Robust 2D Phase Correction for Echo-Planar Imaging Under a Tight Field-of-View

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INTRODUCTION

Nyquist ghost artifacts in echo planar imaging (EPI) originate from the phase difference between even and odd echo images, and can be removed or reduced using phase correction methods. Most phase correction methods assume and calibrate a 1D phase difference function [1-2], which can robustly suppress ghost when the underlying phase difference only depends on spatial location along the readout direction. When significant phase variations along the phase encoding direction are present (e.g., due to oblique scan plane with anisotropic gradients or a large cross-term eddy current), 1D methods fail to correct them, generating images with significant Nyquist ghost. On the other hand, 2D phase correction methods [3-5] correct 2D phase differences, and have been shown promising in removing ghost that the 1D methods cannot correct. However, the existing 2D methods have several unaddressed issues that largely affect their practicality, which include uncharacterized noise behavior, error due to unoptimized phase estimation, and most seriously a new image artifact under tight FOV. All these issues are addressed in this paper.

PROPOSED METHOD

Existing 2D phase correction: Denote $F_e(x,y)$ as the image from taking the 2D inverse Fourier transform of the even echo data (x and y are readout and phase encoding directions, respectively), $F_o(x,y)$ as the image from the odd echo data, and $\varphi(x,y)$ as the phase difference between even and odd echoes. The phase corrected image can be obtained [5] by $I(x,y) = 2[F_e(x,y)e^{-i\varphi(x,y-W/2)}+F_o(x,y)]/[e^{-i\varphi(x,y)}+e^{-i\varphi(x,y-W/2)}]$, where W denotes the field-of-view (FOV) along the phase encoding direction.

Noise characteristics: The 2D phase correction can be viewed as solving a two-coil twofold-acceleration SENSE equation in parallel imaging [6]: The even and odd echoes can be viewed as being acquired by two virtual coils; the coil sensitivity functions are 1 and $e^{-i\varphi(x,y)}$, respectively. Using analysis similar to that in parallel imaging [6], we use a *virtual geometry factor* $g(x,y)$ to measure the loss of signal-to-noise ratio (SNR) due to the "geometry" of $\phi(x,y)$: $g(x,y) = 1/|\cos[(\varphi(x,y)-\varphi(x,y-W/2))/2]|$. Figure 1 shows the virtual geometry factor for correcting the "bunched" sampling pattern (due to cross-term eddy current or oblique scan plane) using the 2D phase correction. When the displacement ε of k-space lines is moderate (e.g., smaller than 20 percent of the Nyquist sampling spacing), the loss of SNR is small (below 5%). Therefore, the 2D correction in principle trades minimal loss of SNR with reduced Nyquist ghost.

Improved estimation of φ: It is critical to have a well-estimated φ as the error in φ can propagate to the final image. We propose to use data from all coils to polynomially fit one set of phase function to obtain maximum robustness to low SNR. As shown in Fig. 2, the joint fitting among all coils leads to reduced image artifact over the coil-by-coil fitting, where significant error in φ occurs due to the low SNR in diffusion weighted images.

Imaging under a tight FOV: When tight FOV is prescribed (FOV smaller than object which occasionally happens in head scans), the existing 2D correction generates a new artifact in the center of the image (Fig. 3). The root cause is that 3 voxels overlap onto each other in the center due to the tight FOV, which cannot be resolved by 2 data points from even and odd echoes. To remove this artifact, data from multiple coils are used in a SENSE-like method [6], and the results are shown in Fig. 3.

RESULTS

Diffusion-weighted spin-echo imaging of human brain was done to demonstrate the performance of the proposed 2D phase correction method. The volunteer rotated his head by roughly 30° about the superior-inferior axis, which appears as a rotated brain image in the axial scout image. An oblique plane (rotated axial plane) was therefore prescribed, as shown by the green square in Fig. 4a. Due to the differences in gradient timing (i.e. anisotropy), this oblique scan generated a large y component in the phase difference map $\phi(x,y)$, which could not be corrected by the 1D correction (Fig. 4b). The resulting Nyquist ghost has about 10% of the tissue intensity, which is large enough to corrupt the tissue contrast. The proposed 2D phase correction generated a literally ghost-free image (ghost level below 1%), demonstrating its outstanding performance in reducing Nyquist ghosts (Fig. 4c).

REFERENCES

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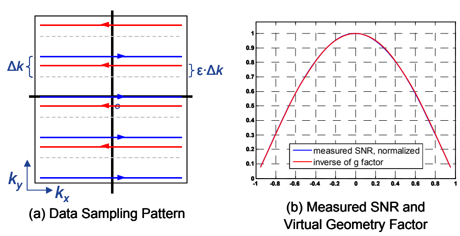

Fig. 1. SNR behavior of the 2D phase correction. (a) "Bunched" sampling pattern due to cross-term eddy current or oblique scan plane. (b) Loss of SNR as a function of odd echo displacement.

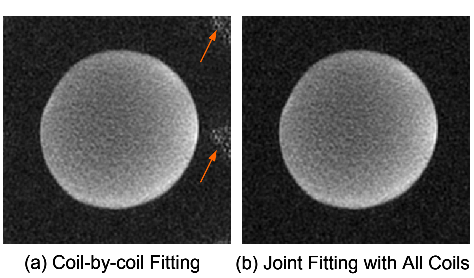

Fig. 2. Diffusion weighted EPI results comparing two phase estimation methods.

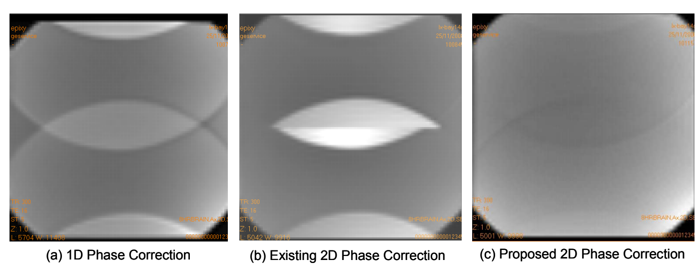

Fig. 3. Gradient-echo EPI phantom results with a tight FOV and large y component in the phase difference function comparing three phase correction methods: (a) 1D phase correction. (b) Existing 2D phase correction. (c) Proposed 2D phase correction.

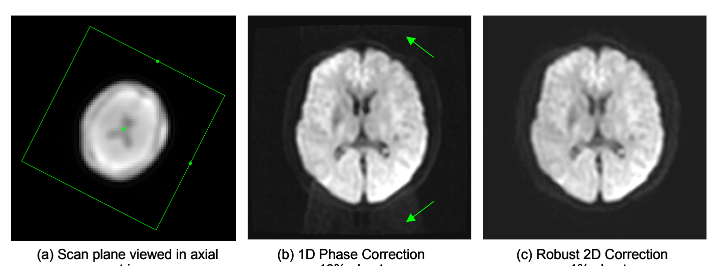

Fig. 4. Diffusion-weighted EPI results comparing the 1D and the proposed 2D phase correction results. (a) Axial scout image showing the rotated head position and the corresponding rotated scan plane. (b) Image reconstructed using 1D phase correction. The 10% Nyquist ghost is due to gradient anisotropy. (c) Image reconstructed using the proposed robust 2D phase correction. The ghost level is suppressed to below 1%.