echo shifting effect always makes the echo time dependent based on the field gradient in the PE direction. Because of this effect, the presence of field inhomogeneity gradients in the phase encoding direction will affect the accuracy of calculation and correction of eddy current induced gradient error[2]. This time we provide a new method, which is applicable under PE direction inhomogeneous main field. The gradient error in readout direction is estimated by using the echo readout line in x-ky space. We also discuss how to calculate and correct eddy current induced linear distortion when linear field inhomogeneities exist in RO direction.

Theory and Methods

In single-shot EPI, when the B_0 is perfectly homogeneous (or B_0 inhomogeneity induced distortions are corrected by previous methods first) and phase error is caused only by gradient error in the RO direction, we can assume that $e_{x,y;k_x,k_y} = xk_yG$, where G is the phase error gradient caused by gradient error in the RO direction and $e_{x,y;k_x,k_y}$ is the phase error at spatial point (x, y) and time at which k-space point (k_x, k_y) was measured. Phase error gradient G can be calculated from the echo RO line (usually center RO line, where the PE preparation gradient induced phase variation is canceled by PE gradients that are performed after each RO gradient) in an $M\times N$ x-k_y space s'_{x,k_y} by:

$$G = phase[\sum_{x=0}^{M-2} s'_{x,e} conj(s'_{x+1,e})] / N_e \quad (1)$$

where $s'_{x,e}$ is a point in the echo RO line in the x-ky space and N_e is the position of echo RO line in the RO lines series. Usually, $N_e=N/2+1$ when main field gradient error does not exist in PE direction and PE gradient perfectly works. *conj* denotes complex conjugation. When the gradient error G is estimated by equation (1), the ideal EPI image can then be reconstructed from the x-k_y space by:

$$I_{x,y} = \sum_{k_y=0}^{N-1} s'_{x,k_y} \exp(i(2\pi y k_y / N + x k_y G)) \quad (2)$$

It is a simple 1-D inverse Fourier Transform with the eddy current induced phase gradient error correction accounted for.

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 phantom with structure. Scans were taken with a slice thickness of 3 mm, a field of view (FOV) of 280×280 mm, an echo time (TE) of 75 ms, and a bandwidth 2300 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 field map Fig.1(d) shows that B_0 inhomogeneity gradient exists in top-down direction. This B_0 gradient causes expansion in an EPI image because the PE direction is top-down too in the EPI scan (Fig.1(b)). The linear shearing distortion in Fig.1(b) is caused by eddy current induced RO gradient error but not B_0 inhomogeneity because no B_0 gradient exists in left-right direction. When PE direction is left-right, both B_0 gradient and RO gradient cause distortion, this is why the shearing distortion in Fig.1(c) is stronger than that in Fig.1(b) and no expansion can be found in fig.1(c). To correct the distortion, the echo RO line was first found by searching the RO line with strongest signal in the k-space. Then Equation (1)(2) were used to estimate the RO gradient induced phase error G and reconstruct the ideal EPI image. The linear distortion in Fig.1(b) was corrected well even though the echo RO line was shifted from the theoretical RO line #65 to real RO line #61 by B_0 gradient. Fig.1(f) shows the non linear shearing distortion EPI image, in which B_0 gradient induced linear shearing distortion was corrected based on the field map Fig.1(d) before G was estimated. In summary, the proposed method corrects linear shearing distortion caused by gradient error in RO direction but not B_0 inhomogeneity induced compression/expansion (Fig.1(b)(c)). After field map based distortion correction, this method works, even when B_0 inhomogeneity gradient exists in RO direction (Fig.1(d)(f)).

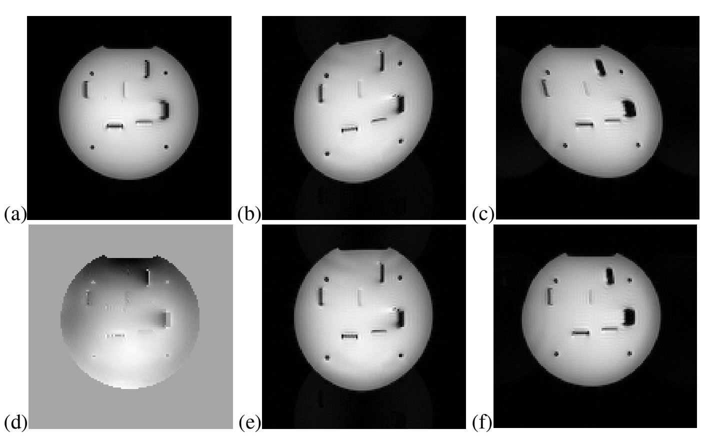

Fig.1 GRE image (a), original EPI (b)(c), field map (d), corrected EPI (e)(f) from (b)(c) respectively , top-down PE (b)(e), left-right PE (c)(f).

References

1.ISMRM2006 #2970.

2.Neuroimage 2002; 15:120-135.