A fast and accurate off-resonance correction method for spiral imaging

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Introduction: Spiral scanning has a number of desirable properties, such as short scan time, resistance to flow and motion artifacts, and short echo time. However, one major limitation is image blurring due to off-resonance effects, which is more pronounced with long readout times and when imaging at high field strength. Most of the existing off-resonance correction methods (1-3) are based on an acquired field map. However, in many applications, only a low resolution field map can be acquired because of scan time limitations, and a low-resolution field map usually does not have sufficient accuracy to support pixelwise off-resonance correction. Automatic methods (4-6) can perform off-resonance correction without acquiring a field map. However, they are computationally inefficient and prone to estimation errors. In this abstract, we propose an off-resonance correction method which combines an acquired low resolution field map with a modified automatic off-resonance correction algorithm to provide rapid and accurate pixelwise off-resonance correction.

Theory: We acquire a low resolution field map using additional data acquisition, typically two single shot spirals with different echo times. Automatic correction (4) is then used for pixelwise deblurring, with a frequency constraint from the low resolution field map. The frequency constraint from the low resolution map is essential, because it enables us to use a small summation window in the automatic method without encountering spurious minima in the estimation of the off-resonance frequency (5). By using a small summation window, we are then able to estimate a high resolution field map. Instead of using the low resolution field map directly, we estimate a linear map from it (3) and incorporate linear off-resonance correction (3) in image reconstruction. The images are then used to calculate the objective function for automatic off-resonance correction (4). The image reconstruction with combined linear off-resonance correction (3) can be expressed as:

$$m(\mathbf{r};\Delta\omega_i') = \int_t s'(t)\exp(j\Delta\omega_i' t)W'(t)\exp[i2\pi\mathbf{k}'(t)\cdot\mathbf{r}]dt\ , \qquad [1]$$

where $s'(t)$ is the signal demodulated by the center frequency; $\mathbf{k}'(t)$ and $W'(t)$ are the warped k-space trajectory and the density compensation function after considering the gradient of the field map, respectively; and $\Delta\omega_i'$ are constant frequencies corresponding to the non-linear components of the off-resonance frequency rather than the full off-resonance frequency. The linear gradient of the field inhomogeneity can skew the point spread function (4). Using Eq. [1] can correct this effect, and therefore improve the effectiveness of automatic correction. Compared to the previous automatic methods (4-7), using Eq. [1] for image calculation can significantly reduce the computation cost. In previous automatic methods (4-7), the images are calculated at a series of constant frequencies corresponding to full off-resonance frequencies which results in a large total range of searching frequencies throughout the FOV and many images need to be calculated accordingly. Conversely, using Eq. [1], we calculate images at $\Delta\omega_i'$ corresponding to non-linear component only, which is usually within a small range throughout the FOV and fewer images need to be calculated. After having calculated the images at different $\Delta\omega_i'$, the objective function is calculated and used to determine the correct value of the non-linear component of the off-resonance frequency. To further reduce the computation cost, we adapted the recursive method described in (7) to calculate the objective function.

In most of our applications, we found a linear map provided a good constraint for pixelwise deblurring. When the field map becomes highly non-linear, we can estimate a higher order polynomial field map from the extra acquired low resolution field map (8) and use it to constrain the pixelwise deblurring. When using a polynomial map as the frequency constraint, we can also calculate the images at a series of constant frequency shifts from the polynomial map to improve the computational efficiency.

Method and Results: We have compared the proposed off-resonance method with conventional low-resolution field-map-based pixelwise off-resonance correction methods and linear off-resonance correction (3) on more than 50 data sets we acquired from Siemens 1.5T scanners. All of these data sets were acquired using various designs of spiral sequences with two single shot spirals for field map acquisition. We employed MFI (2) for conventional pixelwise correction. We performed MFI based on both the acquired low resolution map directly and its polynomial approximation (8), and then chose the better deblurred image for comparison. The proposed method worked robustly and provided high quality image deblurring for all of the data sets. The linear correction is robust, but the image is not fully deblurred and even became blurrier at local regions in some data sets. Conventional pixelwise correction can provide high quality deblurring on some data sets but leads to residual blurring or even exaggerated blurring on other data sets. Figures 1 and 2 are a phantom and an in-vivo coronary artery imaging example from 1.5 T Siemens Avanto and Sonata scanner, respectively. The spiral trajectory has 16.4 ms readout with 14 interleaves. The fat was suppressed in the coronary artery imaging example. Note that the proposed method provided better deblurring than the conventional pixelwise correction in both examples.

Discussion: In our implementation of the proposed algorithm, the computation cost is mild and the algorithm is feasible for online reconstruction. When using an automatic method to evaluate the off-resonance frequency, we must specify several parameters, such as the size of the summation window, the power of the objective function, and the amount of the incidental phase to be removed. We found our algorithm to be insensitive to variations in these parameters. In fact, we used the same parameters for data sets acquired using different spiral sequences and from different scanners. Off-resonance effects in non-Cartesian imaging are more pronounced at high field. The application of the proposed method at 3T should be further investigated.

Conclusion: We proposed a rapid off-resonance correction method for imaging using non-Cartesian trajectories. This method is more robust and can provide better image deblurring than conventional off-resonance correction methods in non-Cartesian imaging.

Reference: 1. Noll et al, ITMI, 10, p629 (1991) 2. Man et al, MRM 37: p785 (1997) 3. Irarrazabal et al, MRM 35, p278 (1996) 4. Noll et al, MRM25: p319 (1992) (5) Man et al, MRM 37: p906 (1997) (6) Lee et al, Proc ISMRM, 11th Annual Meeting, p2678 (2004) (7) Chen et al, MRM 56: p457 (2006) (8) Luk Pat et al, Proc SMR, 3rd Annual Meeting, p617 (1995)

Figure 1: A phantom example. Left: image without deblurring Middle: Low resolution field map based pixelwise deblurring using multifrequency interpolation Right: deblurring using the proposed method

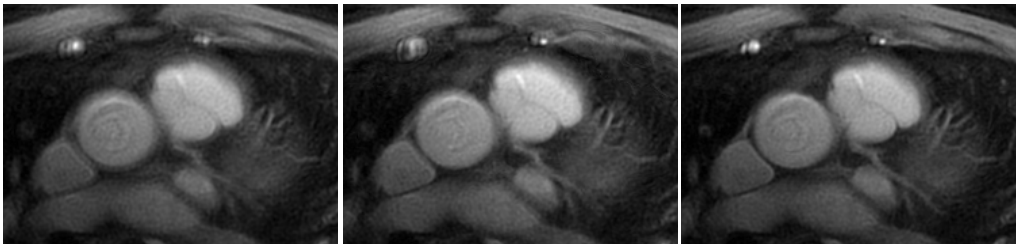

Figure 2: An in-vivo example. Left: image without deblurring Middle: Low resolution field map based pixelwise deblurring using multifrequency interpolation Right: deblurring using the proposed method