Application of k-space energy spectrum analysis to susceptibility field mapping and distortion correction in gradient-echo EPI

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Introduction

Echo planar imaging (EPI), with its high temporal resolution, has become an important technique for various dynamic studies, such as functional MRI and contrast agent enhanced imaging. It is well known that EPI is geometrically distorted by Bo field inhomogeneity. In order to remove the geometric distortions, an extra field mapping scan can be performed prior to EPI based dynamic imaging (Jezzard and Balaban, MRM, 1995, 34:65). However, the acquired field map may become invalid if the subject's position changes during dynamic EPI scans. Furthermore, the experimental time will be increased when an extra field map scan is performed.

Here, a novel algorithm termed *k-space energy spectrum analysis* is presented to map the susceptibility field gradients directly from gradient-echo EPI data. Neither extra field mapping scan nor EPI pulse sequence modification is needed. Based on the calculated susceptibility field gradient maps, the Bo field inhomogeneity map can be derived and used to remove the geometric distortions in EPI data.

Theory and Methods

Echo-shifting effect in gradient-echo EPI: In the presence of susceptibility field gradients, gradient-echo EPI's echo signals deviate from the center of the *k*-space and the degree of this echo-shifting effect depends on (1) the effective echo time, (2) echo-spacing time, (3) image field of view (FOV), and (4) the susceptibility field gradients. If the echo-shifting effects, corresponding to different image-domain regions, can all be measured directly from gradient-echo EPI data, the susceptibility field gradients can be quantified without an extra field mapping scan.

K-space energy spectrum analysis: We have developed a *k-space energy spectrum analysis* algorithm to map EPI's echo-shifting effect along both readout and phase-encoding directions. The procedure for mapping the echo-shifting effect along the phase-encoding direction consists of the following two steps. First, a selected number of *ky* lines are truncated (in post-processing) and replaced by values calculated from the un-truncated data using Cuppen's partial Fourier technique (van Cuppen and van Est, MRI, 1987, 5:526). The modified *k*-space data are then Fourier transformed to an image. The signal intensity of the reconstructed image will resemble the full-Fourier image, if the peak of the corresponding *k*-space signals is located in the un-truncated area. On the other hand, if the peak of the *k*-space signals is located in the truncated *k*-space, there will be significant signal loss in the reconstructed image. Second, by varying the number of truncated/replaced *ky* lines in the first step, a series of images are obtained. The pattern of pixel-wise signal variation in those images is determined by the *k*-space echo shifting effect originating from the susceptibility field gradients. The measured pixel-wise signal variation pattern is therefore termed *k-space energy spectrum*, in which abrupt signal changes occur when the peaks of *k*-space echo signals are being truncated. For example, Figure 1a presents an EPI image and Figure 1b shows the phase-encoding *k-space energy spectrum* of three selected pixels. As indicated by arrows in Figure 1b, the echo-signal peaks are located in *ky* line number 27, 48, and 74, respectively, as a result of spatially varying susceptibility field gradients. The above two steps can also be applied to measure the *k*-space echo-shifting effect along the readout direction, by truncating different number of *kx* lines in EPI data and calculating the corresponding *k*-space energy spectrum.

Measurement of susceptibility field gradients and EPI distortion correction: Once the spatially dependent echo-shifting effects along both readout and phase-encoding directions are measured (N_x and N_y), the susceptibility field gradients along these two directions (G_x and G_y) can be calculated based on Equation 1 and Equation 2, where t_{DW} is the dwell time, TE_{eff} is the effective echo time, and t_{ESP} is the echo-spacing time.

$$G_x = \frac{-N_x}{\gamma FOV_x\,[N_x \times \tau_{DW} + (TE_{eff} + N_y \times \tau_{ESP})]} \quad \text{.........} \ [1]$$

$$G_y = \frac{-N_y}{\gamma FOV_y\,(N \times \tau_{ESP} + TE_{eff})} \quad \text{.........} \ [2]$$

For example, the phase-encoding susceptibility field gradient map calculated from the EPI data in Figure 1a is shown in Figure 1c. When the RF excitation pulse frequency is chosen to be the averaged Larmor frequency of the imaged slice, Bo field inhomogeneity maps can be derived from the susceptibility field gradients, and then used to remove EPI's nonlinear geometric distortions through the previously reported phase modulation method. If the RF pulse frequency is set to off-resonance, there may remain residual global translation after nonlinear distortion correction. This remaining image translation can easily be detected and corrected with rigid body image registration.

Human brain and phantom EPI data acquired at 1.5 T and 3 T GE systems were processed with the proposed *k-space energy spectrum analysis* algorithm. The susceptibility field gradients were calculated based on Equations 1 and 2 (without the need of extra field mapping scan) and then used to correct EPI geometric distortions through the phase modulation method (Chen and Wyrwicz, MRM, 1999, 41:1206).

Results and Discussion

Phantom EPI images acquired at 3T under three different shim settings are shown in Figure 2a. Using the proposed k-space energy spectrum analysis and distortion correction technique, the nonlinear geometric distortions in EPI data are removed, as shown in Figure 2b. Examples of distortion correction in human brain EPI are presented in Figure 3. As shown, there exist significant geometric distortions in human brain EPI (Figure 3a), and these artifacts can be reliably removed using the proposed data processing algorithm (Figure 3b).

The proposed method is superior to conventional field map based EPI correction methods in three ways. First, using k-space energy spectrum analysis algorithm, the field maps can be obtained without performing additional field mapping scan. Second, in the presence of subject movement during dynamic EPI scans, the valid field maps corresponding to different scan times can be reliably obtained with the proposed post-processing method. Third, in the proposed algorithm, complicated in-plane phase unwrapping procedure that is required in most conventional field mapping methods can be avoided. It should be noted that this EPI distortion correction technique is also compatible with parallel imaging methods. Even though the EPI distortions can generally be reduced when data are acquired with parallel imaging schemes, the residual distortions may still degrade the spatial accuracy, especially at high field. Using the proposed post-processing algorithm, the residual distortion in parallel EPI can be further reduced.

Figure 1

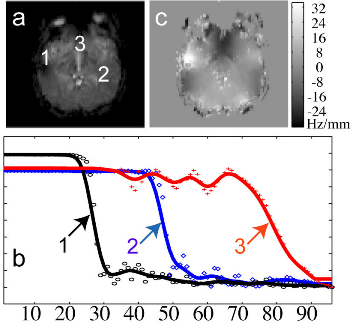

Figure 2

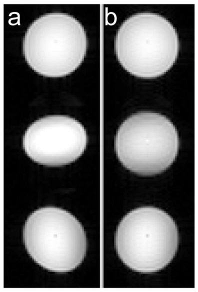

Figure 3