PROPELLER-EPI improved by 2D phase cycled reconstruction

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Introduction: The PROPELLER-EPI (periodically rotated overlapping parallel lines with enhanced reconstruction using EPI as signal readout) has been shown useful for diffusion applications with reduced geometric distortion [1]. PROPELLER-EPI consists of EPI signal readout with alternating gradient polarities, where the phase inconsistencies between odd and even echoes generate oblique N/2 ghost artifact [2] in each rotating blade. A double-FOV reference image can be used for 2D linear phase correction with interlaced Fourier transform (FT) for oblique ghost reduction prior to PROPELLER-EPI reconstruction [3], which however lengthens the acquisitions substantially because the reference scan needs to be performed for every blade. A 2D phase-cycled reconstruction for inherent correction of N/2 ghost without any extra reference scan has been reported recently [4], with only minor pitfalls in low-signal regions. For PROPELLER-EPI, the small matrix size along the phase-encoding direction further entails modifications of the 2D phase-cycled reconstruction method. In this work, therefore, we integrate an improved version of the 2D phase-cycled reconstruction and PROPELLER-EPI, and compare the result to that reconstructed using the more time-consuming 2D reference-based method.

Materials and methods: The 2D phase-cycled reconstruction is an image-domain processing method, which generates a series of corrected images from original data by assuming different 2D phase errors, and then selects the correction result with lowest artifact based on background energy sorted in decreasing order [4]. In its original implementation, the background is defined solely using sigmoid-weighted signals without prior knowledge of object location or shape. Thus the algorithm may fail during the sorting operation in places where the object contains signal-free regions along the phase-encoding direction. In addition, the number of pixels along the phase-encoding direction in each blade image of PROPELLER-EPI is often too small to ensure reliable sorting, leading to signal discontinuity (arrows in Fig.1a). To address both issues, in our study the 2D phase cycled reconstruction was applied to interpolated blade image with Fermi-filtering to increase the matrix size while without introducing Gibbs ringing (Fig.1b), and a mask operation was used instead of the sorting operation to identify the background region. A mask of object shape (object mask) was first produced via PROPELLER reconstruction using only odd echoes of all rotating blades (Figs.2a-2b). The mask generation was straightforward because the ghost energy was spread to different directions with PROPELLER reconstruction (Fig.2a). In this manner a ghost mask could be obtained for each blade by subtracting the object mask with proper rotation (Figs.2c-2d), which was then to identify the background region for 2D phase-cycled reconstruction. Experimental phantom images to demonstrate our method were acquired at 1.5T (Signa HDxt, GE) with FOV 17x17cm, blade size 32*128 (ETL=32), rotating angle 15°, NEX 1, TE 76.8ms, TR 4000ms, 5mm slices without gap, and 12 blades for 180° k-space coverage. Scan time was 48s. The double-FOV reference scans were also acquired for all blades (which took an additional 48s to acquire) for purpose of comparison with reference-based correction.

Results: The single blade images without N/2 ghost correction (Fig.3a), with 2D phase-cycled reconstruction using background energy sorting (Fig.3b), and with 2D phase-cycled reconstruction using ghost masking (Fig.3c) are shown for an object having prominent signal-free regions. Ghost masking was seen to yield much less residual N/2 ghost (arrows). The PROPELLER-EPI reconstructed full-resolution images with reference-based 2D linear phase correction using interlaced FT and reference-free 2D phase-cycled reconstruction using ghost masking are shown in Figs.4a and 4b, respectively, showing comparable quality but twice difference in total scan time.

Discussion & Conclusion: The key improvement proposed in this study for 2D phase-cycled reconstruction is the replacement of energy sorting by ghost masking to identify the background region, making use of the property that the N/2 ghosts in PROPELLER reconstructed images, even before N/2 ghost correction, are spread to different directions with diluted intensities. The interpolation of the low-resolution blade image from 32 to 128 with Fermi-filtering also helped reducing the difficulty in generating the ghost mask, although at the expense of longer processing time. These improvements facilitated successful application of PROPELLER-EPI to objects with substantial portions of signal-free regions. Even for signal-free regions where the ghost mask also showed no signals (yellow arrow in Fig.2d), the correction can still be performed by interpolation between adjacent phase-encoding-lines because the EPI phase error is a spatially continuous function along two dimensions (bottom arrow in Fig.3c). Experimental results show that the final full-resolution PROPELLER-EPI image obtained from 2D phase-cycled reconstruction has comparable quality compared to that reconstructed with 2D reference scan correction method. Our proposed method eliminates the extra acquisition time required for reference scan, which is proportional to number of blades (reference scan time = blades x TR). Our method also eliminates potential error amplification in the 2D reference scan approach resulting from subject movement between reference scan and actual scan. In conclusion, the 2D phase-cycled reconstruction is particularly suitable for correcting oblique ghost in PROPELLER-EPI without any need of extra reference scan, and thus may broaden the clinical use of the PROPELLER-EPI technique.

References: [1] Wang FN, et al, MRM, 54:1232 (2005). [2] Bruder H, et al, MRM, 21:311 (1992). [3] Chang HC, et al, ISMRM 2011 #4612. [4] Chen NK, et al, MRM, 66:1057 (2011)

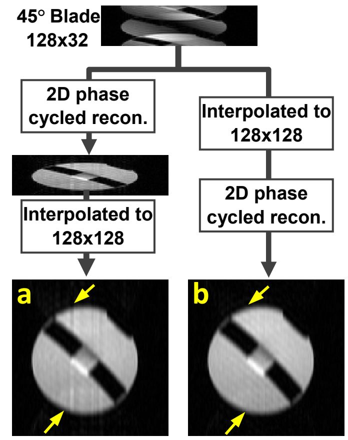

Fig.1 A low-resolution single blade image (45° rotating angle) with 2D phase-cycled reconstruction (a) before and (b) after interpolation.

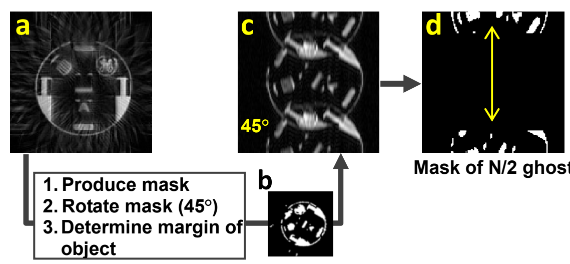

Fig.2 PROPELLER image reconstructed by odd-echo sampling of all blades (a) can produce an object mask (b). A low-resolution single blade image (c) and its corresponding ghost mask (d) produced by comparing the edges of object along phase-encoding direction with the object mask with proper rotation.

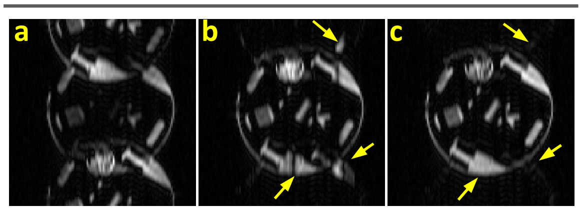

Fig.3 A low-resolution single blade image with substantial signal-free regions without correction (a), with 2D phase-cycled reconstruction using background energy sorting criterion (b), and that with ghost mask energy criterion (c).

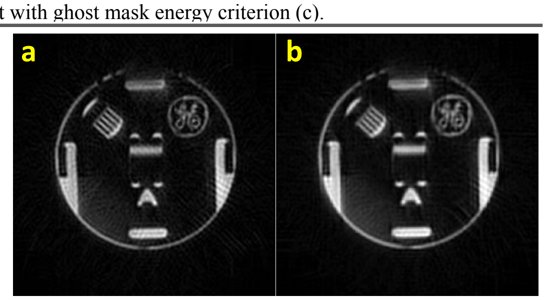

Fig.4 PROPELLER-EPI image reconstructed from blades with 2D reference correction method (a) and reference-free 2D phase-cycled reconstruction (b).