Exact correction of sharply varying off-resonance effects in spiral MRI using spatially varying deconvolution.

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Introduction: Spiral and other non-Cartesian k-space sampling schemes suffer from a trajectory dependent blurring artifact induced by off-resonance. This is a critical concern in spiral cardiac imaging where there is susceptibility related, steeply varying off-resonance. Conventional correction techniques such as conjugate phase reconstruction (CPR) [1] and its derivatives [2,3] perform approximate correction by assuming that the field map is smoothly varying. Man et al [4] present an iterative method to correct the residual blur after a full CPR while Sutton et al [5] propose a solution using time segmentation. Here we propose a fast and accurate method for correcting arbitrary field map variations with flexibility to deblur over specific regions of interest (ROIs).

Theory: The MR signal equation with off-resonance is:

$$s(t) = \int m(\mathbf{x}) e^{-jw(\mathbf{x})t} e^{-j2\pi \mathbf{k}(t)} d\mathbf{x} \qquad (1)$$

After incorporating simple Fourier reconstruction, the effect of off-resonance can be reduced to:

$$m_{off}(\mathbf{x}) = \int m(\mathbf{x}') \overbrace{F_{\mathbf{k}}^{-1}\{e^{-jw(\mathbf{x})t(\mathbf{k})}\}|_{\mathbf{x}-\mathbf{x}'}}^{h(\mathbf{x},\mathbf{x}')} d\mathbf{x}' \qquad (2)$$

where $m_{off}(\boldsymbol{x})$ represents the blurred image and $h(\boldsymbol{x},\boldsymbol{x}')$is the spatial domain blurring function. With this new representation off-resonance can be modeled as a spatially varying convolution in the image domain. If the objective is to deblur a finite discrete image then the integral can be reduced to a summation and the blurring kernel, discretized. Using the matrix treatment of a discrete convolution where actual and corrupted data are viewed as column vectors and the blurring kernel is embedded in the columns of a large matrix we can re-write (2) in the discrete form as: $\boldsymbol{m}_{off}=\boldsymbol{Hm}$. Since the region of support for the blurring kernel is highly localized, an exact solution can be obtained using the conjugate gradient (CG) method which is computationally efficient. CG needs to be applied to the associated normal equations (since H may not be symmetric) with appropriate regularization to achieve a stable solution quickly.

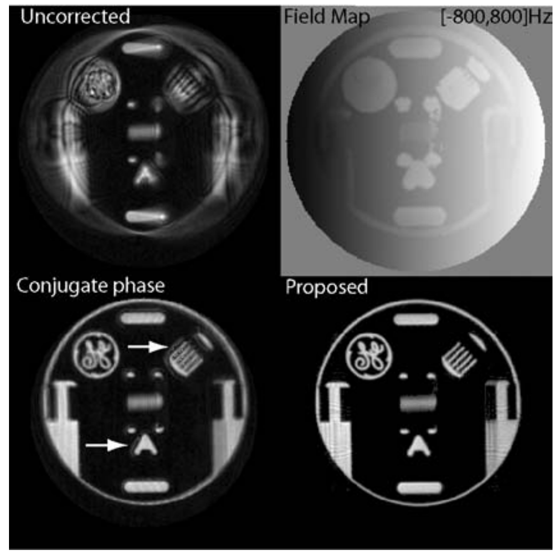

Figure 1: Resolution phantom images reconstructed using the proposed method and CPR.

Methods: The blurred image is divided into small blocks (typically 32x32) and correction is performed independently on each block [2] using CG, which enables ROI-specific deblurring. The columns of H are of the same size as each block and need to be pre-computed in small discrete steps over the entire range of off-resonance. In order to improve computational efficiency, entries of H with amplitude lower than 0.1% of the maximum were zeroed out making the blurring matrix 90% sparse without any visible loss in image quality. Spiral images were acquired on a GE 3T Signa EXCITE system and field maps were computed using the conventional approach. A resolution phantom was imaged with a strong linear shim from left to right, inducing off-resonance from -800 to 800 Hertz. One healthy volunteer was scanned using a breath-held and gated cardiac sequence [6] with fat saturation pre-pulse and scan plane containing the right coronary artery (RCA).

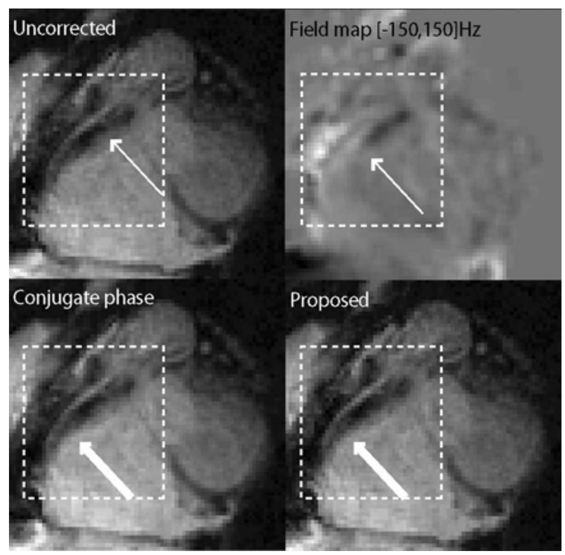

Figure 2: RCA images reconstructed using the proposed method and CPR.

Results: Figure 1 contains reconstructed resolution phantom images. The proposed method corrects most of the visible blurring while CPR performs inadequately due to a steep slope in the field map. Figure 2 contains reconstructed RCA images (thin arrow). The distal portion of the RCA (thick arrow) appears sharper when using the proposed scheme, presumably because of sharply varying off-resonance in that region.

Conclusion: We present a new technique for fast and exact off-resonance correction that makes no assumptions about smoothness of the field map. Phantom and in-vivo results suggest superiority over CPR in areas of steeply varying off-resonance. The proposed method provides flexibility to deblur quickly over specific ROIs, which is particularly important in cardiac real time imaging where fast and exact correction is required.

References:

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