IMAGE ENTROPY-BASED PHASE CORRECTION FOR CLOSELY-SPACED SLICES IN SIMULTANEOUS MULTI-SLICE IMAGING

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Target audience. Researchers interested in fast MRI and artifacts in multiband imaging.

Purpose. Blipped CAIPI acquisitions [1] reduce g-factor noise amplification in simultaneous multi-slice (SMS) experiments by introducing inter-slice image shifts using through-plane (k_z) phase encoding gradients between readout lines during the image readout. For closely-spaced slices (e.g. in cardiac imaging), large G_z blips during the readout can lead to image ghosting due to inconsistencies (e.g. from eddy currents) between gradient waveforms of opposite polarity. The resulting N-fold image ghosts (where N is the SMS factor) overlap with the desired multiband aliasing pattern. In this abstract, we introduce a simple deconvolution model and novel image entropy-based approach to correcting phase errors in a SMS scan.

Methods. Theory. We model the phase error in a blipped CAIPI (single-shot EPI) readout as mainly arising from the largest G_z blip. For a FOV/3 image shift, the phase error that accumulates across k-space in the phase encode direction can be modeled as a staircase function with period 3 (Fig. 1). We step through the full range of phase errors as a function of the step size, and measure the image entropy of the resulting sum-of-squares image. This is a one-parameter model and the phase step corresponding to the corrected image (i.e. minimum entropy) is obtained by fitting the entropy values to a sine curve. This phase correction is repeated for each slice using the single-slice reference data, the results are averaged, and the average phase correction is applied to all acquired datasets.

Data acquisition. Six healthy male volunteers were scanned (ages 28-45 years old). Studies were approved by the local institutional ethics committee. A breath-held cardiac-gated single-shot EPI STEAM sequence [2] was modified to include CAIPI blips (Siemens 3T Trio). Three short axis images (double oblique) were obtained with FOV/3 inter-slice shift (TE/TR 13 ms/2 RRs, matrix 128x42, partial Fourier factor 5/8, FOV 360x180 mm^2, slice thk 8 mm / gap 20 mm, phase-encode slab thk 120 mm, in-plane res. 2.8x2.8 mm^2, EPI BW 2448 Hz/pixel). The 3 slice acquisition consisted of two heartbeats (HBs) for Nyquist ghost (N/2) EPI phase correction and two HBs for a b=20 s/mm^2 image, for a total of 12 HBs.

Results. Fig. 2 shows apical short axis images reconstructed with different phase step sizes. The image ghost is minimized between 60° and 90°. Fig. 3 shows automatic identification of this phase step, and removing the phase modulation from the k-space data removes the image ghost.

Discussion. Robust phase correction is required to obtain accurate image reconstruction of echo-planar SMS data. Blipped CAIPI phase error can be modeled using a phase staircase function, which convolves the true image with the ghost PSF (Fig. 1b). Furthermore, the periodic symmetry of the Fourier transform is broken by this phase modulation, which leads to blurring when uncorrected. A novel image entropy-based approach robustly removes this image ghost. Image entropy has previously been proposed as an image metric for Nyquist ghost (N/2) removal [3], and minimizing this metric focuses the image energy into a single region. The black-blood diffusion-weighted images with reduced (in-plane) FOV are especially suited to this approach because there are large regions in the image with no signal. The main advantage of this approach is that a separate phase-encoded reference is not required. The method can also be used for retrospective correction of existing data.

Conclusion. A novel image entropy-based approach to correcting phase errors in a blipped CAIPI SMS scan was presented that does not require an additional reference scan. We anticipate that this phase correction method will enable multiband accelerated scans of the heart for closely spaced simultaneously excited slices.

References. [1] Setsompop K et al., MRM 2012;67(5):1210-1224. [2] Edelman RR et al., MRM 1994;32(3):423-428. [3] Clare S et al., ISMRM 2003:1041.

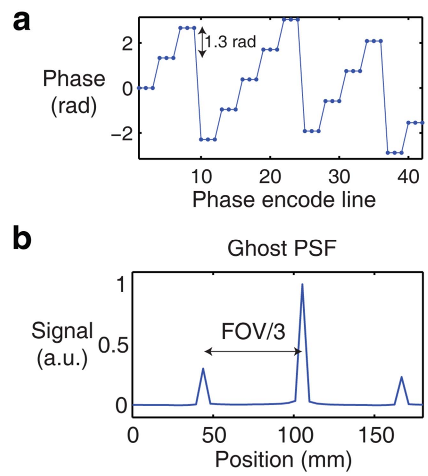

Fig. 1. Model for phase error due to large G_z blips in blipped CAIPI. (a) A phase staircase modulates the acquired k-space data across the phase encode direction. (b) Corresponding magnitude point spread function with three-fold ghosting.

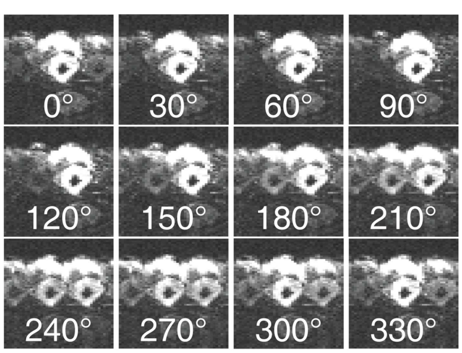

Figure 2. Images reconstructed with different phase step sizes. The 3-fold image ghost is minimized between 60° and 90°.

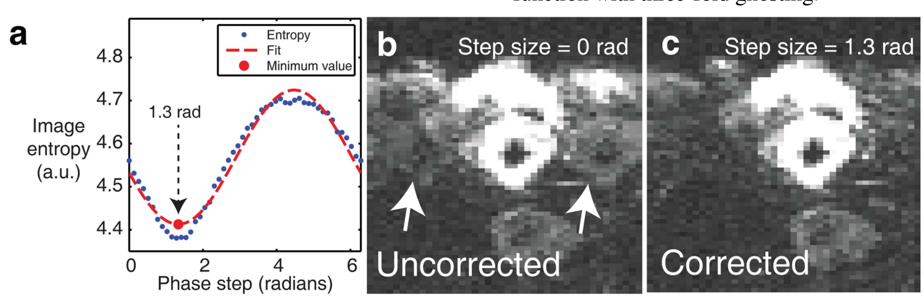

Figure 3. Image entropy-based approach to correct eddy current related phase errors in a blipped CAIPI acquisition. (a) The phase step that corresponds to minimum image entropy is identified and used to remove the three-fold image ghost (b) resulting in the corrected image (c). The images are cropped to 180x180 mm^2.