Off-resonance correction for 3D imaging using a stack of spirals trajectory

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Introduction: Various non-Cartesian 3D trajectories have been developed to increase scan efficiency. 3D spiral trajectories, such as a stack of spirals and a sphere of spirals [1], are commonly used non-Cartesian 3D trajectories. The scan efficiency can be increased by an order of 10 by using 3D spiral trajectories compared to standard 3D methods, such as 3D GRE. The main factor limiting the reliability of spiral imaging is image blurring caused by off-resonance signal reception, which has been discussed in the 2D case. In this abstract, we propose a scheme to perform 3D off-resonance correction for a stack of spirals trajectory by performing 2D off-resonance correction slice by slice in 3D. We demonstrate our scheme by linear off-resonance correction [2] and multiple frequency interpolation [3]. Our scheme can also be used for other off-resonance correction methods.

Method: The 3D signal equation, considering inhomogeneity $\Delta\omega(x,y,z)$, can be written as following:

$$s(t)=\int_z \exp(-i2\pi k_z z)\left[\iint_{x,y} m(x,y,z)\exp(-i2\pi(k_x x+k_y y))\exp(-i\Delta\omega(x,y,z)t(k_x,k_y,k_z))dxdy\right]dz\ ,$$

where k_x, k_y and k_z are the 3D k-space coordinates. For non-Cartesian 3D trajectories, the signal sampling time t usually is a function of k_x, k_y and k_z. However, for a stack of spirals trajectory, the signal sampling time only depends on k_x and k_y, and is independent of k_z. Therefore, the inner 2D integral in the above equation becomes independent of k_z, and we can apply 1D Fourier transform on k_z directly on the time signal to obtain the following equation:

$$s_a(t)=\int_{k_z} s(t)\exp(i2\pi k_z z)dk_z=\iint_{x,y} m(x,y,z)\exp(-i2\pi(k_x x+k_y y))\exp(-i\Delta\omega(x,y,z)t(k_x,k_y))dxdy\ .$$

Within each slice, since z becomes a constant, the above equation becomes the familiar 2D signal equation. Therefore, after a 1D Fourier transform along k_z, we can use well-developed 2D off-resonance correction methods to obtain the deblurred image $m(x,y,z)$ slice by slice.

Linear off-resonance correction is one of the most commonly used methods because it has almost no reconstruction time penalty. The original 2D linear correction method can be extended to 3D directly by estimating a 3D linear map that best fits the 3D field map and then using it to deblur the image. A linear fit in 3D requires the field map $f(x,y,z)$ to be approximated as $f(x,y,z)\approx f_0+f_x x+f_y y+f_z z$, where f_0, f_x, f_y, and f_z are the center frequency, x, y, and z gradients, respectively. This means the field map is approximated by the same linear terms within all slices with a linearly changing constant term from slice to slice. Such an approximation usually over-simplifies the non-linearity of the field map in 3D and can result in a large fitting residual. By using our off-resonance correction scheme, we can improve the effectiveness of 3D linear off-resonance correction. We estimate a linear map for each slice of the 3D field map, and then use these different 2D linear maps to perform 2D linear correction for each slice of the data. The linear maps estimated in this way usually have less fitting residual, and therefore a better deblurring can be achieved than a regular 3D linear correction.

Many pixel-by-pixel based 2D off-resonance correction methods have been proposed in the literature. By using our scheme, we can apply these 2D off-resonance correction methods directly in 3D, which simplifies the pixel-by-pixel based 3D off-resonance correction. In the result section, we demonstrate this by multiple frequency interpolation [3].

Results: We applied our 3D deblurring scheme on an *in-vivo* 3D brain dataset. The data was acquired on a 1.5 T Avanto scanner (Siemens Medical Solutions). 32 slices were acquired. Fat saturation was employed to suppress the fat signal during the scan. Each slice consisted of 14 interleaves of spiral trajectories with two additional single-shot spiral acquisitions used for a low-resolution field map estimation. The readout time of each spiral interleaf was 16.4 ms. A low resolution 3D field map was reconstructed and used for all off-resonance correction methods. The maps on the edge of the slice direction contaminated by aliasing were removed when performing regular 3D linear correction. The results show that our 3D linear off-resonance correction scheme can achieve better deblurring than the regular 3D linear correction. MFI based on our 3D off-resonance correction scheme can achieve the best deblurring effect among the three off-resonance correction methods. Figure 1 shows results for one slice without deblurring, with regular 3D linear correction, with our 3D linear correction, and with our 3D MFI correction. The image was zoomed in to a local region so the difference can be better visualized.

Discussion and Conclusion: We proposed a 3D off-resonance correction scheme for non-Cartesian imaging using a stack of spirals trajectory. By first performing a 1D Fourier transform along the z direction, we obtain time signals that are localized in z. A linear off-resonance correction based on our scheme can provide a better deblurring than the regular 3D linear off-resonance correction. Using our scheme, pixel-by-pixel based 2D off-resonance correction methods can be directly applied in 3D, which simplifies the pixel-by-pixel based 3D off-resonance correction.

Reference:

[1] Irarrazabal et al, MRM 33: 656-662 (1995) [2] Irarrazabal et al, MRM 35, 278-282 (1996)
[3] Man et al, MRM 37: 785-792 (1997) [4] Noll et al, MRM 25: 319-333 (1992)

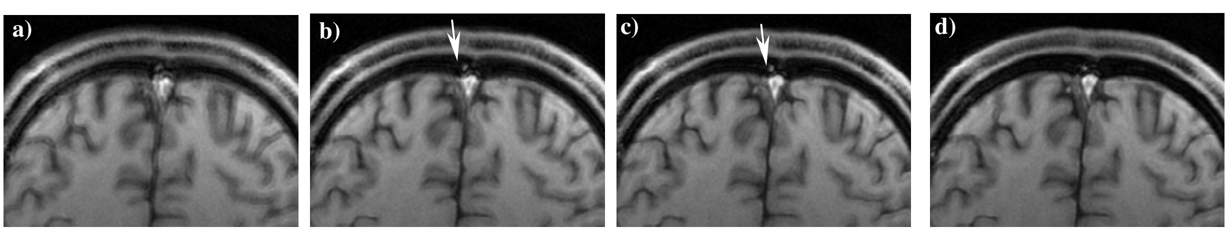

Figure 1: One slice from a 3D image acquired using a stack of spirals trajectory. The image was zoomed in to a local region so the difference between images can be better visualized. a) Image reconstructed with no deblurring, b) image deblurred with a regular 3D linear off-resonance correction, c) image deblurred with our 3D linear off-resonance correction, and d) image deblurred with our 3D MFI off-resonance correction. Note that our 3D linear correction achieves a better deblurring than regular 3D linear correction. The white arrow shows a region where the difference is obvious between two linear corrections.