Recovering fine-scale features in spiral imaging with piecewise linear off resonance correction (PLORC)

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Introduction: Spiral trajectories can efficiently achieve fine spatial resolution; however their point spread functions are susceptible to blurring in the presence of off resonance. Blurring reduces the effective image resolution and often distorts or hides fine-scale details. The block regional off resonance correction (BRORC) algorithm [1] has been proposed as a fast deblurring method. BRORC divides the image into overlapping blocks which are each demodulated by the average field map frequency in that block. The BRORC's deblurring performance is comparable to frequency-segmented off resonance correction (FSORC) [2], but is more memory and computationally efficient. A natural extension of the BRORC method is to incorporate linear off resonance correction [3]. The proposed piecewise linear off resonance correction (PLORC) method utilizes the efficiency of the block-based approach to improve the reconstruction of fine-scale image features with an operations count similar to standard FSORC.

Methods: Because the field map may contain linear trends at multiple scales, the PLORC method forms successive piecewise linear approximations in which the pieces halve in size in successive stages. We describe PLORC enlisting the notation from [1]. In the first stage, a global linear fit $\hat{\boldsymbol{G}}_1$ is made to the field map $\boldsymbol{G}$ and global linear off resonance correction is performed by adjusting the k-space sample locations based on the time map. The residual field map, $\boldsymbol{G}_1$, at the end of stage one is $\boldsymbol{G}_1 = \boldsymbol{G} - \hat{\boldsymbol{G}}_1$. In subsequent stages, the corrected image from the previous stage is divided into blocks, linear fits are made to the residual field map in each block, each block's k-space locations are commensurately adjusted, and a new residual field map is calculated. Thus, at stage j, the NxN corrected image from stage j−1 is divided into MxM blocks, where $M = N/2^{j-1}$. For each block, a local linear fit to $\boldsymbol{G}_{j-1}$ is made. Each MxM sub-image is transformed to the Fourier domain where linear correction is performed using the N/M-fold decimated time map. The corrected block is then transformed back to the image domain. To avoid edge artifacts, only the central rM x rM pixels are retained ($0<r\leq 1$). The 2^{2j-2} local linear approximations are combined to form the piecewise linear fit $\hat{\boldsymbol{G}}_j$, and the new residual $\boldsymbol{G}_j = \boldsymbol{G} - \hat{\boldsymbol{G}}_j$ is calculated. The process is continued until $\|\boldsymbol{G}_j\|$ is acceptably small.

Spiral acquisitions were made to evaluate the performance of PLORC in a phantom (20 interleafs, 0.5 mm resolution) and a healthy volunteer (16 interleafs, 0.7 mm resolution, cardiac-gated and breath-held). A field map was acquired in each case. A linear shim was added for the phantom scan to increase the off resonance behavior. The same data were processed by both FSORC (20 demodulation frequencies) and PLORC (with r = 0.5 and 4 correction stages).

Results: Figure 1 shows images corrected by FSORC and the proposed PLORC procedure. For the phantom, the average spectrum is plotted to demonstrate recovery of higher spatial frequency energy with PLORC.

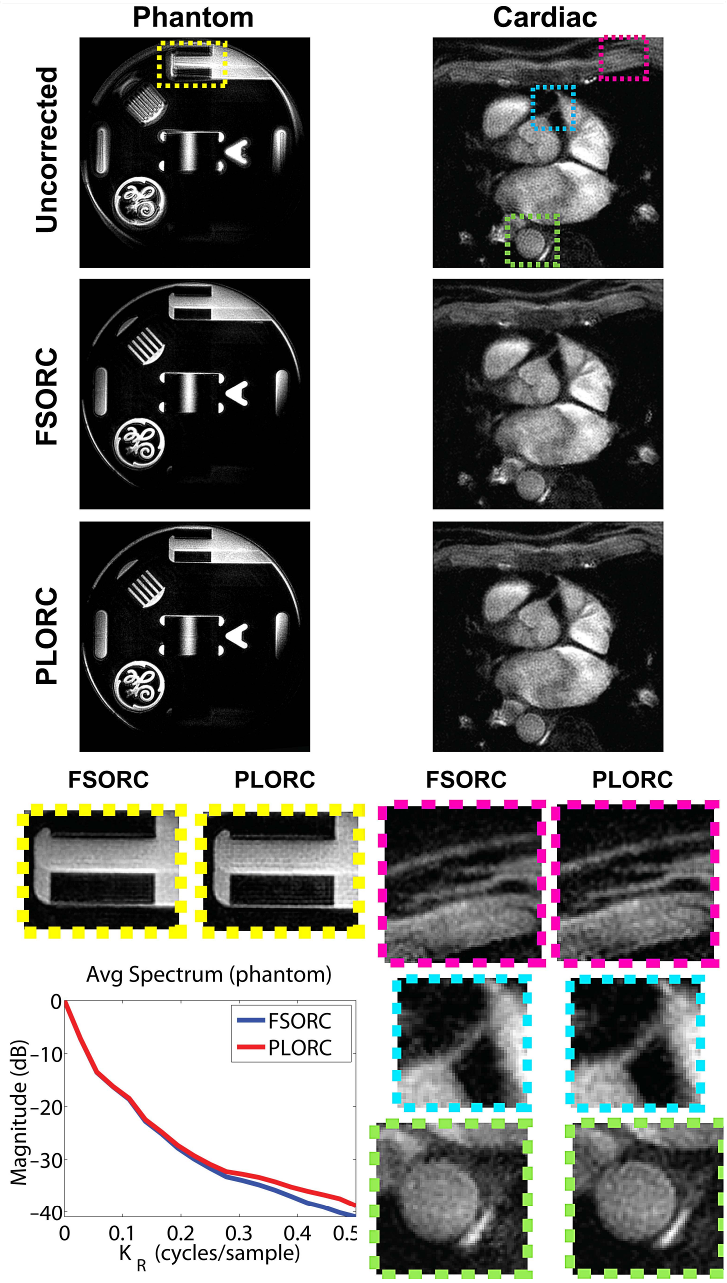

Fig. 1: Phantom (left) and cardiac (right) images after no correction, FSORC, and PLORC. The colored boxes indicate zoomed regions and show improved deblurring with PLORC. The plot shows PLORC recovers higher spatial frequency energy and finer image details in the phantom.

Discussion: Compared to FSORC, the PLORC images show improved reconstruction of fine-scale features and reduced blurring artifacts. In the phantom, PLORC recovered up to 3 dB more energy at higher spatial frequencies. Inaccuracies and noise in the field map is better handled by PLORC because of the weighted least squares linear field map approximations. In terms of computational complexity, FSORC and PLORC are roughly equivalent. The operations counts of both methods are dominated by the 2D-FFT ($2N^2\log_2 N$ multiplications). For 20 demodulation frequencies and N = 256, FSORC requires 21e6 operations. For r = 0.5, 4 stages of PLORC requires 20e6 operations. Note that each successive PLORC stage requires fewer and fewer operations due to the halving of M and the logarithmic operations dependence. As with BRORC, further time savings is possible if only a region of the image is corrected. Future research will determine if the proposed PLORC approach is amenable to automatic field map estimation [4] in each block.

Conclusion: The proposed deblurring method, PLORC, has a computational complexity similar to standard FSORC but is capable of reconstructing image details with higher accuracy.

References: [1] Moriguchi, et al. MRM 2003;50:643-648. [2] Noll, et al. IEEE TMI 1991;10:629-637. [3] Irarrazabal, et al. MRM 1996;35:278-282. [4] Chen, et al. MRM 2006;56:457-462.