

Inherent Correction of Motion-Induced Phase Errors in Multishot Spiral Imaging using Iterative Phase Cycling

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Introduction

Spiral imaging has recently emerged as an alternative to echo-planar imaging for diffusion tensor imaging (DTI) because of its efficient k-space coverage and low sensitivity to flow artifacts (1–3). Multishot spiral trajectories are typically required to achieve a high resolution while maintaining a short readout duration to minimize off-resonance effects. However, shot-to-shot phase variations induced by motion in the presence of diffusion gradients lead to severe artifacts. Variable-density spiral trajectories can be used to generate a low-resolution phase estimate from the oversampled central k-space for each shot and correct for such artifacts (1–3). However, the readout duration is increased by up to 70% (4), resulting in a longer scan time and/or a higher sensitivity to off-resonance effects. Here, we propose a novel iterative phase cycling method that can correct for motion-induced phase errors in multishot spiral imaging without requiring any additional navigator, thus allowing a shorter scan time as compared to variable-density spiral acquisitions.

Methods

For simplicity, we consider a 2-shot spiral acquisition with an $N \times N$ matrix size, but extension to any number of shots is straightforward. For each shot m , the point spread function is first computed as: $\text{PSF}_m(x, y) = \sum_n \text{DCF}(n) \exp\{i2\pi[xk_x(n, m) + yk_y(n, m)]\}$, where DCF is the density compensation function, (k_x, k_y) the spiral k-space trajectory, and (x, y) the spatial position on a $(2N-1)^2$ grid.

The k-space data from each shot is then reconstructed separately (by zero-filling the missing data), resulting in aliased images due to undersampling. For each pixel (x_0, y_0) , the relation between these images and the unaliased image to be reconstructed can be expressed as: $\mathbf{a} = \mathbf{E} \cdot \mathbf{u}$ [1], where \mathbf{a} is a 2×1 array containing the pixel values from the aliased images and \mathbf{u} is a $N^2 \times 1$ array whose (x_0, y_0) th element contains the pixel value from the unaliased image (Fig. 1). In the absence of motion, \mathbf{E} is a $2 \times N^2$ matrix whose rows contain the $N \times N$ subsets $(N - x_0 + 1:2N - x_0, N - y_0 + 1:2N - y_0)$ of PSF_1 and PSF_2 (red squares), whereas in the presence of motion, the second row of \mathbf{E} is multiplied by $\exp[-i\phi(x_0, y_0)]$, where ϕ is the motion-induced phase error between the two shots. Thus, if ϕ is known, the unaliased image can be determined by solving Eq. [1] for each pixel.

However, since ϕ is generally unknown, we use a phase cycling method, which consists in reconstructing a series of images using different ϕ values and choosing the image with the least amount of aliasing. Here, we assume that ϕ is spatially linear, i.e., $\phi(x, y) = \phi_0 + xg_x + yg_y$, where ϕ_0 is a global phase offset and (g_x, g_y) are linear phase gradients along (x, y) , and cycle through different values of ϕ_0 , g_x , and g_y . This model is sufficient to correct for phase errors induced by rigid-body motion (5), but can easily be extended to correct for nonlinear phase errors induced by nonrigid motion.

The image with the least amount of aliasing is chosen as the one with the lowest signal intensity in the background (i.e., outside the object). To avoid having to manually define the background region, the pixel values of each image are sorted in ascending order and the lowest 25% are summed to yield the background energy. As the energy does not need to be computed in the entire background, this threshold is not critical and can range from 5% to 50%.

Because cycling through all possible values of ϕ requires a long computation time, we propose two strategies to drastically speed up the reconstruction. First, the phase cycling is performed only on low-resolution images reconstructed from the central k-space, which remains effective as long as the resolution is sufficient to distinguish the background from the object. Once ϕ is known, the final image is reconstructed at full resolution. Second, the phase cycling is performed iteratively, starting with a large range and step size for ϕ_0 , g_x , and g_y . Once an estimate for ϕ is found, both the range and step size are reduced at the next iteration. The initial step size should be small enough to avoid local minima in the background energy.

As a proof-of-concept, we studied a healthy volunteer on a 3 T GE scanner using a 2-shot spiral pulse sequence with TR/TE = 1580/30 ms, FOV = 24.3 cm, matrix size = 64×64, and slice thickness = 3.8 mm. Image reconstruction was performed in Matlab on a 3.4 GHz PC.

Results and Discussion

The uncorrected image (Fig. 2A, red square) as well as representative images reconstructed at full resolution using different g_x and g_y values have very different aliasing patterns. The sorted signal intensity (Fig. 2B) shows that one of these images has the lowest signal in the background (blue line in yellow area) as compared to the uncorrected image (red line) or any other image (black lines). A plot of the background energy as a function of g_x and g_y shows that the minimum energy is reached for $(g_x, g_y) = (1, -2)$ (in units of k-space line shift) (Fig. 2C). These results demonstrate that the background energy minimization can identify the image with the least amount of aliasing (Fig. 2A, blue square). Similar results are obtained when cycling through ϕ_0 .

By performing the phase cycling at a lower resolution of 16×16, the computation time per slice is reduced from 100 h to 1 h. In addition, by using five iterations of phase cycling with a variable step size rather than a single iteration, the computation time is further reduced to 13 s, which represents a total reduction by a factor 3×10^4 .

These initial results demonstrate that the proposed iterative phase cycling method can effectively and efficiently correct for motion-induced phase errors in multishot spiral imaging without requiring any additional navigator. Further work is currently underway to optimize this method and to demonstrate its advantages for multishot spiral DTI.

References

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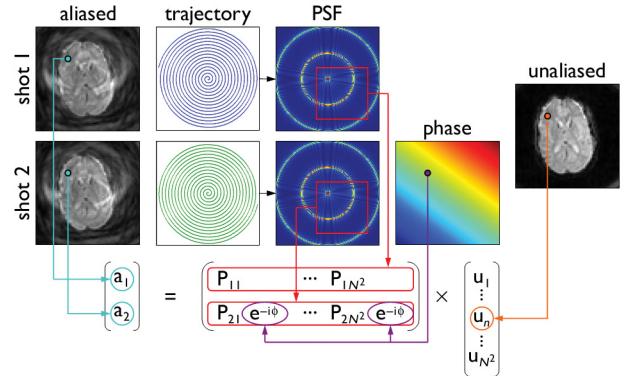


Fig. 1: Relation between the aliased and unaliased images, the PSFs, and the motion-induced phase error.

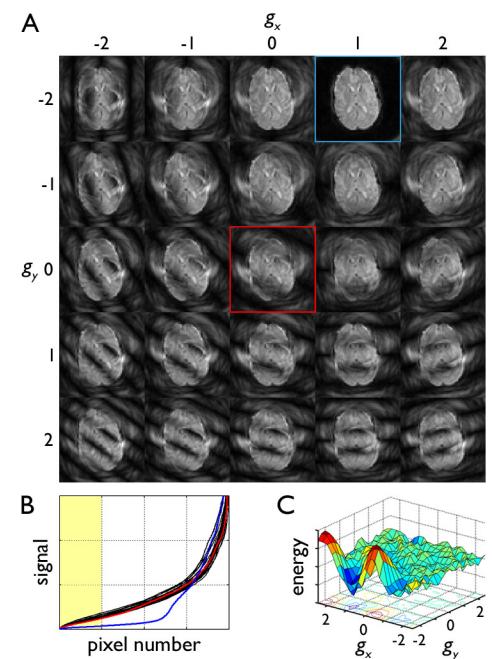


Fig. 2: Images reconstructed using different g_x and g_y values (A). Sorted signal intensity of each image (B). Background energy as a function of g_x and g_y (C).