Removal of EPI Nyquist Ghost Artifacts With Two-Dimensional Phase Correction

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Odd–even echo inconsistencies result in Nyquist ghost artifacts in the reconstructed EPI images. The ghost artifacts reduce the image signal-to-noise ratio and make it difficult to correctly interpret the EPI data. In this article a new 2D phase mapping protocol and a postprocessing algorithm are presented for an effective Nyquist ghost artifacts removal. After an appropriate \(k\)-space data regrouping, a 2D map accurately encoding low- and high-order phase errors is derived from two phase-encoded reference scans, which were originally proposed by Hu and Le (Magn Reson Med 36:166–171;1996) for their 1D nonlinear correction method. The measured phase map can be used in the postprocessing algorithm developed to remove ghost artifacts in subsequent EPI experiments. Experimental results from phantom, animal, and human studies suggest that the new technique is more effective than previously reported methods and has a better tolerance to signal intensity differences between reference and actual EPI scans. The proposed method may potentially be applied to repeated EPI measurements without subject movements, such as functional MRI and diffusion coefficient mapping. Magn Reson Med 51:1247–1253, 2004. © 2004 Wiley-Liss, Inc.

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Phase inconsistencies between EPI echoes corresponding to different readout gradient polarities generate Nyquist ghost artifacts in the reconstructed images. The Nyquist ghost artifacts not only degrade EPI image quality, but also result in inaccurate EPI based quantitative measurements, such as EPI-based apparent diffusion coefficient (ADC) mapping (1). These phase inconsistencies may originate from different factors, such as field inhomogeneities (2), eddy current effects (3,4), imperfect gradient waveforms (5), and anisotropic gradient delays in oblique-plane EPI (6).

Three types of approaches have been reported to date to remove EPI ghost artifacts. The first approach is 1D phase correction based on information from reference scans. The phase shift information can be measured with either a single non-phase encoded reference scan (7) or two phase-encoded scans (2). The reference information is then applied to correct phase errors using 1D Fourier transform modulation in subsequently obtained EPI data. This approach is easy to implement for both single-shot and segmented EPI. The phase errors along the phase-encoding direction, however, cannot be corrected with this 1D approach. In oblique plane EPI, for example, 2D phase errors due to anisotropic gradient delays cannot be completely removed with 1D correction (6). In addition, spatially dependent eddy current effects could also generate high-order echo shifts along both readout and phase-encoding directions. The second approach is 2D correction with pulse sequence compensation (4,6). It has been shown that, using a modified EPI pulse sequence with additional compensation blips, 2D linear phase errors due to hardware imperfections can be reduced (4,6). Since no reference image is required, this method is appropriate for EPI based real-time scans, such as cardiac imaging. However, high-order phase errors due to spatially dependent eddy current effects may not be effectively removed with this approach. In addition, its tolerance to subject-dependent field inhomogeneities has not been investigated. The third approach removes ghost artifacts by estimating phase errors from the EPI data itself. As described by Buonocore and Gao (5), an accurate 2D map indicating odd–even echo inconsistencies can be calculated from odd-echo-only and even-echo-only EPI data, provided that the parent image and the ghost do not overlap in the original EPI. In this case, high-order phase errors along both readout and phase-encoding directions can be corrected and artifact-free EPI can be reconstructed (eqs. 11 and 12 in Ref. 5). Practically, parent image and ghost overlap significantly. Therefore, phase errors can only be measured in a manually selected region in which parent image and ghost do not overlap. Phase information outside this nonoverlapping region needs to be estimated with linear extrapolation, assuming that the phase distribution is a 1D spatial function along the readout direction. As a result, phase errors along the phase-encoding direction are not corrected in this technique. Successful implementation of this approach for segmented EPI with odd-number segments (3,8) and even-number segments (9) have recently been reported.

To remove the EPI ghost artifacts more effectively, a new approach based on 2D phase correction was developed and is presented here. Two reference scans are first acquired with the phase-blipped reference EPI sequence reported by Hu and Le (2). Using a new \(k\)-space data regrouping protocol, a 2D map that accurately encodes EPI phase errors due to odd–even echo inconsistency can be obtained. The calculated 2D phase map is then applied in a developed mathematical model to effectively remove the...
Nyquist ghost artifacts in subsequently acquired EPI data. With a good tolerance to field inhomogeneities and its capability of correcting high-order phase errors along both readout and phase-encoding directions, the new method is superior to previously reported methods. We expect that the new method will be especially important for EPI-based quantitative measurements, such as functional MRI and ADC mapping, in which the Nyquist ghost artifacts may affect the accuracy of the quantification.

**THEORY**

The pulse sequence of the two reference scans used for 2D phase mapping is shown in Fig. 1a. Since the corresponding echoes in two reference scans are acquired with opposite polarity readout gradient polarities, the corresponding $k_y$ lines are shifted in opposite directions, as illustrated by simplified $k$-space diagrams shown in Fig. 1b. An odd-echo-only image can be generated by taking the Fourier transform of 2D $k$-space data in which odd echoes are zero-filled, and an even-echo-only image can be generated from $k$-space data with even echoes zero-filled (Fig. 1c). Using the convention of Buonocore and Gao (5), the odd-echo-only image of the first reference data is represented by Eq. 1, in which the overlapping proton density map $M(x,y)$ is overlapped with its ghost signal shifted by half of the field of view (FOV). The even-echo-only image derived from the first reference data is represented by Eq. 2, in which the overlapping proton density map and its ghost signal are modulated with additional 2D phase errors $\theta(x,y)$, due to odd–even echo asymmetry. The odd-echo-only and even-echo-only images derived from the second reference data are represented by Eqs. 3 and 4, respectively.

$$
Ref_{1_{od}}(x,y) = \frac{1}{2} \left( M(x,y) + M(x,y - \frac{FOV}{2}) \right) \quad [1]
$$

$$
Ref_{1_{evn}}(x,y) = \frac{1}{2} \left( M(x,y) \exp(i\theta(x,y)) - \frac{1}{2} \left( M(x,y - \frac{FOV}{2}) \exp(i\theta(x,y - \frac{FOV}{2})) \right) \right) \quad [2]
$$

$$
Ref_{2_{od}}(x,y) = \frac{1}{2} \left( M(x,y) \exp(i\theta(x,y)) + \frac{1}{2} \left( M(x,y - \frac{FOV}{2}) \exp(i\theta(x,y - \frac{FOV}{2})) \right) \right) \quad [3]
$$

$$
Ref_{2_{evn}}(x,y) = \frac{1}{2} \left( M(x,y) - M(x,y - \frac{FOV}{2}) \right) \quad [4]
$$

It should be noted that the coordinate in all equations is to be taken cyclically (i.e., $(y - \frac{FOV}{2})$ for the lower half, and $(y + \frac{FOV}{2})$ for the upper half of the image).

A 2D map describing EPI phase errors due to odd–even echo asymmetry can be obtained by regrouping the odd-echo-only and even-echo-only images of the two reference scans (Fig. 1d). The data regrouping procedure can be represented by Eqs. 5 and 6 and the 2D phase map can be calculated with Eq. 7.

$$
Regrouped_1 = Ref_{1_{evn}}(x,y) + Ref_{2_{od}}(x,y)
= M(x,y)\exp(i\theta(x,y)) \quad [5]
$$

$$
Regrouped_2 = Ref_{1_{od}}(x,y) + Ref_{2_{evn}}(x,y) = M(x,y) \quad [6]
$$

$$
MAP_{od} = \frac{Regrouped_1}{Regrouped_2} = \exp(i\theta(x,y)). \quad [7]
$$

It should be noted that the regrouped reference images and the calculated 2D phase map are free from Nyquist artifact, as illustrated by Eqs. 5, 6, and 7. It should also be noted that the phase map obtained with Eq. 7 measures the phase errors originating from EPI odd–even echo inconsistency, which is different from the Bo field inhomogeneity induced phase errors measured with conventional field mapping protocols (10,11).

The ghost artifacts in successive EPI measurements can be removed using a 2D phase map calculated with Eq. 7. EPI data to be corrected are first decomposed into odd-echo-only and even-echo-only images, as illustrated by
Eqs. 8 and 9, where the proton density map $\tilde{M}(x,y)$ is generally different from the proton density map $M(x,y)$ in the reference scans.

$$EPI_{odd}(x,y) = \frac{1}{2} \left( M(x,y) + \tilde{M}(x,y - \frac{FOV}{2}) \right)$$  \[8\]

$$EPI_{even}(x,y) = \frac{1}{2} \left( \tilde{M}(x,y) \exp\left(i \theta(x,y) \right) - \frac{1}{2} \tilde{M}(x,y - \frac{FOV}{2}) \exp\left(i \theta(x,y - \frac{FOV}{2}) \right) \right).$$  \[9\]

As described previously (5,12,13), an image with reduced ghost artifacts can be obtained with 2D filtering, as presented in Eq. 10. However, the effectiveness of the correction based on Eq. 10 will be reduced when the signal intensities in the reference images are significantly different from those in the subsequent EPI measurements.

$$\tilde{M}(x,y) = EPI_{odd} + EPI_{even} \frac{Ref2_{even}}{Ref1_{even}}$$

if $M(x,y) = \tilde{M}(x,y)$. \[10\]

EPI ghost artifacts can be removed more effectively and reliably by solving the linear Eqs. 8 and 9. The resultant formula is shown in Eq. 11. Using this formula, an image without ghost artifact can be derived from the dynamic EPI data and the previously measured 2D phase map. It should be noted that the derivation of the proton density map in Eq. 11 does not require an assumption of similar signal intensities in both the reference and the actual EPI scans.

$$\tilde{M}(x,y) = \frac{2 \left( EPI_{odd}(x,y) \exp\left(i \theta(x,y - \frac{FOV}{2}) \right) + EPI_{even}(x,y) \right)}{\exp\left(i \theta(x,y) \right) + \exp\left(i \theta(x,y - \frac{FOV}{2}) \right)}. \quad \text{[11]}$$

In image background area, phase values may fluctuate and therefore the denominator of Eq. 11 may be very close to zero. As a result, the background noise may be amplified. This noise amplification phenomenon can be avoided with two different approaches. First, by setting the phase terms of background pixels to zero (i.e., $\exp\left(i \theta(x,y) \right) \mid_{\text{background}} = 1$), the noise amplification phenomenon can be greatly reduced. However, there may exist residual ghost artifacts in the reconstructed image due to the phase discontinuity between $\exp\left(i \theta(x,y) \right)$ and $\exp\left(i \theta(x,y - \frac{FOV}{2}) \right)$. Second, the phase values of background area can be calculated from the parent image phase terms, with appropriate phase unwrapping and surface fitting procedures (see Materials and Methods). Using the fitted phase values in the background area, the noise amplification phenomenon can be avoided when using Eq. 11. In nonbackground area, the denominator of Eq. 11 may also approach zero and result in noise amplification for a specific phase map pattern where $\theta(x,y) - \left( x,y - \frac{FOV}{2} \right) = (2n + 1)\pi$. This issue will be addressed in the Discussion section.

### MATERIALS AND METHODS

The effectiveness of the proposed method was first evaluated with a phantom study on a 4.7 T GE Omega system. The phantom consisted of a water-filled outer tube and a silicon oil-filled inner tube. Because of the significant chemical shift difference between water and silicon oil (about 800 Hz at 4.7 T), EPI ghost artifact removal for both water and silicon oil components is challenging. Successful ghost artifact removal for this two-component phantom would indicate that the employed technique has a good tolerance to off-resonance factors. This phantom was also used to illustrate the application of the technique to spin-echo diffusion-weighted EPI, as water and silicon oil have significantly different diffusion coefficients. A gradient-echo image was first acquired as a reference with the following parameters: FOV 60 × 60 mm, slice thickness 2 mm, matrix size 256 × 256, TR 1 sec, and TE 20 msec. Two EPI reference scans were obtained using the sequences shown in Fig. 1a. A 2D phase map was then derived using Eqs. 5, 6, and 7. A nonphase-encoded reference EPI was also acquired to test the effectiveness of the 1D nonlinear correction method (7). After reference scans, spin-echo EPI with and without diffusion weighting were obtained, with $\delta = 7$ msec, $\Delta = 24$ msec, and diffusion sensitizing gradient values 12 and 0 Gauss/cm, respectively. Five different ghost artifact removal methods were evaluated in terms of their effectiveness measured by ghost-to-signal ratio (GSR) within the same manually selected ROIs: (1) 1D nonlinear correction based on a non-phase-encoded reference scan (7), (2) 1D nonlinear correction based on two phase-encoded reference scans (2), (3) 1D correction with phase error estimation (5), (4) previously described 2D filtering method based on Eq. 10 (5,12,13), and (5) the new 2D correction method based on Eq. 11.

The developed EPI ghost artifact removal technique was then applied to rabbit brain images to investigate the in vivo performance of this technique. Spin-echo EPI acquisition parameters included FOV 60 × 60 mm, matrix size 64 × 64, and slice thickness 2 mm. Two datasets were acquired under different shimming conditions (corresponding to 22 and 46 Hz linewidth in a 8 mm thick region), to test the tolerance of the proposed method to field inhomogeneities. Phase-encoded reference scans and a nonphase-encoded reference scan were obtained for method comparison. The proposed method was also applied to human brain imaging. EPI data of 24 slices covering the whole brain were acquired from healthy subjects ($n = 5$) using a 3 T GE scanner, after obtaining informed consent. Scan parameters included FOV 240 × 240 mm, matrix size 64 × 64, slice thickness 5 mm, and echo spacing time 0.592 msec. Both nonphase-encoded reference data and phase-encoded reference data were obtained for method comparison. The dataset acquired in each scan session consisted of 10 dynamic EPI scans and the mean and standard deviation of the achieved ghost-to-signal ratios across 10 dynamic time points were calculated.
When reconstructing images using Eq. 11, two different approaches were applied to minimize background noise amplification. First, the phase values of background pixels were simply set to zero, as described in the Theory section. Second, the phase map values in background pixels were calculated using a three-step procedure: 1) the parent image phase terms of the first and second regrouped images (Eqs. 5 and 6) were unwrapped, 2) the phase values in background area (of two regrouped images) were extrapolated with a polynomial surface fitting, 3) the phase map values in background area were calculated by subtracting the fitted background phase values in two regrouped images. The measured phase values (Eq. 7) in nonbackground area and the calculated phase values in background area were combined, then used in Eq. 11.

RESULTS

Results of the phantom study are presented in Fig. 2. The gradient-echo image (Fig. 2a) illustrates the geometry of two tubes filled with water (outer) and silicon oil (inner). The image reconstructed from raw EPI data without any correction is degraded by both geometric distortions and Nyquist ghost artifacts. Major artifacts in this image reconstructed from raw EPI data without any correction is degraded by both geometric distortions and Nyquist ghost artifacts. The gradient-echo image shows the geometry of a two-component phantom consisting of water (outer tube) and silicon oil (inner tube). b: The EPI image reconstructed without using any correction is degraded by both geometric distortions and Nyquist ghost artifacts. c: The magnitude reconstruction of the first regrouped data (using Eq. 5). d: The real components of the complex images derived from the first regrouped dataset (using Eq. 5). e: The real components of the complex images derived from the second regrouped dataset (using Eq. 6). 2D phase variation due to EPI odd–even-echo asymmetry can be measured from d and e. Ghost artifact removal with different methods are shown in f–i. Data in f are processed with the 1D nonlinear correction based on a non-phase-encoded reference scan (7). Data in g are processed with the 1D nonlinear correction based on two phase-encoded reference scans (2). Data in h are processed with phase information estimated from the EPI data itself (5). Data in i are processed with the proposed technique based on Eq. 11. Ghost artifact removal in diffusion-weighted EPI with different techniques are shown in j–m. j: Obtained with the 1D nonlinear correction based on a non-phase-encoded reference scan. k: Obtained with the 1D nonlinear correction based on two phase-encoded reference scans. l: Obtained with Eq. 10. m: Processed with Eq. 11.

Figure 2f–i compares EPI data processed with different correction methods. The corresponding GSR of water and silicon oil signals, measured from ROIs shown in Fig. 2c, are presented in Table 1. Image reconstructed using the 1D nonlinear correction method based on a nonphase-encoded reference scan is shown in Fig. 2f. The GSRs of water and silicon oil signals are both 22.9%. Using the 1D correction method based on two phase-encoded reference scans (2), the ghost artifacts of both water and silicon oil are further reduced (Fig. 2g), with corresponding GSRs of 12.3% and 14.8%, respectively. Figure 2h shows the image corrected using phase error information estimated from EPI itself, as reported by Buonocore and Gao (5). The GSRs of water and silicon oil signals are 7.9% and 69.0%, respectively. Ghost artifact of water signal is suppressed much more effectively than that of silicon oil signal, since the phase error information is estimated in an area containing only water signal. It is possible that the silicon oil ghost artifact observed in Fig. 2h may be reduced if the data are processed with the phase error information estimated in an area containing only silicon oil signal. Using
the proposed algorithm for 2D phase error correction based on Eq. 11, and EPI image with minimal ghost artifacts can be obtained (Fig. 2l). As shown in Table 1, the GSRs corresponding to water and silicon oil signals in the reconstructed images were reduced to 2.6% and 4.1%, respectively. Since the signal intensity of the EPI data to be corrected is virtually the same as that in reference scans, effective correction can also be accomplished using the previously reported 2D filtering method (5,12,13) based on Eq. 10 (data not shown).

Figure 2j–m shows diffusion-weighted EPI (δ = 7 msec, Δ = 24 msec, G = 12 Gauss/cm) processed with different artifact removal methods. The water signal is greatly attenuated by diffusion sensitizing gradients and a significant image contrast between water and silicon oil components is attained. The corresponding GSR of both water and silicon oil signals in the reconstructed images are presented in Table 1. The image processed with a 1D nonlinear correction method based on a non-phase-encoded reference scan (7) is shown in Fig. 2j. The GSRs are 53.0% and 48.7% for water and silicon oil signal, respectively. Data processed with a 1D nonlinear correction method based on two phase-encoded reference scans (2) are shown in Fig. 2k. The corresponding GSRs are 69.5% and 20.7% for water and silicon oil signals, respectively. The image processed with the previously reported 2D filtering method (5,12,13) based on Eq. 10 is shown in Fig. 2l. The corresponding GSRs for the two components are 14.3% and 7.0%, respectively. Equation 10 assumes that image signal intensities in reference scans and EPI scans are virtually the same. Since this assumption does not apply to the diffusion-weighted EPI data, significant residual ghost artifacts can be observed in the reconstructed image (Fig. 2l). The data processed with the new technique, based on Eq. 11, presented in Fig. 2m, resulted in 8.8% and 3.6% GSRs for water and silicon oil signals, respectively. This phantom experiment suggests that the new method is effective, has a good tolerance to off-resonance factors, and remains effective even when the signal intensities in reference scans and actual EPI data are very different.

Results from the in vivo imaging experiments are shown in Fig. 3, where the phase-encoding is along the vertical direction. EPI rabbit brain images acquired with optimal shimming and processed with the 1D nonlinear correction method (7) and the new technique are presented in Fig. 3a,b, respectively. Corresponding GSRs are 12.8% and 3.3% measured within the same manually selected ROIs (shown in Fig. 3a). EPI images obtained in the presence of a stronger field inhomogeneity, processed with the 1D nonlinear correction method and the proposed technique are shown in Fig. 3c,d, respectively. Corresponding GSR are 64.1% and 5.2%. Results of this animal study demonstrate that the developed ghost artifact removal method remains effective in vivo application, and has a much better tolerance to field inhomogeneity than the previously reported 1D nonlinear correction method.

Figure 4a–d compare human brain EPI data of a selected axial slice processed with different Nyquist artifact removal methods. The left and right panels in each dataset show the same image, but with different display scales, so that the residual Nyquist artifact can be visualized. The Nyquist ghost artifacts are clearly visible when no correction method is applied (Fig. 4a). Using conventional nonlinear correction method based on a non-phase-encoded reference scan (7), the majority of artifacts can be suppressed (Fig. 4b). By setting the background phase values to zero, the EPI data reconstructed with Eq. 11 have a lower ghost level, as shown in Fig. 4c. However, there remain some residual artifacts, as indicated by the arrow.

Table 1

<table>
<thead>
<tr>
<th>Diffusion gradient</th>
<th>0</th>
<th>12 Gauss/cm</th>
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<tbody>
<tr>
<td>Method applied</td>
<td>m1</td>
<td>m2</td>
</tr>
<tr>
<td>GSR of water (%)</td>
<td>22.9</td>
<td>12.3</td>
</tr>
<tr>
<td>GSR of silicon oil (%)</td>
<td>22.9</td>
<td>14.8</td>
</tr>
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</table>

GSR: ghost-to-signal ratio; m1: 1D nonlinear correction based on a non-phase encoded reference scan (7); m2: 1D correction method based on two phase encoded reference scans (2); m3: 1D correction based on phase information estimated from the EPI itself (5); m4: previously reported 2D filtering method based on Equation 10 (12); m5: proposed 2D correction technique based on Eq. 11.

FIG. 3. Ghost artifact removal in rabbit brain EPI images. a and b compare EPI data acquired with appropriate shimming, and then processed with the 1D nonlinear correction (a) (7) and the proposed 2D method based on Eq. 11 (b). Another dataset was acquired with intentionally misadjusted shim values so that the effectiveness of the ghost removal techniques could be evaluated in the presence of a significant field inhomogeneity, as presented in c and d. A much more effective artifact removal can be achieved with the proposed 2D method (d), in comparison to the previously reported 1D nonlinear correction (c).
These residual artifacts can be further removed, if the fitted phase map values in background areas are used in Eq. 11, as shown in Fig. 4d. The GSR measured from manually selected ROIs (indicated in Fig. 4a) are 36.7%, 8.4%, 2.6%, and 1.4% in images presented in Fig. 4a–d, respectively.

Table 2 compares the ghost-to-signal ratios measured from three-dimensional ROIs (37.5 × 18.75 × 60 mm) of human brain EPI data (five subjects in nine scan sessions), processed with 1D nonlinear phase correction (7) and the proposed 2D phase correction technique (with fitted phase map in the background area). The mean and standard deviation of the GSR across 10 dynamically acquired EPI images in each scan session were presented. Statistical results shown in Table 2 illustrate that the Nyquist artifact can be reduced more effectively using the proposed 2D phase correction method.

### DISCUSSION

An EPI image with the minimum ghost artifact can be reconstructed with Eq. 11, after obtaining the 2D phase error map from two reference scans. EPI reconstruction based on Eq. 11 is superior to previously reported ghost artifact reduction algorithms in three ways. First, linear and high-order phase errors along both readout and phase-encoding directions can be removed using Eq. 11, while only 1D phase errors can be corrected using previous methods. Second, successful ghost artifact removal for both water and silicon oil signals in the phantom experiment suggests that the EPI reconstruction based on Eq. 11 has a good tolerance to off-resonance factors. Third, artifact removal based on Eq. 11 remains effective even when the signal intensities in reference scans and actual EPI data are very different, as illustrated in Fig. 2m, since the mathematical derivation of Eq. 11 does not rely on any assumption about the signal change between EPI and reference scans.

For a certain phase map pattern where \( \theta(x,y) = \frac{x - \frac{\text{FOV}}{2}}{2(n + 1)} \), the denominator of Eq. 11 approaches zero and thus the image noise may be amplified in nonbackground area. This phenomenon was not observed in our experiments at 4.7 T and 3 T systems, since the phase errors due to EPI odd–even echo inconsistency along the phase-encoding direction were generally not significant. When there exists significant eddy current due to the readout-phase cross-terms, it is possible that the denominator of Eq. 11 may approach zero. The existence of a significant phase variation can be identified with the proposed 2D phase mapping procedure (Eq. 7). In this case, the gradient systems should be further calibrated to reduce eddy current due to the readout-phase cross-terms before the proposed Nyquist removal method can be applied.

### Table 2

<table>
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<tr>
<th>Scan session</th>
<th>Date</th>
<th>Subject ID</th>
<th>Slice orientation</th>
<th>GSR:1Dpc (%)</th>
<th>GSR:2Dpc (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>2/25/2003</td>
<td>ID1</td>
<td>axial</td>
<td>8.1 ± 0.06</td>
<td>2.9 ± 0.03</td>
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<tr>
<td>2</td>
<td>2/25/2003</td>
<td>ID2</td>
<td>axial</td>
<td>5.5 ± 0.03</td>
<td>1.6 ± 0.04</td>
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<tr>
<td>3</td>
<td>2/25/2003</td>
<td>ID3</td>
<td>axial</td>
<td>10.6 ± 0.06</td>
<td>1.7 ± 0.04</td>
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<tr>
<td>4</td>
<td>12/11/2003</td>
<td>ID4</td>
<td>axial</td>
<td>5.5 ± 0.08</td>
<td>4.5 ± 0.15</td>
</tr>
<tr>
<td>5</td>
<td>12/16/2003</td>
<td>ID2</td>
<td>axial</td>
<td>5.1 ± 0.03</td>
<td>1.5 ± 0.08</td>
</tr>
<tr>
<td>6</td>
<td>12/16/2003</td>
<td>ID5</td>
<td>axial</td>
<td>2.6 ± 0.02</td>
<td>1.3 ± 0.06</td>
</tr>
<tr>
<td>7</td>
<td>12/17/2003</td>
<td>ID2</td>
<td>axial</td>
<td>5.6 ± 0.03</td>
<td>2.1 ± 0.02</td>
</tr>
<tr>
<td>8</td>
<td>12/17/2003</td>
<td>ID2</td>
<td>axial</td>
<td>3.6 ± 0.01</td>
<td>1.7 ± 0.04</td>
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<tr>
<td>9</td>
<td>12/17/2003</td>
<td>ID2</td>
<td>sagittal</td>
<td>5.1 ± 0.03</td>
<td>3.4 ± 0.05</td>
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GSR: ghost-to-signal ratio; 1Dpc: 1D nonlinear correction based on a non-phase encoded reference scan (7); 2Dpc: the proposed 2D correction technique based on Eq. 11.
If the phase map used in image reconstruction (i.e., $\theta(x,y)$ in Eq. 11) is inaccurate, then the Nyquist artifact may not be reduced effectively in reconstructed EPI. We have performed a mathematical simulation to study the impact of inaccuracy in phase map on the reconstructed EPI quality and GSR. Our simulation indicates that the signal intensity of the parent image decreases when the inaccuracy in phase map increases, within the range of $\pm \pi$, while the associated Nyquist signal intensity increases with the inaccuracy in phase map (data not shown). Our simulation also shows that the inaccuracy in phase map needs to be within the range of $\pm 0.2$ (radian) for a GSR less than 10%. In our experimental studies we found that the EPI odd–even echo asymmetry could be measured accurately with the proposed phase mapping procedure and the Nyquist artifact was always reduced effectively.

It has been shown by Hennel (3) and Buonocore and Zhu (8) that the pattern of the odd–even echo asymmetry in a single-shot EPI is the same as that in a segmented EPI with odd number alternating interleaves. In both cases, phase errors related to the readout gradient polarities are attributed to alternating lines and the resulting single ghost artifact is shifted by FOV/2 from the parent image. Therefore, the ghost artifact removal technique developed for a single-shot EPI can be directly applied to segmented EPI with odd number alternating interleaves. To remove the ghost artifacts in a segmented EPI, two reference scans, in which the corresponding $k_y$ lines are acquired with opposite readout gradient polarities, need to be obtained for measurement of 2D phase errors. Similar to the algorithm shown in Fig. 1c,d or Eqs. 5–7, a 2D phase map can be derived by appropriately regrouping the odd-echo-only and even-echo-only images of the two reference scans. Removal of ghost artifact in subsequently acquired segmented EPI can be achieved using Eq. 11.

CONCLUSIONS

We present a novel 2D phase mapping approach that measures the phase errors due to EPI odd–even echo inconsistency. EPI Nyquist artifacts can be effectively removed using the developed phase correction formula, as demonstrated with animal and human studies. The capability of correcting nonlinear phase errors along both readout and phase encoding directions results in effective removal of ghost artifacts due to both gradient imperfections and complicated eddy current effects.

REFERENCES