Multi-Frequency Reconstruction from an Intensity-Weighted, Locally-Averaged Field Map

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Introduction: Despite the numerous advantages of non-cartesian k-space trajectories in MR imaging, the applications of this type of trajectories are restricted by off-resonance blur [1]. Multi-frequency reconstruction is a post-processing method most widely used to reduce the off-resonance artifacts [2]. This method uses a priori knowledge of the field map to properly demodulate the raw data prior to the reconstruction of each pixel. This deblurring method is effective only if the field map is smoothly-varying. A theoretically correct reconstruction is a weighted sum of all the demodulated pixels [3]. However, the weighting coefficients are difficult to calculate and also sensitive to field map inaccuracies [4]. In this work, we show that multi-frequency reconstruction may still provide adequate deblurring at sharp edges if an intensity-weighted, locally-averaged field map is used as the demodulation map. This modification to multi-frequency reconstruction is virtually as fast as the original approach. It is robust to field map errors and also tolerates more variations in the field map.

Method: In multi-frequency reconstruction each pixel is refocused by demodulating the raw data according to the off-resonance frequency at that pixel. This approach neglects the effect of nearby pixels; namely, if the off-resonance frequency of the surrounding pixels are substantially different from the demodulation frequency, there will be leakage from blurry reconstruction of those neighboring pixels. This problem arises because the demodulation frequency is chosen without considering the cross-talk from adjacent pixels. Choosing a demodulation frequency that is close to local off-resonance frequencies in an average sense may provide appropriate refocusing for all pixels, hence reducing the overall reconstruction error. To illustrate this effect, consider a simple 1D case of an object consisting of two adjacent spins resonating at different frequencies $f_1$ and $f_2$. Figure 1 shows the relative reconstruction error of the first pixel when the demodulation frequency, $f_d$, varies from $f_1$ to $f_2$. The spins are assumed to be 2 pixels apart and equal in the intensity. The 1D k-space trajectory is non-cartesian ($k(t) = \pm t^2$) and the difference between the off-resonance frequencies corresponds to one cycle of phase accrual during the read-out time. This plot shows that the conventional approach in which $f_d = f_1$ does not provide the minimum error, and the optimal demodulation frequency is in fact a weighted average of the two off-resonance frequencies. This result, in general, implies that a good candidate for the demodulation map is an average of the field map. Because neighboring pixels with high intensities contribute more to the reconstruction error, this average should be localized and intensity weighted.

Results: Figure 2 is a portion of the central slice of a 3D image of a resolution phantom. This image is acquired using a 3D spherical stack-of-spirals trajectory [5] with 14 ms read-out time. The FOV is $24\times24\times6$ cm$^3$ and voxel size is 1.2 mm in each dimension. The blurred field map used for Fig. 2-a is obtained by intensity weighting and local averaging of the original field map used for Fig. 2-a. The localizing kernel is a cube 1.5 cm wide on each side. In both cases, the demodulation maps are optimally quantized [6] into 8 levels. The deblurred image using the smoothed field map shows better definition throughout the image.

Conclusion: Intensity-weighted and locally-averaged field map is a better demodulation map to be used in multi-frequency reconstruction. It provides more effective deblurring especially when either the field map or the image contains high spatial frequency components. This scheme is less sensitive to field map errors because of the averaging step. It is also subject to less quantization error because of the limited range of variation of the smoothed field map. Because of intensity weighting, this approach does not require an intensity threshold to provide the binary mask that is typically used to avoid background phase errors.

References:

Figure 1: Reconstruction error vs. demodulation frequency (horizontal axis is normalized as $(f_d - f_1) / (f_2 - f_1)$).

Figure 2: Multi-frequency reconstruction using a) the original field map, b) the smoothed field map.