Retrospective, reference-less ghosting correction in PROPELLER EPI

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Introduction: Propeller EPI [1] is a multi-shot EPI technique with built-in phase- and motion-correction, and is used for such applications as motion-corrected imaging, and multi-shot diffusion-weighted imaging. However, anisotropic gradient time delays cause 2D phase errors for "oblique" blades that are not aligned with the physical gradient axes, resulting in ghosting that cannot be removed using conventional 1D correction schemes. The conventional approach to 2D phase correction is to measure the time-delays using calibration scans obtained prior to image acquisition, and inserting compensatory gradient "blips" into the pulse sequence itself [2]. We propose an alternative approach to 2D phase correction that uses only the acquired image data itself, and relies on estimating the on-axis delays, and performing interlaced sampling reconstruction along the phase-encode direction for each blade. The proposed correction technique is performed retrospectively, and does not require reprogramming the pulse sequence or obtaining additional reference scans.

Methods: PROPELLER EPI data was obtained in a uniform water-filled ball phantom (2.1x2.1x5 mm^3 voxel size; FOV 25 cm; 20 phase-encode (PE) lines per blade) and in the brain of a healthy volunteer (1.5x1.5x5 mm^3 voxel size; FOV 24 cm; 20 PE lines per blade), on a GE Signa 3T scanner (gradients capable of 4 G/cm amplitude and 15 G/cm/ms slew rate). Image reconstruction was performed in Matlab, and consists of four steps: First, the physical gradient delays Dx and Dy are calculated from the blades with readout direction oriented along the physical X and Y gradient axes, respectively (see Fig. 1), by reconstructing the "odd" and "even" phase-encode lines separately, and comparing the image phase in the narrow un-aliased strip near the center of the (aliased) images. Second, odd/even k-space shifts Dkr and Dkp along the readout and phase-encode directions, respectively, are calculated for each blade using Eqs. (10-11) from Ref. [2]. Third, the raw k-space data for each blade is sinc-interpolated along the readout direction, which brings all phase-encode lines into alignment along the readout direction. Finally, to correct for k-space shifts Dkp along the phase-encode direction, the raw k-space data is interpolated onto a regular Cartesian grid using interlaced sampling theory [3]. Following these reconstruction steps, the (corrected) raw data was gridded onto a regular Cartesian grid, and inverse Fourier transformed to obtain the final image. For comparison, images were also reconstructed directly from the acquired data (i.e. using no correction), and after omitting the interlaced sampling step (i.e. using 1D correction along the readout direction only).

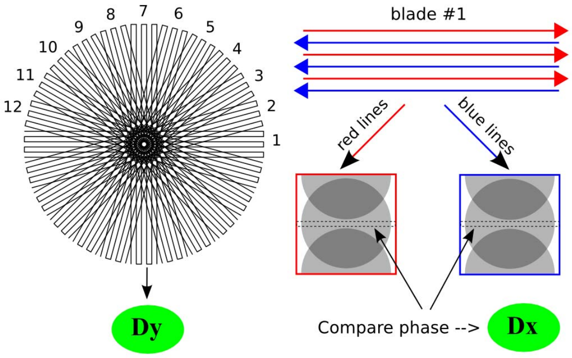

Fig. 1. The gradient delays Dx and Dy along the physical X and Y gradient axis, respectively, are calculated directly from the acquired propeller EPI data, using the blades with the readout direction oriented along the physical X and Y gradient axis, respectively.

Results: Fig. 2 shows low-resolution images of the ball phantom reconstructed from the blade oriented at 0 (top row) and 60 (bottom row) degrees. 1D correction performs well for the on-axis scan, but fails to remove the ghosting pointed to by the arrows in the oblique scan. Fig. 3 shows an in-vivo brain scan (axial slice) using all the acquired blades, obtained after performing 1D correction (left) or 2D (right) correction.

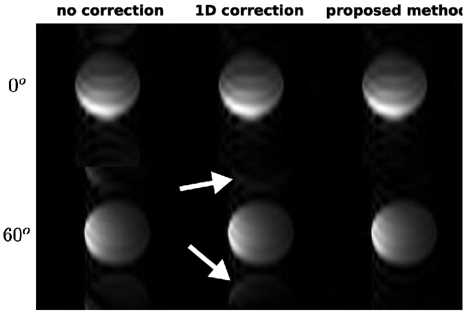

Fig. 2: Low-resolution images reconstructed from individual blades oriented at 0 (top row) and 60 (bottom row) degrees. Shown are images without any correction (left), with 1D correction only (middle), and using the proposed 2D correction method (right).

Discussion: The "weak link" in the proposed method is the interlaced sampling reconstruction step, which will fail if Dkp is sufficiently large to cause odd and even PE lines to overlap. However, this scenario is unlikely on modern scanners with less than 4 microsecond relative gradient time delays. Nevertheless, interlaced sampling reconstruction does come with an SNR penalty compared to prospective EPI ghosting correction [3], which increases with increasing Dkp. In addition, although ghosting suppression appears to be quite robust with data acquired on our scanner, the interlaced sampling reconstruction step can introduce a signal discontinuity at the center of the image. Finally, we note that it is possible to include multiple off-axis blades when estimating Dx and Dy, by measuring Dkr for each blade, and fitting these measurements to Eq. (10) from Ref. [2].

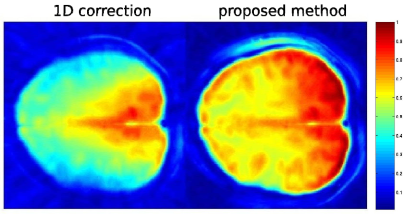

Fig. 3: Image after gridding, using (left) 1D ghosting correction, and (right) the proposed method. The color scale was chosen to highlight the differences between the images.

Conclusion: The proposed method allows retrospective 2D ghosting correction in PROPELLER EPI, without the need for additional reference scans.

[1] Wang et al, MRM 2005; **54**: 1232 [2] Reeder et al, MRM 1999; **41**: 87
[3] Bracewell RN, "The Fourier Transform and Its Applications". McGraw Hill, 1986.