Robust EPI Nyquist Ghost Removal by Incorporating Phase Error Correction With Sensitivity Encoding (PEC-SENSE)

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Purpose: The existing approach of Nyquist ghost correction by parallel imaging in echo planar imaging (EPI) can suffer from image noise amplification. We propose a method that estimates a phase error map from multi-channel data itself and incorporates it into the sensitivity encoding (SENSE) reconstruction for Nyquist ghost correction without compromising the image SNR.

Methods: This method first reconstructs two ghost-free images from positive and negative echoes using SENSE, respectively, from which the phase error map is computed. This map is then incorporated into the coil sensitivity maps for the negative echo image during the joint SENSE reconstruction of all k-space data to obtain the final ghost-free image. Phantom and in vivo EPI experiments at 7 T and 3 T were performed to evaluate the proposed method.

Results: Nyquist ghost was effectively removed in all images even under oblique imaging and poor eddy current conditions. Resulting image signal-to-noise ratio (SNR) was comparable to that by the traditional linear phase error correction method and higher than that by a previous SENSE-based parallel imaging correction approach.

Conclusion: The proposed correction method can robustly correct the Nyquist ghost by estimating a phase error map and incorporating its correction during the final SENSE image reconstruction. This phase error correction approach, termed PEC-SENSE, first reconstructs two ghost-free images from positive and negative echoes, and higher than that by a previous SENSE-based parallel imaging correction method.

Key words: MRI; EPI; Nyquist ghost; parallel imaging; SENSE

INTRODUCTION

Echo planar imaging (EPI) is widely applied in various MRI applications because of its fast imaging capability. However, because EPI acquires k-space data in both readout polarities, gradient time delay, eddy current, field inhomogeneities, and other hardware imperfections misalign k-space trajectory in opposite readout polarities, producing a Nyquist ghost in the reconstructed images.

A number of methods have been proposed to correct the Nyquist ghost, most of which correct the k-space misalignment along the readout direction (1–3). These methods estimate k-space misalignment from non-phase-encoded or phase-encoded scans or data itself and, subsequently, correct the phase difference along the readout direction in the image domain. These methods can remove most of the Nyquist ghost. However, all these methods are problematic when high-order 2D phase errors are present attributed to eddy current or magnetic susceptibility effect, especially in oblique imaging where different physical gradients may have different eddy current and time delay (4). The 2D phase error correction methods estimate the phase error map from calibration scans (5,6), and phase inconsistency between positive and negative echo images is subsequently removed in the image space. These methods can robustly correct the Nyquist ghost, but require extra EPI calibration scans.

The use of phased array coils has enabled several new methods for Nyquist ghost correction based on parallel imaging (7–11). In these methods, single-shot EPI k-space data are separated into positive and negative echo groups based on their readout polarity. Each group can be treated as a data set that is undersampled by twice the acceleration factor and thus can be reconstructed into a ghost-free image using parallel imaging reconstruction methods. However, all these methods can suffer from signal-to-noise ratio (SNR) reduction attributed to noise amplification during parallel imaging reconstruction. A recently proposed method, termed dual-polarity generalized autocalibrating partial parallel acquisition (GRAPPA) (DPG) (12), trains multiple GRAPPA kernels from temporally encoded calibration scans and then utilizes these kernels to synthesize missing k-space data and correct inherent EPI phase errors simultaneously. This method can robustly remove an EPI ghost induced by high-order phase errors and improve image quality, but it requires EPI calibration scans.

In this study, we propose a sensitivity encoding (SENSE)-based (13) Nyquist ghost correction method to robustly correct the Nyquist ghost by estimating a phase error map and incorporating its correction during the final SENSE image reconstruction. This phase error correction approach, termed PEC-SENSE, first reconstructs two ghost-free images from positive and negative echoes.
expressed by Equations [1] and [2]:

\[ I_p \] and \[ I_n \] can be separated into two groups based on their readout polarities, with the missing data filled with zeros. Then, two aliased images are unaliased by SENSE to generate two ghost-free images. A 2D phase error map is calculated as their phase difference. A 2D bilateral filter is applied to the phase error map to suppress the SENSE-amplified noise effect. The final image is reconstructed jointly by Equations [1] and [4] with the smoothed phase map incorporated into the coil sensitivity maps for negative echo SENSE reconstruction described by Equation [4].

**METHODS**

Theory

As shown in Figure 1, single-shot EPI k-space data can be separated into two groups based on their readout polarity. The positive echo image \( I_p^{\text{aliased}}(x, y) \) can be generated by taking an inverse Fourier transform of EPI k-space data in which negative echoes are replaced with zero and the negative echo image \( I_n^{\text{aliased}}(x, y) \) from EPI k-space data with positive echoes filled with zero. The positive image and negative image in \( j^{th} \) coil can then be expressed by Equations [1] and [2]:

\[
I_{p,i}^{\text{aliased}}(x, y) = \frac{1}{2} \left( C_i(x, y) I_p(x, y) + C_i(x, y + \frac{N_y}{2}) I_p(x, y + \frac{N_y}{2}) \right) \\
\text{[1]}
\]

\[
I_{n,i}^{\text{aliased}}(x, y) = \frac{1}{2} \left( C_i(x, y) I_n(x, y) - C_i(x, y + \frac{N_y}{2}) I_n(x, y + \frac{N_y}{2}) \right) \\
\text{[2]}
\]

Where \( C_i(x, y) \) is the coil sensitivity map in the \( i^{th} \) coil and \( N_y \) the number of pixels in the phase encoding (PE) direction. Note that the \( (x, y + \frac{N_y}{2}) \) coordinate in all equations is the circular shift of \((x, y)\) by half of the field of view (FOV) along the phase encoding direction. Two aliased images, \( I_{p,i}^{\text{aliased}}(x, y) \) and \( I_{n,i}^{\text{aliased}}(x, y) \), can be unaliased by SENSE (13) to generate two ghost-free images, \( I_p(x, y) \) and \( I_n(x, y) \). \( I_p(x, y) \) and \( I_n(x, y) \) are images formed with pure positive and negative echoes, respectively, but contain opposite phase errors (14). A joint SENSE reconstruction of both positive and negative images, the phase error map is first computed from these images, the phase error map is then be directly obtained from Equations [1] and [2] as in the phased array ghost elimination (PAGE) method (8). However, the image SNR will decrease by the geometry factor (g-factor) (11,13,15) because SENSE is utilized to unalias the positive and negative echo images, separately.

In EPI, it is well known that the phase difference between \( I_p \) and \( I_n \) constitutes the 2D phase error in image space (6,16). This phase error map contains all phase errors induced by various sources of the Nyquist ghost and can be used for robust Nyquist ghost removal. This 2D phase error map can be calculated as \( \Delta \varphi(x, y) = \text{Arg}(I_p(x, y)I_n^*(x, y)) \). Although \( I_p \) and \( I_n \) reconstructed by SENSE can be degraded by noise amplification in both amplitude and phase images, the true phase error map is expected to be spatially smooth. Thus, a 2D bilateral filter (17) that smooths the map while preserving the edge information is applied to denoise the phase error map in order to remove the phase noise introduced by the \( I_p \) and \( I_n \) SENSE reconstruction.

In theory, the final ghost-free image in \( i^{th} \) coil can now be directly obtained from Equations [1] and [2] as Equation [3]:
Thus, Equation [2] can be reformulated as Equation [4]:

\[ I_{\text{aliased}}(x, y) = \frac{1}{2} \left( C_i(x, y)I_p(x, y) - C_i\left(x, y + \frac{N_y}{2}\right)I_p\left(x, y + \frac{N_y}{2}\right) \right) \]  

However, the background image noise may be amplified because the phase error value in the nonobject background area cannot be accurately estimated (6). More importantly, it is not straightforward to apply this procedure to the accelerated EPI data because k-space data subsampling causes further aliasing to the already aliased positive and negative echo images. Such aliasing invalidates Equation [3]. Instead of directly obtaining a ghost-free image in each coil using Equation [3], the phase error map \( \Delta \phi(x, y) \) can be treated as a modification of the coil sensitivity maps for the negative echo image, and its correction can then be incorporated into SENSE. Thus, Equation [2] can be reformulated as Equation [4]:

\[ I_{\text{aliased}}(x, y) = \frac{1}{2} \left( C_i(x, y)I_p(x, y) + C_i\left(x, y + \frac{N_y}{2}\right)I_p\left(x, y + \frac{N_y}{2}\right) \right) \]  

where the modified coil sensitivity maps are \( C_i(x, y) = C_i(x, y)\exp(-i\Delta \phi) \). Equations [1] and [4] have the same unknowns to be solved (i.e., \( I_p(x, y) \) and \( I_p\left(x, y + \frac{N_y}{2}\right) \)), thus these two sets of equations from all coils can be jointly solved using SENSE. The additional set of equations in Equation [4] contain a change in the sign for the aliased component, which improves the conditioning of the complete joint SENSE encoding matrix and leads to better preservation of the image SNR.

The overall image reconstruction process is illustrated in Figure 1. Although the concept of PEC-SENSE is explained here with fully sampled k-space data as an example, this framework can be directly extended to accelerated EPI k-space data.

Experiments

Experiments were carried out on a 7 T Bruker scanner (70/16 PharmaScan; Bruker Corporation, Billerica, MA, USA) equipped with a four-channel rat head surface coil and a Philips Achieva (Philips Medical Systems, Best, The Netherlands) 3 T MRI scanner equipped with an eight-channel SENSE human head coil.

Phantom Experiments

To evaluate the Nyquist ghost correction, especially when multiple physical gradients are involved in phase encoding and readout direction, gradient echo (GE) EPI data of a cylindrical phantom were acquired at 7 T in coronal, oblique, and double-oblique planes. 3 TE EPI data were acquired on a water phantom in a double-oblique plane.

To assess the robustness of PEC-SENSE for Nyquist ghost correction in the presence of severe eddy current, experiments were performed under different eddy current conditions by changing the time constants and gains of gradient pre-emphasis unit in three physical axes on the well-adjusted 7 T Bruker MRI system (Bruker Corporation). Eddy current effect was examined by changing the short (time constant 2 ms and gain 36%) or long (200 ms and 36%) term separately in readout direction. The combined effect of short (2 ms and 36% in phase encoding direction) and long (200 ms and 36% in slice direction) eddy current were also examined.

GE EPI acquisition parameters for all phantom experiments at 7 T were: echo time (TE)/repetition time (TR) = 25/2,000 ms, flip angle = 90°, FOV = 50 × 50 mm², matrix size = 128 × 128, echo spacing = 0.32 ms, bandwidth (BW) = 400 kHz, and slice thickness = 2 mm. At 3 T, the acquisition parameters were: TE/TR = 30/2,000 ms, flip angle = 90°, FOV = 160 × 160 mm², matrix size = 96 × 96, echo spacing = 0.3 ms, BW = 320 kHz, and slice thickness = 4 mm. For nonaccelerated data, coil sensitivity maps were generated from the ghost-corrected images acquired with a two-frame phase labeling for additional coordinate encoding (14) EPI scan using the same acquisition parameters. For accelerated data, coil sensitivity maps were generated from the ghost-corrected images that were obtained from a multi-shot EPI scan (with the shot number equal to acceleration factor) and corrected by an entropy-based ghost correction method (2) in order to demonstrate the flexibility in obtaining coil sensitivity maps.

In Vivo Experiments

In vivo experiments were carried out at 3 T to evaluate PEC-SENSE on human brain EPI. The experiments were approved by the local institutional review board. Spin echo (SE) EPI data were collected with the following parameters: TE/TR = 30/2,000 ms, FOV = 230 × 230 mm², matrix size = 96 × 96, slice thickness/gap = 4/2 mm, and number of slices = 15. Other parameters were identical to those in the 3 T phantom experiments. An SE EPI scan was also performed with an acceleration factor = 2 and 3 to assess the performance of PEC-SENSE on accelerated EPI data.

Data Analysis

For comparison, two commonly used Nyquist ghost correction methods, 1D linear phase correction (LPC) based on image entropy minimization (2) and PAGE (8), were also implemented.

Nyquist ghost level was quantitatively evaluated by ghost-to-signal ratio (GSR) (7,11). GSR was defined as the ratio of the average signal within a ghost region of interest (ROI) to that within a signal ROI. In this study, the signal ROI was defined as the signal region without overlapping from the ghost signal. The ghost ROI was generated by shifting the signal ROI by half of the FOV along the phase encoding direction.

For phantom experiments, SNR was first measured using the image difference method (11,18,19) on a phantom. In brief, two sets of magnitude images were reconstructed from two data sets that were consecutively acquired with identical parameters. The signal was defined and measured as the mean signal within a ROI from the sum of these two images, whereas the noise was measured as the standard deviation of the signals within the same ROI in the difference image. The SNR of phantom images was further evaluated using a pseudo multiple replica method (19–21). Note, at 3 T, only four channels out of eight were utilized to demonstrate the SNR map difference between two methods.
more clearly. For in vivo experiments, SNR was measured using the multiple replica method (19–21), which is the same as method for temporal SNR measurement (22). An SNR map was generated by dividing the temporal standard deviation with the temporal mean after linear detrending. A g-map was also calculated as $g_i = \sqrt{(S_i^H S_i)^{-1}_{ii}(S_i^H S_i)_{ii}}$ (13) for both PEC-SENSE and PAGE methods, where S is the encoding matrix and its size is doubled in PEC-SENSE compared with PAGE.

RESULTS
Phantom Results
Figure 2 shows the water phantom images acquired at 7 T and 3 T and reconstructed by linear phase correction (LPC), PAGE (i.e., magnitude sum of $I_p$ and $I_n$), and the proposed PEC-SENSE methods. Phase maps from positive and negative echo images, (i.e., $\varphi_p$ and $\varphi_n$), their difference map $\Delta \varphi$, and smoothed phase error map (used for PEC-SENSE) are also shown. Nyquist ghost residue remained visible in images corrected by LPC, but was invisible in PAGE and PEC-SENSE. The phase error map was mostly linear along the readout direction (left to right) in the central region, but it changed dramatically and was no longer linear in the left and right boundary regions, reflecting the presence of high-order phase errors.
FIG. 3. (a) Nonaccelerated GE-EPI images of a water phantom in coronal (top), oblique (middle), and double-oblique (bottom) imaging planes at 7 T using a four-channel surface RF coil. Each image is displayed with normal and enhanced brightness (×4) to visualize the ghost. Each data set was Nyquist ghost corrected by LPC, PAGE, and PEC-SENSE. The Nyquist ghost remained visible in images corrected by LPC, but invisible in those by PAGE and PEC-SENSE. One signal ROI for GSR quantification is illustrated in one image by a red circle. (b) EPI images of a water phantom under various eddy current conditions by changing gradient pre-emphasis settings acquired in coronal view. Eddy current was deliberately worsened by adding excessive short-term (time constant 2 ms and gain 36%) or long-term (200 ms and 36%) pre-emphasis unit adjustment in readout direction. Short-term (2 ms and 36%) and long-term (200 ms and 36%) adjustments were also jointly made in the phase encoding direction and slice selection direction, respectively. PEC-SENSE performed well in Nyquist ghost correction under various eddy current conditions, with GSR ranging from 1.82% to 2.27%, which were similar to PAGE but better than LPC.
longer linear in the left and right boundary regions, reflecting the presence of high-order phase errors that likely arose from field inhomogeneities (6). The Nyquist ghost in the images corrected by PEC-SENSE was fully removed.

Figure 3a shows the water phantom images acquired in coronal, oblique, and double-oblique imaging planes at 7 T. All images are displayed with the normal and enhanced brightness for better visualization of image details. Nyquist ghost residue remained visible by LPC in coronal images, particularly in oblique images. However, the Nyquist ghost was nearly invisible in all images reconstructed by PAGE and PEC-SENSE. The GSRs were similar in the images reconstructed by PEC-SENSE (1.69–1.78%) and PAGE (1.68–1.88%), which were much lower than those by LPC (4.64–17.71%). Figure 3 shows the images reconstructed from data acquired at 7 T under deliberately worsened eddy current conditions. Again, PEC-SENSE performed well in Nyquist ghost correction, with GSRs ranging from 1.82% to 2.27%, which were similar to those by PAGE but better than those by LPC.

Figure 4 shows the SNR assessment and computed g-maps. ROIs for SNR measurements are shown in Figure 4a. The image SNRs in ROI-1 and ROI-4 at 7 T were measured to be 182.68 and 199.12 by PEC-SENSE, 183.19 and 199.12 by LPC, and 170.83 and 181.76 by PAGE, respectively. At 3 T, they were 511.58 and 222.10 by PEC-SENSE, 509.34 and 219.51 by LPC, and 492.23 and 204.39 by PAGE, respectively. Image SNRs in ROI-2 and ROI-3 were similar because there was no aliasing in these regions. Generally, PEC-SENSE preserved the image SNR when compared with LPC. In contrast, PAGE suffered from the undesired noise amplification in the aliased regions. The SNR maps calculated by the pseudo multiple replica method are shown in Figure 4b, indicating that PEC-SENSE generally exhibited a better SNR than PAGE in the aliased region. The g-maps for PAGE and PEC-SENSE are shown in Figure 4c. The g-factor in PAGE was mostly around 1.1 at both 7 T and 3 T, which corresponded to around a 9% SNR decrease in theory and was consistent with the actual SNR measurements. However, the g-factor in PEC-SENSE was close to 1, with the maximum g-factor equal to 1.003, which was in agreement with the slight SNR improvements.

In Vivo Results

Typical in vivo multi-slice human brain images acquired without and with 2-fold acceleration are shown in Figure 5a and 5b, respectively. Images are displayed with both normal and enhanced brightness. Nyquist ghost residue was still detectable after correction by LPC, especially around the boundary regions. Contrast, it was fully removed by PAGE and PEC-SENSE without introducing any other image artifacts. In accelerated EPI, both PEC-SENSE and PAGE removed the Nyquist ghost effectively, but PEC-SENSE exhibited higher image SNR. The SNR maps clearly demonstrate that the SNR performance by three methods was similar in nonaccelerated EPI, likely because temporal SNR measurement was dominated by the temporal physiological noise. In 2-fold accelerated EPI, the SNR of images corrected by PEC-SENSE was substantially higher than that by PAGE, particularly in the aliased regions. The results from the 3-fold accelerated EPI data are also presented in Supporting Figure S1, which demonstrated that PEC-SENSE could greatly preserve image SNR. The phase error maps before and after the smoothing are shown in Supporting Figure S2.

DISCUSSION

A simple and robust approach for Nyquist ghost correction, termed PEC-SENSE, is presented in this paper. It first calculates the 2D phase error map from the SENSE reconstructed positive and negative echo images and
then incorporates the phase error correction with the joint SENSE reconstruction of all k-space data for effective Nyquist ghost removal. PEC-SENSE is a pure post-processing procedure, without the need for pulse sequence modification or any EPI calibration scan. Thus, this method can be readily applied to all EPI-based applications, such as functional MRI (fMRI) and diffusion tensor imaging (DTI).

Our phantom results have demonstrated that PEC-SENSE is robust in dealing with the Nyquist ghost under various conditions. In EPI, several factors, including gradient time delay, imperfect gradient waveform, eddy current, and local susceptibility-induced gradient field, produce not only linear, but also high-order phase errors in image space. Although these phase errors can be approximately represented and corrected by a linear
phase error and then uses 2D polynomial fitting to estimate the phase error map, may also be utilized. Last, it should be noted that though the amplified phase error and noise discussed above can be substantially suppressed by the smoothing filter, the severe SENSE artifacts, which can occur for highly accelerated data, may significantly affect the accuracy of the phase error map and robust Nyquist ghost removal. These SENSE artifacts can be mitigated by using regularized or iterative SENSE.

Both PEC-SENSE and DPG methods correct high-order and 2D phase errors. Apart from the general difference between SENSE and GRAPPA, DPG obtains phase error information from temporally encoded calibration scans whereas PEC-SENSE directly obtains it from data itself. Thus, at very high acceleration factors, DPG will face less difficulty than PEC-SENSE, but at the expenses of sequence modification, prolonged calibration time, and loss of the ability to track dynamic phase errors. Nevertheless, we expect these two methods to have similar performance in most applications with typical acceleration factors, given that both have properly handled high-order phase errors and addressed the SNR issue. In fact, we have briefly compared PEC-SENSE and DPG by simulations (Supporting Fig. S3). Both methods effectively removed the Nyquist ghost induced by high-order and 2D phase errors at various acceleration factors. In addition, PEC-SENSE exhibited similar, or slightly better, SNR performance. This might likely arise from the explicit usage of coil sensitivity maps, which, in principle, allows optimal SNR to be achieved in SENSE-based methods (26,27). In essence, PEC-SENSE presents a SENSE-based alternative to DPG in correcting high-order and 2D phase errors in EPI data at typical acceleration factors, but without requiring an EPI calibration scan.

This proposed method is directly applicable to in-plane accelerated EPI. It can also be extended to multi-band EPI (28) to robustly remove the Nyquist ghost where the phase error map can be slice-location dependent. In this case, the positive and negative echo images will be treated as images with both slice and in-plane acceleration, and they can be unaliased by SENSE. A phase error map in each slice can be then determined and incorporated into the final SENSE reconstruction to unalias the folded slices, in a manner similar to a recent multi-band EPI study (23) that corrects the slice-dependent Nyquist ghost using a linear phase error model approach.

CONCLUSION

A Nyquist ghost correction method incorporating 2D phase error correction with SENSE, termed PEC-SENSE, has been proposed. This method estimates the 2D phase error map from multi-channel data itself. The map is first smoothed and then incorporated into the coil sensitivity maps for the negative echo image during the joint SENSE reconstruction of all k-space data. This method is robust in Nyquist ghost correction, even under oblique imaging and poor eddy current conditions, while preserving the final image SNR. This correction method provides a SENSE-based alternative to the recently proposed dual-polarity GRAPPA method. It requires no additional EPI calibration data beyond standard coil sensitivity maps. It
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can be readily applied to various EPI-based applications, such as fMRI, DTI, in-plane acceleration, and multi-band imaging.

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REFERENCES


SUPPORTING INFORMATION

Additional supporting information can be found in the online version of this article.

Fig. S1. In vivo multislice human brain SE-EPI images acquired at 3 T using an eight-channel head coil with 3-fold acceleration. Images were reconstructed with PAVE and PEC-SENSE and are displayed with normal and enhanced brightness. No ghost was observed in all images. The images reconstructed by PAVE suffered greatly from the g-factor noise. In contrast, PEC-SENSE could successfully reconstruct the image with better SNR.

Fig. S2. Raw and smoothed phase error maps from nonaccelerated data (R = 1), 2- and 3-fold accelerated data (R = 2 and 3). These phase error maps were used in reconstructing images shown in Figure S1 and Supporting Figure S1. The noise in the phase raw error map increased with the acceleration factor, but was mostly suppressed by 2D bilateral filtering. Note that, at 3-fold acceleration, a rectangular window filter was applied in k-space before bilateral filter.

Fig. S3. Simulation comparison between PEC-SENSE and dual-polarity GRAPPA (DPG) in reconstructing data containing high-order and 2D phase errors. An eight-channel T2-weighted image (matrix size Nx Ny of 144 x 144) is used as reference. 1D nonlinear and 2D phase errors were introduced to the reference image to simulate EPI data. 1D nonlinear quadratic readout (RO) phase error was defined as \( \frac{\pi}{4} + \frac{\pi}{4} x^2 + x^4 + 0.1 x \), whereas 2D phase error was nonlinear in the RO direction with the same parameters as described above for 1D, and in linear in PE direction varying from -0.1 to +0.1. These two data sets were further added with 30 dB of white noise and subsampled by a factor of 2 and 3 in k-space. For DPG, GRAPPA kernels with size \( k_y \times k_x \) of 2 x 5 were trained from the central 64 lines of the reference k-space. For PEC-SENSE, the coil sensitivity maps were estimated from the central 64 lines. The error maps between the reconstructed image and reference image are shown with brightness \( \times 40, \times 20, \) and \( \times 10 \) for \( R = 1, 2, \) and 3, respectively. Generally, PEC-SENSE was observed to remove the ghost as effectively as DPG and result in similar, if not higher, SNR. In essence, the proposed PEC-SENSE presents a SENSE-based alternative to DPG in correcting high-order and 2D phase errors in EPI data at typical acceleration factors, but without requiring EPI calibration scan.