Ghost and Distortion Correction in DW-EPI using Phase Labeling Approach

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Introduction: Diffusion weighted (DW) images are usually acquired with EPI sequence, thus prone to Nyquist ghost and geometric distortion. In DW-EPI images, the geometric distortion is caused by not only the field inhomogeneities, but also eddy currents that vary with the magnitude and direction of the diffusion sensitizing gradient. Geometric distortion could cause misalignment of images acquired with different diffusion strengths and orientations, resulting errors in post-processing operations such as apparent diffusion coefficient (ADC) and diffusion tensor calculation [1]. Numerous methods have been proposed to correct the EPI ghost and distortion artifacts, but very few could deal with them simultaneously. In this study, we applied a new phase labeling scheme we recently proposed [2] to simultaneously correct both Nyquist ghost and geometric distortion artifacts in DWI images.

Methods: ***Theory*** Fig. 1 illustrates the basic data acquisition and reconstruction flow chart of our proposed phase labeling method that entails two EPI shots [2]. In the second repetition, an area equal to one phase encoding blip is subtracted from pre-phase of phase encoding gradient to shift the acquired k-space down by one Δk_y. Thus the k-space in consecutive acquisition, *k(t-1)* and *k(t)*, are sampled in opposite readout direction. Their combination can eliminate phase errors from readout direction alternation in EPI, resulting in a Nyquist ghost free image for GRAPPA calibration. Then positive echo image *Ip(t)* and negative echo *In(t)* are reconstructed by GRAPPA, respectively [3]. Note that positive echoes in adjacent time frame, i.e., *Ip(t)* and *Ip(t-1)*, are acquired with a shift in *k*-space as the phase label. After applying a linear phase to one of them to eliminate phase ramp caused by *k*-space shift, a phase shift map Δφ between two images is calculated, which contains the phase error induced by both field inhomogeneities and eddy currents. Then the geometric distortion in *Ip(t)* can be corrected by modulating the k-space data as described in reference [4]. After distortion correction, the images from positive echo *Ip(t)* and negative echo *In(t)* are combined to generate the final corrected image *I(t).* ***Data acquisition and analysis*** All experiments were performed on a 7T horizontal-bore Bruker MRI scanner with a 4-channel surface coil. Prior to single-shot GE-EPI acquisition with the modified sequence, global shimming was performed. The image acquisition parameters were: TE/TR = 50/4000ms, readout bandwidth = 400kHz, matrix size = 128×128, FOV = 3mm^2, NA = 1, NEX = 10, and 5 slices with thickness = 2mm. The diffusion gradient was applied in X (readout), Y (phase encoding) or Z (slice) direction with b-value = 500s/mm^2. T2 weighted images were acquired using RARE sequence with TE/TR = 32/1500ms, matrix size = 256×256, the edge of T2W image was extracted and overlaid to DW-EPI image to visualize image distortion. Ghost level was quantitatively evaluated by comparing ghost-to-signal ratios (GSR), which was the ratio of integral image intensities within the manually selected region of interest (ROI) covering the ghost and the object.

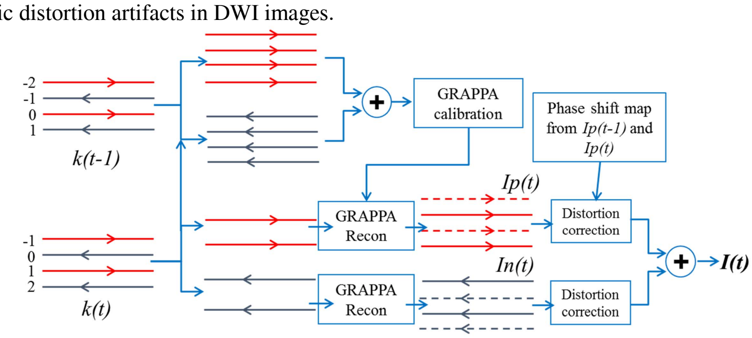

Fig. 1 Data acquisition and reconstruction flow chart.

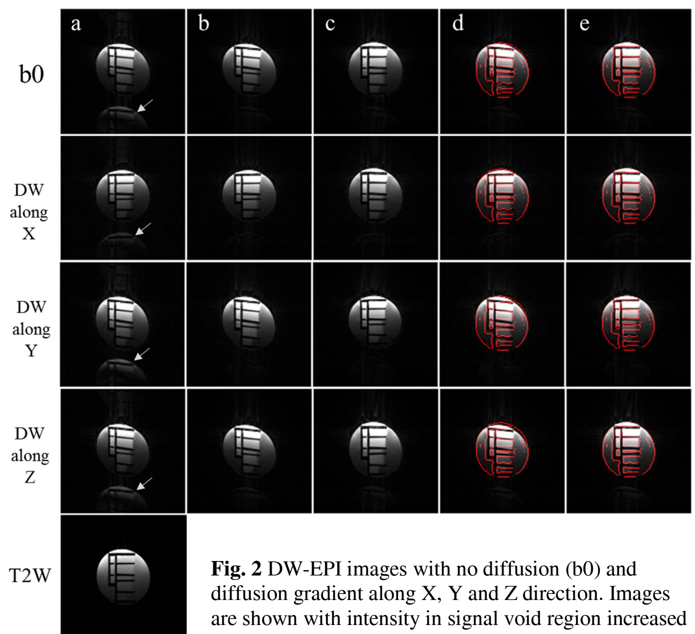

Fig. 2 DW-EPI images with no diffusion (b0) and diffusion gradient along X, Y and Z direction. Images are shown with intensity in signal void region increased by 10 times. (**a**) DW-EPI images after Nyquist ghost correction by reference scan. (**b**) Images after Nyquist ghost correction by the proposed method. (**c**) Images after Nyquist ghost and geometric distortion correction by the proposed method. (**d**) Images in (b) overlaid with edges extracted from T2W images. (**e**) Images in (c) overlaid with the edges. T2W image is also shown.

Results: Fig. 2 shows the phantom images acquired without diffusion and with diffusion gradient along X, Y or Z directions, respectively. The Nyquist ghost was visible in images corrected by linear phase error correction using the reference scan method [5] (Fig. 2a) with GSR equal to 4.13%. However, it was completely removed by the proposed method (Fig. 2b) with GSR reduced to 1.54%. The ghost corrected X Y and Z DW images were distorted differently compared with b0 image in the form of shearing, scaling and shifting along the phase encoding direction, respectively. After the distortion correction, these DW images were well aligned with edge extracted from T2W images (Fig. 2e). The ADC maps calculated from X DW images with 8 b-values ranging from 0 to 500s/mm^2 are shown in Fig. 3. The ADC map generated from distortion corrected images (Fig. 3a) yielded much better quality with clear boundary and correct geometry, when compared with that from uncorrected images (Fig. 3b).

Discussion and Conclusion: The proposed approach can effectively remove Nyquist ghost and geometric distortion in DW-EPI simultaneously. The phase shift maps are generated dynamically from images reconstructed using positive or negative echoes from two EPI shots, and contain phase error from both main field inhomogeneities and eddy currents. Thus this method has the ability to correct geometric distortion from both sourses. The distortion correction is carried out by modulating the frequencies in the k-space instead of performing a spatial domain shift. After Fourier transform, not only the voxel location is restored but also its intensity is corrected. The proposed method does not need any additional scan or experiment to model phase error of readout direction alternation, main field inhomogeneities or eddy currets, thus it is still efficient in DW-EPI acquisitions. Though two EPI shots are needed in this approach, two resulting images could be combined to increase the image SNR by averaging which is common in DW imaging applications. In conclusion, we have proposed a method that can effectively remove both Nyquist ghost and geometric distortion in the DW-EPI images through a phase labeling acquisition and post-processing.

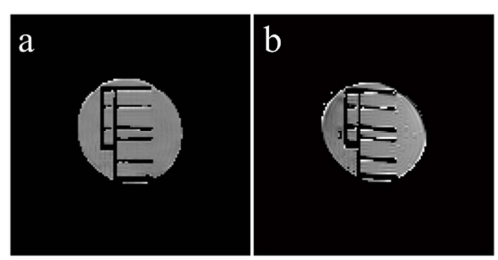

Fig. 3 ADC map generated from DW images with (**a**) and without (**b**) distortion correction.

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