Geometrical Distortion Correction in EPI using Two Images with Orthogonal Phase-Encoding Directions

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Introduction

In echoplanar imaging, B_0 field inhomogeneities produce distortions in the geometry and intensity of the imaged object. Geometrical distortions are observed primarily in the phase-encoding direction because the effective bandwidth in the phase-encoding direction is much smaller than in the readout direction (typically by a factor which is approximately the number of lines of k space scanned). Common registration algorithms that correct for geometrical distortions are based on collecting a residual field map from a phase map so that pixel-relocation can be achieved.[1-3] Other methods rely on using gradients with reversed polarity that will produce distortions in opposite directions[4].

In this report we describe a different approach. We show that it is possible to correct geometrical distortions by only using the information from the magnitude of two echoplanar images that were collected by switching phase- and frequency-encoding directions. No residual field map is determined a priori by phase mapping. Rather, an approximation to the residual B field is computed iteratively that is consistent with the geometrical distortions in the two echoplanar images. The effectiveness of this method is demonstrated on simulated data and real MRI EPI experiments.

Theory

The phase evolution of the signal can be written in the form

$$d\varphi = 2\pi\gamma(G_r(t)x + G_p(t)y + \Delta B_0(x,y,z))dt \qquad (1)$$

where γ is the gyromagnetic ratio, $G_r(t)$ the readout gradient along x, $G_p(t)$ the phase-encoding gradient along y, and $\Delta B_0(x,y,z)$ the inhomogeneity of the z-component of the magnetic field vector. In blipped EPI with trapezoidal read gradients, single excitation and image size of NxN, the pixel shift in the phase-encoding direction is

$$\Delta r = 2\pi\gamma\Delta B_0(x,y,z)\,N(2\tau_{ramp} + N\,\Delta t)) \qquad (2)$$

where τ_{ramp} is the ramp time, Δt the sampling interval. The location y_p of a pixel in the geometrically distorted image is then related to the position y of the pixel in the undistorted image by

$$y_p = y + \Delta r(x,y,z). \qquad (3)$$

Since z is constant for images collected in the x-y plane, we can omit z. If now two images A(x,y) and B(x,y) are collected with perpendicular phase-encoding directions, the images must satisfy the equation

$$B(x,y') = A(x',y) \qquad (4)$$

where

$$x' = x + \Delta r(x',y) \qquad (5)$$

and

$$y' = y + \Delta r(x,y'). \qquad (6)$$

To correct for moderate distortions the shifting matrix $\Delta r(x,y)$ can be expanded in a power series up to second order in x and y by

$$\Delta r(x,y) = \underset{0<i+j<3}{\quad} c_{ij}x^i y^j \qquad (7)$$

where c_{ij} are unknown coefficients. In the following the c_{ij} are represented by a cumulative index k, i.e. $c_{ij} = c_k$. Because of noise and other intensity variations in the images A and B, a solution of Eq.4 usually does not exist. But we can find a best solution by converting Eq.4 into an optimization problem by defining a function f according to

$$f(c_1, c_2, ..., c_9) = (B(x,y') - A(x',y))^2 \qquad (8)$$

so that f has to be minimized by varying the coefficients $c_1 \ldots c_9$. The minimization is performed using a conjugate gradient method. This method is in general very robust, however it requires sufficient good initial values in order to converge. Expanding Eq. 4 up to first order yields

$$\Delta r^{(0)}(x,y) = \frac{(A(x,y) - B(x,y))(1 - \frac{d\Delta r^{(0)}(x,y)}{dy})}{\frac{dB(x,y)}{dy}(1 - \frac{d\Delta r^{(0)}(x,y)}{dx}) - \frac{dB(x,y)}{dx}(1 - \frac{d\Delta r^{(0)}(x,y)}{dy})}. \qquad (9)$$

This equation is solved for $\Delta r^{(0)}(x,y)$ and then fitted to Eq.7 using a least square minimization routine to obtain the initial coefficients $c_1^{(0)} \ldots c_9^{(0)}$. With these initial estimates, a conjugate gradient method optimizes $f(c_1 \ldots c_n)$ in Eq.8 in a few iterations. With the final estimate of $\Delta r(x,y)$ the undistorted image C(x,y) can be computed from either A(x,y) or B(x,y) by

$$C(x,y) = A(x',y) \qquad (10)$$

or

$$C(x,y) = B(x,y'). \qquad (11)$$

Note, that Eq.5 and 6 have an implicit dependence on x' and y'. These equations are solved by a standard root-finding algorithm. The existence of a solution then defines the domain of the image C(x,y) where the intensity is unequal to zero.

Methods

We simulated a pair of distorted images from a source image with a non-uniform intensity distribution. The distortions were computed by using magnetic field offsets up to third order in x and y and applied to either direction (i.e. x or y) to simulate geometrical distortions in the phase-encoding direction in EPI. The image size had a dimension of 64x64 pixels.

For a real application, we collected axial QA phantom data and human head data by slightly offsetting the shim gradients in x and y on a 1.5T GE Horizon Lx MRI scanner (Waukesha, WI). The EPI scanning protocol consisted of the parameters: Flip 90 deg, TE 50ms, TR 2000ms, FOV 24cm x 24cm, slice thickness 7mm, 64 x 64 imaging matrix, 125 kHz receiver bandwidth.

Results and Discussion

The results of our proposed method are shown in Figure 1 and 2. A field inhomogeneity (1c) was created first and applied in the vertical and horizontal direction to a rectangular object (1f) with non-uniform intensity distribution. The distorted images (1a, 1b) were then effectively unwarped by our method using Eq.10 or Eq.11 resulting in virtually identical images (1d, 1e). Similarly, QA phantom data from an EPI experiment where the shim gradients were slightly offset (2a, 2b) were corrected substantially. The correction, however, were slightly dependent on the final image transformation used (compare 2c, 2d). Preliminary results on human EPI data revealed that distortions from local field inhomogeneities are more difficult to unwarp due to contributions from higher order terms in the magnetic field.

a b c d e f

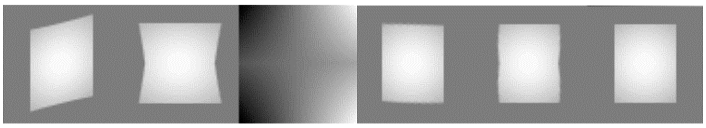

Figure 1. Simulated distortions and recovery of original image: vertically-distorted image (a), horizontally-distorted image (b), underlying field inhomogeneity (c), unwarped image using Eq.10 (d), unwarped image using Eq.11 (e), original image (f).

a b c d e

Figure 2. QA phantom EPI experiment: distorted image with vertical phase-encoding direction (a), distorted image with horizontal phase-encoding direction (b), unwarped image using Eq.10 (c), unwarped image using Eq.11 (d), original image (e).

Conclusion

A new technique is described to correct for geometrical distortions in EPI, which does not require a measurement of the residual field by phase-mapping. Rather, the distortion field is computed iteratively from a pair of intensity images where the phase-encoding directions were chosen to be perpendicular to each other. The method, as applied to simulated data and MRI phantom data, achieves a high degree of unwarping. Preliminary results to correct for distortions in human head EPI studies show moderate improvements due to the difficulty in dealing with strong local field gradients.

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