Reducing Spurious Minima in Automatic Off-Resonance Correction for Spiral Imaging

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Introduction One efficient way of correcting the blurred image due to off-resonant spins in spiral imaging is a multi-frequency interpolation method based on a separately acquired field map [1]. Automatic off-resonance correction (AORC) can be an effective deblurring method when short scan time is desirable because it doesn't involve an extra acquisition for the field map or estimation error from it [2]. Large off-resonant phase accrual from a long readout time or wide off-resonance frequency range can lead to wrong estimation of a field map due to spurious minima. Multistage field map estimation was suggested to reduce this problem [3]. Because AORC shows meaningful results when off-resonant phase accrual is small, it may fail to improve the quality if the image is acquired with a long readout time under high field circumstances. We present here an improved approach for reducing the spurious minima by modifying the low-resolution field map estimation and the objective function used as a measure of off-resonance.

Theory and Methods Essentially, we follow the algorithm suggested in [3] while using a low-frequency part in k-space for the low-resolution field map estimation rather than full k-space as in Fig.1. This is an equivalent approach to summation in image domain since the convolution with a rectangular window in image space is a low pass filtering in k-space. But, in contrast to using an arbitrary window size in the conventional approach, we decide the low-frequency region of k-space in a quantitative manner based on the readout time and the maximum off-resonance frequency. In theory, if the maximum off-resonant phase accrual is within ±1 cycle in the low-frequency region we have little chance to encounter the spurious minima. But, sometimes, we have little or no k-space data within this region due to a large TE requirement. To extend the applicability of AORC we have to find a way to relax the ±1 cycle constraint. We can achieve this by a modified focusing criteria. In Fig.2, it is shown that new objective function is potentially less sensitive to the spurious minima because imaginary part, the conventional objective function, is just an approximation of amplitude multiplied by angle in the sense that sinθ ≈ θ for small θ. In other words, the deviation near π increases the probability of spurious minima.

objective function:

$$S_i(m,n) = \sum\sum_{A(m,n)} \left| amp\{I(m,n;\Delta f_i)\} \times ang\{I(m,n;\Delta f_i)\} \right|^{\alpha} \quad \text{where } \Delta f_i = [-\Delta f_{\max}, +\Delta f_{\max}] \text{ with } i \in [0, L-1], \text{ and } A(m,n) \text{ is } w \times w \text{ summation window}$$

corrected image:

$$I_c(m,n) = I(m,n;\Delta f_{k(m,n)}) \quad \text{choose } k(m,n) \text{ s.t. } k(m,n) = \arg\min_i S_i(m,n)$$

Field map estimation is performed in 2 stages and each stage is based on a different number of demodulation frequencies (L1, L2) and a different summation window size (ws1, ws2): L1<L2 for efficiency and ws1>ws2 for the improvement in estimation.

algorithm:

1. *Demodulate the original reconstructed image in k-space with L2 evenly distributed frequencies over the off-resonance range.*
2. *Reconstruct L1 different low-resolution images based on low-frequency region where the maximum phase accrual is within ±m cycles and L2 different high-resolution images from entire k-space.*
3. *Acquire a low-resolution field map by comparing objective function of each pixel of low-resolution images and estimate a high-resolution field map with high-resolution images considering demodulation frequencies near the low-resolution field map.*
4. *Composite the final image based on the high-resolution field map .*

Algorithm was applied to phantom and in vivo images acquired using GE Signa 3.0T LX system with gradients supporting 40 mT/m amplitude and 150 T/m/s slew rate.

Results and Discussion In Fig.3, (b,e) shows the effect of spurious minima when the range of off-resonance is set large while we still get consistent result with the modified algorithm (c,f). New approach is also found to be less sensitive to the variations in the parameters such as w, α of the objective function. This method can be applied to other radial sampling schemes such as projection reconstruction since the phase accrual is centered at the origin in k-space.

References

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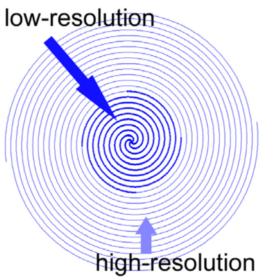

Figure 1: *k-space usage for low and high resolution field map estimation*

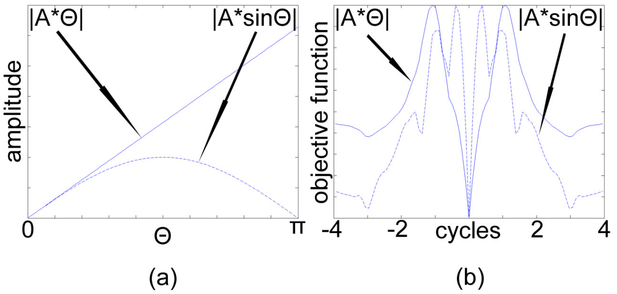

Figure 2: *Comparison of objective functions when I(m,n) = Aexp(jΘ) (a) approximation error (b) objective function with 5x5 summation window of an impulse object with spiral imaging*

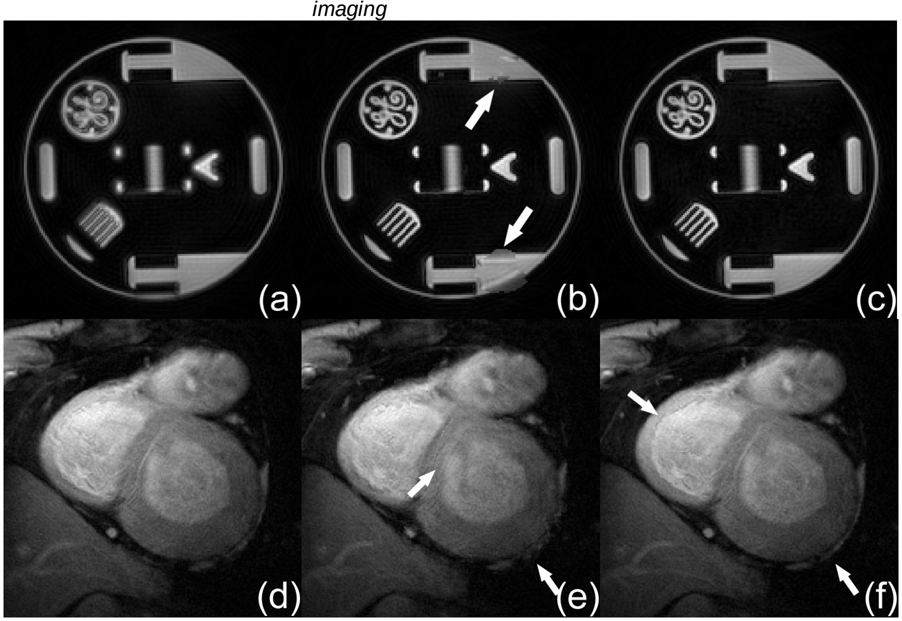

Figure 3: *Spiral phantom and cardiac images with α = 1, m = 2, L1=11, L2 = 41, ws1 = 15, and ws2 = 5 (a,b,c) Δf_{max} = 188Hz, TE = 2.5 ms, RD= 8.2ms, TR = 42 ms, and 16 interleaves (d,e,f) Δf_{max} = 120Hz, TE = 5.2 ms, RD= 16.4ms, TR = 51 ms, and 32 interleaves (a,d) uncorrected (b,e) corrected with original multistage method (c,f) corrected with modified method*