Partial Fourier imaging in multi-dimensions: A means to save a full factor of two in time

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Introduction

Speed improvements are always sought in order to reduce patient imaging times, to improve resolution or to improve the temporal resolution of dynamic records. However, the goal in speeding up acquisition times is to maintain image quality. Reconstruction of data from limited k-space coverage has the potential of improving acquisition speed in magnetic resonance imaging and preserving the resolution. However, previous partial Fourier methods (1-3) have been designed for only one dimensional applications, they save less than a factor of two in time because of the extra lines collected for the center of k-space and they can suffer from phase induced artifacts unless enough of k-space is covered. In this paper, we propose that half-fourier imaging using phase constraints in multiple dimensions. The method we propose allows a full factor of two savings in time with much better coverage of the central k-space information and, hence, fewer artifacts. This should prove particularly valuable in dynamic three-dimensional (3D) applications of MR angiography.

Methods

Phase constrained methods have been used previously to reconstruct MR images from 1D asymmetric k-space data. Generally, if the object is real, then the missing data can be reconstructed by imposing complex conjugate symmetry on the data. For gradient echo imaging, this is not the case and, before this constraint can be invoked, the background phase behavior must be accounted for. This has been accomplished previously by using the phase from the central part of k-space as an estimate for the global phase of the object and removing its effect from the data. For gradient echo imaging, this usually required at least 32 points before the echo and in some cases 64 points before the echo. In the latter case, with 128 points after the echo, this meant that only 25% of the imaging time was eliminated.

In this paper, we view the reconstruction problem as one where the reconstruction of partial k-space data is an underdetermined problem since we do not know the number of data points. The application of a phase constraint adds a sufficient number of constraints to make the problem solvable. How well this method works very much depends on how close the estimated phase is to the true phase. The higher the spatial frequency content desired, the more accurately the phase image needs to be known. For an N x N complex data set, the phase adds at most N^2 constraints. This means that, potentially, only N/2-k-space points need to be acquired to obtain not only a unique solution but also the correct solution.

We choose to take the upper corner of k-space, for example, with N + M points. Setting (N + M)^2 = 4N^2 gives M = 0.41N. This means that for N = 128, as in the 1D case discussed above, that M = 53 and the center of k-space will be 106 x 106, a very large coverage for the phase estimate, and a full factor of two savings in time will be realized. The take home message is that one can obtain better phase estimates in higher dimensions and, hence, expect to better reconstruct the image in 50% of the original time.

To evaluate the method, we test it with simulated images, phantom images and clinical data sets. The simulations are designed to evaluate the ability of the method to correct for phase variations of varying degrees across the object and across a range of small circles (the circles ranged from 2 pixels to 10 pixels in diameter when the image matrix is 256 x 256. Phase variations across the structures are as high as 2π/4 across 10 pixels (where we then expect the method to fails anyway). A similar comparison is then done with actual MR data on a phantom. Clinical examples are presented for 3D MRA studies and a 3D T1 weighted study of whole brain coverage. All studies are done with exactly half the usual data coverage.

Comparisons with the original data were made by subtracting the image obtained from the partial Fourier reconstruction from the original image. The amplitude of any remnant ringing was then measured along horizontal, vertical and 45° lines on either side of the vertical line to quantify the residual error. (The image reconstruction scheme itself is an iterative POCS implementation of the projection onto convex sets (POCS) method (4).

Results and Discussion

For the simulated data when the phase variation was smaller than 2π/10 across a voxel, the error along the horizontal and vertical lines was less than 6% while that along the 45° lines was about the size of Gibbs ringing (9%) due to a slight blurring of the object in that direction. This blurring is imperceptible to the eye when the two images are viewed side by side. When phase variations are greater than 2π/10 per pixel, errors begin to rise sharply to 20 to 30%.

For the resolution phantom, the 2D iterative POCS reconstruction reduced greatly Gibbs ringing in both the horizontal and vertical directions for larger circles. On the other hand, in the vicinity of the smaller structures, the process introduces a diagonal artifact. This artifact rapidly diminished as M was increased to 0.41N or higher. As in any bandlimited reconstruction with closely spaced small objects, a coherent form of Gibbs ringing was also seen on occasion.

For the 3D MRA gradient echo leg data set, we truncate the original k-space data for each slice and then perform the POCS reconstruction. An MIP is performed and the resulting image compared with the MIP from the original data set. We tested the method with different values of M and found that the rapid phase variations caused by fat (this was an opposed phase value for TE making it a particularly difficult problem) vanished when M was greater than 0.41N.

For the 3D brain images, the POCS reconstructions revealed no observable edge artifacts in the brain tissue. This suggests that it would be reasonable to take a long 10 minute 3D acquisition and acquire the data in 5 minutes and use the POCS reconstruction as long as the loss of sqrt(2) in SNR is acceptable. This is likely to be the case today when the resolution is 1 x 1 x 2 mm^3 at 1.5T or 1 x 1 x 1 mm^3 at 3T. The latter scan currently takes 16 minutes to acquire for full brain coverage and reducing it to 8 minutes makes it a much more viable clinical scan. The success of this method in human data is due, in part, to the fact that edges are not as sharp as in phantoms and hence the k-space decays away faster making the large central phase estimate good enough to do a good job reconstructing the image.

Conclusion

Two-dimensional phase constrained partial Fourier imaging has been shown here to be a powerful means to reconstruct a pristine image based on only half of the usual number of k-space points. It is a particularly powerful method for 3D gradient echo imaging where a very accurate estimation of the phase image is required.

References