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Joint correction of Nyquist artifact and minuscule motion-induced aliasing artifact in interleaved diffusion weighted EPI data using a composite two-dimensional phase correction procedure

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Abstract

Diffusion-weighted imaging (DWI) obtained with interleaved echo-planar imaging (EPI) pulse sequence has great potential of characterizing brain tissue properties at high spatial-resolution. However, interleaved EPI based DWI data may be corrupted by various types of aliasing artifacts. First, inconsistencies in k-space data obtained with opposite readout gradient polarities result in Nyquist artifact, which is usually reduced with 1D phase correction in post-processing. When there exist eddy current cross terms (e.g., in oblique-plane EPI), 2D phase correction is needed to effectively reduce Nyquist artifact. Second, minuscule motion induced phase inconsistencies in interleaved DWI scans result in image-domain aliasing artifact, which can be removed with reconstruction procedures that take shot-to-shot phase variations into consideration. In existing interleaved DWI reconstruction procedures, Nyquist artifact and minuscule motion-induced aliasing artifact are typically removed subsequently in two stages. Although the two-stage phase correction generally performs well for non-oblique plane EPI data obtained from well-calibrated system, the residual artifacts may still be pronounced in oblique-plane EPI data or when there exist eddy current cross terms. To address this challenge, here we report a new composite 2D phase correction procedure, which effectively removes Nyquist artifact and minuscule motion induced aliasing artifact jointly in a single step. Our experimental results demonstrate that the new 2D phase correction method can much more effectively reduce artifacts in interleaved EPI based DWI data as compared with the existing two-stage artifact correction procedures. The new method robustly enables high-resolution DWI, and should prove highly valuable for clinical uses and research studies of DWI.

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Keywords

diffusion-weighted imaging; interleaved echo-planar imaging; multiplexed sensitivity encoding; Nyquist ghost correction; two dimension phase correction

Introduction

Diffusion-weighted imaging (DWI) of high spatial-resolution and low geometric distortion is potentially achievable with interleaved diffusion-weighted echo-planar imaging (EPI) protocols. However, it is well known that interleaved EPI based DWI data may be corrupted by various types of aliasing artifacts. First, originating from asymmetric receiver response [1] or gradient waveform imperfection [2], inconsistencies in k-space data corresponding to opposite readout gradient polarities result in Nyquist artifact. Typically, image-domain phase errors along the readout direction are measured with reference scans, and then removed from EPI data in post-processing with a 1D phase correction procedure [2]. Although 1D phase correction is designed to remove the majority of EPI Nyquist artifact, the residual artifact may still be pronounced, particularly in oblique plane EPI [3] or in the presence of eddy current cross terms [4]. Recent studies have shown that EPI Nyquist artifact can be most effectively removed with 2D phase correction, in which the phase errors along both readout and phase-encoding directions need to be first either measured from reference scans [5–9] or estimated inherently from EPI data [10]. Second, in addition to EPI Nyquist artifact, image-domain aliasing artifacts resulting from minuscule motion induced shot-to-shot phase variations may also corrupt interleaved EPI based DWI data. It has been shown that high-quality interleaved DWI images can be produced by alternative reconstruction algorithms (instead of 2D Fourier transform) that take shot-to-shot phase variations into consideration [11–24].

In existing interleaved DWI reconstruction pipelines, the Nyquist artifact is always first removed from interleaved EPI data. The Nyquist-corrected DWI data are then processed with reconstruction procedures that take shot-to-shot phase variations into consideration [11–24], to produce images with minimal aliasing artifact. Experimental data have shown that these existing interleaved DWI reconstruction pipelines perform well for non-oblique plane EPI data in well-calibration systems, where 1D Nyquist correction is sufficient. However, as will be shown in this paper, the subsequent correction of Nyquist artifact and minuscule motion induced aliasing artifacts in two stages may actually amplify the artifacts, as a result of the interference between subsequently performed 2D Nyquist phase correction and minuscule motion-induced phase correction, particularly in oblique-plane EPI or when eddy current cross terms are pronounced. To address the above-mentioned challenge, here we report a new composite 2D phase correction procedure, which removes Nyquist artifact and shot-to-shot phase variations in a single step and can robustly produce high-resolution DWI images with minimal artifact even in the presence of pronounced eddy current cross terms.

Theory

A mathematical simulation was first performed to illustrate the limitations of existing interleaved EPI based DWI reconstruction protocols, in which Nyquist artifact correction and shot-to-shot phase correction (performed subsequently in two stages) may interfere with each other and produce additional artifacts. The Shepp-Logan phantom was used as the input to simulate two-shot interleaved-EPI data set in the presence of Nyquist artifact and motion-induced shot-to-shot phase variations. Shot-to-shot phase variations in multi-shot DWI data mainly originate from translational and rotational motion in the presence of strong diffusion sensitizing gradients, and these phase variations can be approximated by zero-order and first-order spatial function [25]. According to the shifting theorem of Fourier transform, the first-order phase variations (i.e., the phase gradient) would result in translation of k-space data points. Figures 1a1 to 1a4 show ideal k-space trajectory (1a1), k-space trajectories distorted only by inconsistent eddy current cross terms between k_y lines corresponding to opposite readout gradient polarities (1a2: mainly along the phase-encoding direction), k-space data trajectories distorted only by minuscule motion-induced shot-to-shot phase variations (1a3: along both readout and phase-encoding directions), and k-space data trajectories distorted by both eddy current cross terms and minuscule motion-induced shot-to-shot phase variations (1a4), respectively. Solid and dashed lines in Figures 1a1 to 1a4 represent k-space data of the first and second shots, respectively. Figures 1b1 to 1b4 show the magnitude images reconstructed from k-space data of Figures 1a1 to 1a4, respectively, with 2D Fourier transform.

In existing interleaved EPI based DWI reconstruction pipelines, the Nyquist artifact and shot-to-shot phase variations induced aliasing artifact are corrected subsequently in two stages. Those existing pipelines generally perform well for non-oblique plane EPI data in well-calibration systems, where 1D Nyquist correction is sufficient. However, when 2D phase correction is needed to remove Nyquist artifact resulting from pronounced cross-term eddy currents, the subsequently applied Nyquist correction and motion-induced aliasing artifact correction may undesirably interfere with each other, leading to amplified artifacts in reconstructed images as shown in Figures 1c1 to 1c3. Figure 1c1 shows the image reconstructed from k-space data of Figure 1a4 with 2D phase correction for Nyquist artifact removal only. Although in theory the Nyquist-corrected image should look like Figure 1b3 (i.e., corrupted by only motion-induced aliasing artifact), the Nyquist corrected image shown in Figure 1c1 is additionally corrupted by horizontal lines. As a result, even after applying shot-to-shot phase correction to Nyquist-corrected EPI data, the produced image (Figure 1c2) is still affected by artifacts due to the interference between two subsequent phase correction steps. This interference can also be observed in the image reconstructed from k-space data of Figure 1a4 with correction for shot-to-shot phase variations only (Figure 1c3). Although in theory the image without shot-to-shot phase variations induced artifact should look like Figure 1b2 (i.e., with only Nyquist artifact), the reconstructed image shown in Figure 1c3 contains additional artifacts. To address this challenge, our new composite 2D phase correction method is designed to effectively eliminate both Nyquist artifact and shot-to-shot phase variations in a single step (Figure 1c4), as described below:

The distorted two-shot k-space trajectory shown in Figure 1a4 can be decomposed into four subsets (Figures 1d1 to 1d4: each contains k_y lines obtained with the same readout gradient polarity from the same EPI shot), and the corresponding images reconstructed with 2D Fourier transform are shown in Figures 1e1 to 1e4. Figures 1f1 to 1f4 show the motion-induced shot-to-shot phase variations that were used to create our simulated EPI data (e.g., Figure 1a4), corresponding to four k-space data subsets shown in Figures 1d1 to 1d4. For example, shot-specific phase terms for the first shot are shown in Figures 1f1 (and equivalently: Figure 1f3), and shot-specific phase terms for the second shot are shown in Figures 1f2 (and equivalently: Figure 1f4). K-space data shown in Figures 1d3 and 1d4 are additionally affected by eddy current cross terms along the phase-encoding direction (i.e., the sources of Nyquist artifact created as the input of our simulation), as shown in Figures 1g3 and 1g4. In actual interleaved EPI based DWI studies, 2D phase maps shown in Figures 1f and 1g need to be either measured from reference scans / navigator echoes or inherently estimated from DWI data [10, 19].

The total phase errors for each k-space subset (Figures 1d1 to 1d4), which are the summation of shot-to-shot phase variations (Figure 1f) and 2D Nyquist phase terms (Figure 1g), will be used to produce aliasing-free images from corrupted k-space data (Figure 1a4 or 1d) with a composite 2D phase correction approach. As shown in Equation 1, signals of four aliased pixels (u_1 , u_2 , u_3 , and u_4) in images reconstructed from four k-space subsets (Figures 1e1 to 1e4) are the function of signals of four unaliased pixels (P_1 , P_2 , P_3 , and P_4 : separated by a quarter of the FOV), 2D Nyquist phase terms (δ_1 , δ_2 , δ_3 , and δ_4), and shot-to-shot phase variations (θ_1 , θ_2 , θ_3 , and θ_4 for first shot; ϕ_1 , ϕ_2 , ϕ_3 , and ϕ_4 for second shot).

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \frac{1}{4} \begin{bmatrix} e^{i\theta_1} & e^{i\theta_2} & e^{i\theta_3} & e^{i\theta_4} \\ e^{i\varphi_1} & e^{i(\frac{\pi}{2}+\varphi_2)} & e^{i(\pi+\varphi_3)} & e^{i(-\frac{\pi}{2}+\varphi_4)} \\ e^{i(\theta_1+\delta_1)} & e^{i(\pi+\theta_2+\delta_2)} & e^{i(\theta_3+\delta_3)} & e^{i(\pi+\theta_4+\delta_4)} \\ e^{i(\varphi_1+\delta_1)} & e^{i(-\frac{\pi}{2}+\varphi_2+\delta_2)} & e^{i(\pi+\varphi_3+\delta_3)} & e^{i(\frac{\pi}{2}+\varphi_4+\delta_4)} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} \quad (1)$$

Based on Equation 1, signals of four unaliased pixels (P_1 , P_2 , P_3 , and P_4) can be reconstructed through matrix inversion, in which Nyquist artifact and shot-to-shot phase variations induced aliasing artifact are simultaneously removed. As shown in Figure 1c4, the image reconstructed with Equation 1 is free from residual aliasing artifact.

We would like to point out that signals of four unaliased pixels in Equation 1 can be calculated only when the full-FOV phase error information from multiple sources are jointly used in a matrix-inversion based reconstruction (e.g., Figure 1c4). The main reason for the failure of sequential phase correction (e.g., Figure 1c2) is that the partially phase-corrected images (e.g., Figure 1c1) have significant residual artifacts with a spatial-overlapping pattern corresponding to a reduced FOV (e.g., 25% of FOV for 4-shot DWI), which cannot be further removed with a full-FOV phase error map due to inconsistent FOV definition.

The composite 2D phase correction procedure described above (for two-shot interleaved-EPI data obtained with a single-channel RF coil) can be integrated with our recently multiplexed sensitivity encoded (MUSE) reconstruction algorithm [19] to reconstruct N -shot interleaved

DWI data obtained with multi-channel phased array coils, as summarized below. First, both 1D and 2D Nyquist correction parameters are estimated either from reference scans or reference-less phase cycled reconstruction of baseline T2-weighted interleaved-EPI [10]. Second, 1D Nyquist correction is applied to interleaved EPI based DWI data to minimize phase errors along the readout direction. Third, 1D Nyquist-corrected interleaved DWI data are then processed with a composite 2D phase correction algorithm, comprising four steps: 1) Images free from motion-induced aliasing artifacts are estimated from each segment using either the conventional sensitivity encoding (SENSE) algorithm [26]. 2) Shot-to-shot phase variations are calculated from images produced in step 1 (with some undesirable noise amplification associated with SENSE reconstruction) and then spatially smoothed (to suppress noises). Alternatively, shot-to-shot phase variations can also be estimated from navigator echoes. 3) The odd and even echoes from each of N -shot EPI segments are further decomposed to $2N$ -shot EPI subsets as shown in Figure 2 (with subset #1 to N corresponding to the positive readout gradient polarity, and # $N+1$ to $2N$ corresponding to the negative readout gradient polarity; also see Figure 1d for the case of $N=2$). 4) All the subsets of interleaved EPI data (step 3), the known coil sensitivity profiles, shot-to-shot phase variation information (step 2), and 2D Nyquist correction parameters are all incorporated into a mathematical framework that jointly solves the unknown magnitude source signals (based on Equation 2) to produce a set of images without Nyquist ghost and motion-induced aliasing artifacts. Note that the magnitude source images reconstructed in step 4 are free from undesirable noise amplification associated with SENSE reconstruction, as described previously [19, 27].

$$\begin{bmatrix} u_1^w \\ u_2^w \\ \vdots \\ u_N^w \\ u_{N+1}^w \\ u_{N+2}^w \\ \vdots \\ u_{2N}^w \end{bmatrix} = \frac{1}{2N} \begin{bmatrix} S_1^w e^{i\frac{2\pi}{2N} \cdot 0 \cdot 0} & S_2^w e^{i\frac{2\pi}{2N} \cdot 0 \cdot 1} & \dots & S_{2N}^w e^{i\frac{2\pi}{2N} \cdot 0 \cdot (2N-1)} \\ S_1^w e^{i\frac{2\pi}{2N} \cdot 1 \cdot 0} e^{i\Theta_1^2} & S_2^w e^{i\frac{2\pi}{2N} \cdot 1 \cdot 1} e^{i\Theta_2^2} & \dots & S_{2N}^w e^{i\frac{2\pi}{2N} \cdot 1 \cdot (2N-1)} e^{i\Theta_{2N}^2} \\ \vdots & \vdots & \ddots & \vdots \\ S_1^w e^{i\frac{2\pi}{2N} \cdot (2N-1) \cdot 0} e^{i\Theta_1^N} & S_2^w e^{i\frac{2\pi}{2N} \cdot (2N-1) \cdot 1} e^{i\Theta_2^N} & \dots & S_{2N}^w e^{i\frac{2\pi}{2N} \cdot (2N-1) \cdot (2N-1)} e^{i\Theta_{2N}^N} \\ S_1^w e^{i\frac{2\pi}{2N} \cdot 0 \cdot 0} e^{i\varphi_1} & S_2^w e^{i\frac{2\pi}{2N} \cdot 0 \cdot 1} e^{i\varphi_2} & \dots & S_{2N}^w e^{i\frac{2\pi}{2N} \cdot 0 \cdot (2N-1)} e^{i\varphi_{2N}} \\ S_1^w e^{i\frac{2\pi}{2N} \cdot 1 \cdot 0} e^{i\Theta_1^2} e^{i\varphi_1} & S_2^w e^{i\frac{2\pi}{2N} \cdot 1 \cdot 1} e^{i\Theta_2^2} e^{i\varphi_2} & \dots & S_{2N}^w e^{i\frac{2\pi}{2N} \cdot 1 \cdot (N-1)} e^{i\Theta_{2N}^2} e^{i\varphi_{2N}} \\ \vdots & \vdots & \ddots & \vdots \\ S_1^w e^{i\frac{2\pi}{2N} \cdot (2N-1) \cdot 0} e^{i\Theta_1^N} e^{i\varphi_1} & S_2^w e^{i\frac{2\pi}{2N} \cdot (2N-1) \cdot 1} e^{i\Theta_2^N} e^{i\varphi_2} & \dots & S_{2N}^w e^{i\frac{2\pi}{2N} \cdot (2N-1) \cdot (2N-1)} e^{i\Theta_{2N}^N} e^{i\varphi_{2N}} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_N \\ p_{N+1} \\ p_{N+2} \\ \vdots \\ p_{2N} \end{bmatrix} \quad (2)$$

where u_k^w represents the aliased image-domain signal (i.e., from a certain voxel in reduced-FOV image) of the k -th EPI segment ($k=1,2,\dots,2N$; with N is the total number of acquired EPI segments) measured with coil number w ($w=1,2,\dots,W$; with W is the total coil number);

p_n represents unaliased full-FOV image signal at location n ($n=1\dots2N$; separated by $\frac{FOV_y}{2N}$ along the phase-encoding direction); S_n^w represents the known coil sensitivity profile for coil number w ($w=1,2,\dots,W$; with W is the total coil number) at location n ; Θ_n^k represents the shot-specific phase values at location n for the k -th and $(k+N)$ -th EPI subset; $e^{j\phi_n}$ represents the 2D Nyquist phase error at location n .

Methods

Interleaved EPI based human brain DWI data ($b=0$ and $b=800$ s/mm²) were acquired from two healthy subjects on a 3 Tesla MRI scanner (General Electric, Waukesha, WI) using an 8-channel phased-array head coil. Multiple sets of images were acquired with four different scan protocols: 1) 4-shot interleaved EPI based DWI in sagittal plane, 2) 4-shot interleaved EPI based DWI in (pseudo-axial) oblique plane, 3) 8-shot interleaved EPI based DWI in (pseudo-axial) oblique plane, and 4) 16-shot interleaved EPI based DWI in (pseudo-axial) oblique plane. Phase correction parameters required for Nyquist artifact removal were calculated from T2-weighted baseline EPI data set using our previously reported phase-cycled reconstruction method [10]. Motion-induced shot-to-shot phase variations were estimated from SENSE produced images in 4-shot DWI scans, and were measured from embedded navigator echoes in 8-shot and 16-shot DWI scans. Imaging parameters included: in-plane matrix size = 256×256 , in-plane matrix size of navigator echoes = 256×96 (for 8-shot and 16-shot EPI protocols), partial Fourier factor = 60% (for imaging echo) and 67% (for navigator echoes in 8-shot and 16-shot EPI protocols), FOV = 25.6×25.6 cm², slice thickness = 4mm, TR = 5000ms, TE = 64.7ms (for 4-shot EPI protocols) or 51.6ms (for 8-shot and 16-shot EPI protocols), and number of diffusion directions = 15 (for 4-shot EPI protocols) or 3 (for 8-shot and 16-shot EPI protocols). The acquired data were processed 1) the new composite 2D MUSE phase correction approach and 2) the conventional two-stage correction approach (i.e., 2D Nyquist correction prior to MUSE reconstruction), and the reconstructed images were then compared. Additionally, the developed composite 2D MUSE phase correction approach was used to reconstruct two-shot interleaved EPI based DWI data (in sagittal plane) obtained from 60 participants.

Results

Figures 3a and 3b show T2-weighted (pseudo-axial) oblique-plane interleaved EPI images (i.e., free from aliasing artifact due to shot-to-shot phase variations) reconstructed with 1D and 2D Nyquist correction, respectively. The same images shown in Figures 3a and 3b are displayed in Figures 3c and 3d with a different scale, so that residual Nyquist artifact can be more easily visualized. It can be seen that, because of eddy current cross terms in oblique-plane EPI, the residual artifact is pronounced even after 1D Nyquist correction (Figures 3a and 3c). The Nyquist artifact in 4-shot, 8-shot and 16-shot oblique-plane EPI can be effectively removed only with 2D Nyquist correction (Figures 3b and 3d). Figure 3e shows

interleaved EPI based DWI images produced with conventional reconstruction pipelines that remove 2D Nyquist phase errors and motion-induced shot-to-shot phase variations subsequently in two stages. In agreement with our mathematical simulation (Figure 1), the residual artifact is pronounced in EPI images produced with the conventional two-stage phase correction pipelines. Figure 3f shows that Nyquist artifact and motion-induced aliasing artifact can be effectively removed in 4-shot, 8-shot and 16-shot DWI data using our new composite 2D phase correction method.

Figure 4 compares sagittal-plane 4-shot interleaved DWI images reconstructed with the conventional two-stage artifact correction approach (Figure 4a) and the new composite 2D phase correction method (Figure 4b). It can be seen the residual artifact (indicated by arrows) associated with two-stage artifact removal can be greatly removed using the new composite phase correction technique.

Overall, we found that the developed composite 2D phase correction technique can reliably and effectively remove aliasing artifacts in interleaved EPI based DWI data, when the subjects remained still during DWI scans.

Discussion

The new composite phase correction method can simultaneously eliminate Nyquist artifact and motion-related aliasing artifacts in interleaved EPI based DWI data. The developed method is particularly useful for oblique plane and sagittal plane EPI acquisition, for which 1D Nyquist correction is insufficient due to more significant eddy current cross terms. Our experimental data also demonstrate that the developed method is compatible with interleaved DWI of different segment numbers (e.g., 4, 8 and 16 in our studies), and is effective for interleaved DWI data with and without navigator echoes.

In our study the effectiveness of the new method that integrates MUSE reconstruction and Nyquist phase correction is demonstrated only with multi-slice interleaved EPI based DWI data. We would like to point out that, as shown in recent papers [20, 28], it is straightforward to extend the MUSE algorithm (originally designed to remove in-plane aliasing artifacts) to multi-band MUSE, removing both in-plane and through-plane aliasing artifacts in multi-band (i.e., simultaneous multi-slice) interleaved DWI data. Therefore, we expect that it is feasible to implement a composite 2D multi-band phase correction procedure, which integrates 2D Nyquist phase correction and multi-band MUSE algorithm, to simultaneously remove 1) Nyquist artifact, 2) in-plane minuscule motion-induced aliasing artifact and 3) through-plane aliasing artifact in multi-band interleaved EPI based DWI data.

In this paper we only investigate the in-plane aliasing artifact originating from minuscule motion induced shot-to-shot variations in interleaved DWI scans. As shown in recent studies [29, 30], large-scale intra-scan motion (e.g., > 1 voxel) would also result in significant aliasing artifact in interleaved EPI based DWI scans. The large-scale motion artifacts in interleaved DWI need to be reduced either with prospective motion correction [29] or using a reconstruction procedure that takes large-scale motion into consideration [30]. We expect that our new composite 2D phase correction procedure can be further generalized to be

compatible with approaches that are designed to remove large-scale motion artifacts in interleaved DWI data [29, 30]. The second limitation of our 2D phase correction procedure is the lack of considering intra-slice phase variation. In most cases, the intra-slice phase variation is insignificant and thus a 2D phase correction can effectively remove artifacts due to motion-induced shot-to-shot phase variation. However, DWI data with increased slice thickness and b -value may potentially be affected by artifacts due to intra-slice phase variation, which may require a 3D phase correction. Additionally, in our current implementation we have not considered the fact that 2D Nyquist phase terms may potentially change due to gradient coil heating during lengthy acquisition period [7, 31], although in our data we found that the Nyquist artifacts were largely consistent across T2-weighted EPI and DWI data for each individual subject.

The majority of the current human DWI studies are conducted with phased-array coils. Therefore, in our study the composite 2D phase correction procedure is integrated with the MUSE method (see Equation 2) to reconstruct DWI data obtained with phased-array coils. For interleaved EPI based DWI data obtained single-channel RF coils, the 2D composite phase correction should be implemented based on Equation 1.

We would like to point out that interleaved EPI is only one of the many pulse sequences that could be used to acquire high-resolution DWI data. It has been shown in recent studies that high-resolution DWI can also be achieved with interleaved spiral imaging [23, 27, 32–35], PROPELLER [36, 37], PROPELLER-EPI [14, 15], readout-segmented EPI [17, 38, 39], steady-state free precession (SSFP) imaging [40], and radial fast spin-echo imaging [41].

In conclusion, both Nyquist artifact and minuscule motion-induced aliasing artifact can be effectively removed from interleaved EPI based DWI data using the new composite 2D phase correction procedure, even in the presence of pronounced eddy current cross terms. The developed method should prove highly valuable for clinical DWI and neuroscience studies that require high spatial-resolution.

Acknowledgments

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Figure 1.

a1 to 1a4 show ideal two-shot EPI k-space data (a1), k-space data distorted only by inconsistency due to opposite readout gradient polarities (i.e., the source of Nyquist artifact: a2), k-space data distorted only by minuscule motion-induced shot-to-shot phase variations (a3), and k-space data distorted by both Nyquist phase errors and minuscule motion-induced shot-to-shot phase variations (a4). Solid and dashed lines represent k-space data of the first and second shots, respectively. b1 to b4 show the magnitude images reconstructed from k-space data of a1 to a4, respectively, with 2D Fourier transform. c1 shows the image reconstructed from k-space data of a4 with 2D phase correction for Nyquist artifact removal only. c2 shows the image reconstructed from k-space data of a4 with subsequent correction of Nyquist artifact and shot-to-shot phase variations. c3 shows the image reconstructed from k-space data of a4 with correction of only shot-to-shot phase variations. c4 shows the image reconstructed from k-space data of a4 with the new composite 2D phase correction procedure. d1 to d4 show four subsets of k-space data of the distorted two-shot k-space data shown in a4, and the corresponding images reconstructed with 2D Fourier transform are shown in e1 to e4, respectively. f1 to f4 show the motion-induced shot-to-shot phase variations corresponding to each of the four k-space subsets. g1 to g4 show the phase inconsistencies between k-space data of opposite readout gradient polarities, for each of the four k-space subsets, using the first subset as phase reference. Values of phase errors are indicated with a circular colormap.

Figure 2.

(a) k-space trajectory of N -shot interleaved EPI. (b) The odd and even echoes from each of N -shot EPI segments are further decomposed to $2N$ k-space subsets (with subset #1 to N corresponding to the positive readout gradient polarity, and $\#(N+1)$ to $2N$ corresponding to the negative readout gradient polarity)

Figure 3.

(a) shows T2-weighted (pseudo-axial) oblique-plane interleaved EPI images reconstructed with 1D Nyquist correction. (b) shows T2-weighted oblique-plane interleaved EPI images reconstructed with 2D Nyquist correction. (c) shows the same images as in (a) but with a different display scale. (d) shows the same images as in (b) but with a different display scale. (e) shows interleaved EPI based DWI images produced with conventional reconstruction pipelines that remove 2D Nyquist phase errors and motion-induced shot-to-shot phase variations subsequently in two stages. (f) shows images reconstructed with the new composite 2D phase correction method.

Figure 4.

(a) shows a sagittal-plane 4-shot interleaved DWI image reconstructed with the conventional two-stage artifact correction approach. (b) shows the image reconstructed from the new composite 2D phase correction technique.