SPIRAL PARALLEL MAGNETIC RESONANCE IMAGING

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ABSTRACT

Spiral k-space scanning is a rapid magnetic resonance imaging (MRI) technique that can provide an order of magnitude reduction in scan time compared to conventional spin warp techniques. Parallel imaging is another method for reducing scan time that exploits spatially varying radiofrequency (RF) coil sensitivities to reduce the amount of data required to reconstruct an image. Combining spiral scanning with parallel imaging provide a scan time reduction factor that is the product of the reduction factors for each of the techniques and thus can permit very rapid imaging. Image reconstruction for spiral parallel MRI is more involved than for spin warp parallel MRI and is an area of active research. Two techniques for performing this image reconstruction are PILS, a simple image-domain method that relies on localized coil sensitivities, and BOSCO, a method that is based on successive convolution operations in k-space.

1. INTRODUCTION

Magnetic resonance (MR) images are reconstructed from samples of the spatial Fourier transform of the object. Spatial Fourier transform space is referred to as k-space in the MRI literature. Imaging involves scanning k-space to collect samples over the desired region, with the instantaneous position in k-space determined by the time integral of the magnetic field gradient waveforms up to that point in time. These gradient waveforms are under the control of the pulse sequence programmer, within certain hardware and physiological limits, so that an infinite number of k-space trajectories are possible. By far the most common trajectory is a raster scan of k-space, which is referred to as spin warp or 2DFT imaging. Spin warp imaging is robust and has a number of advantages, although it does require a relatively large number of readouts (e.g., 256 for a fully-sampled 256x256 image).

One alternative scanning technique is to collect data on a spiral path through k-space [1]. In theory, one can collect all of k-space in a single readout using a spiral scan, although typically a few interleaved scans are used. Still, the number of readouts required is reduced by an order of magnitude or more compared to a spin warp scan, although each individual readout is typically longer. A spiral k-space trajectory and the corresponding readout gradients are shown in Fig. 1. Spiral scanning is an efficient technique with good performance in the presence of object motion, although it suffers from image blurring in the presence of main field inhomogeneity if this is not compensated for in image reconstruction. Spiral image reconstruction is typically performed by gridding, which convolves the data onto a rectilinear grid in k-space, so that the Fourier inversion can be performed rapidly using a 2D Fast Fourier Transform (FFT). Spiral scanning has been used for real-time and breath-held cardiovascular imaging and for functional brain imaging, among other applicaitons.

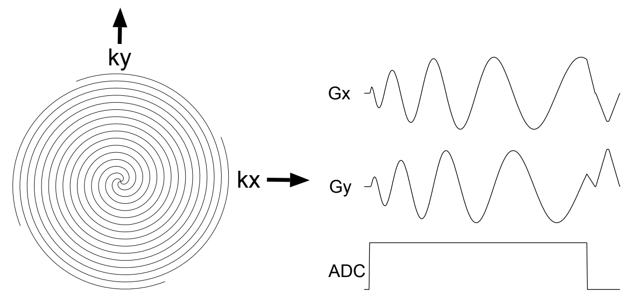

Fig. 1. Interleaved spiral k-space trajectory (left) and corresponding readout gradients and ADC window for one of the interleaves (right).

In addition to changing the k-space trajectory to collect more data in each readout, another way to speed up scanning is to acquire data samples less densely in k-space. The density of samples in k-space determines the field-of-view (FOV) of the scan, which is the size of the largest object that can be reconstructed without spatial wraparound or aliasing artifacts. Fortunately, modern MRI scanners collect data simultaneously with a number of different RF coils with differing spatial sensitivity profiles. Each of the N RF coils is connected to an independent receiver channel, so that the amount of data available to reconstruct the image is increased by a factor of N. By using this extra data, parallel imaging techniques permit less dense sampling in k-space and thus a scan time reduction of 2-4 or more [2]. Parallel image reconstruction techniques include k-space domain methods (e.g., SMASH [3] and GRAPPA [4]) and image domain methods (e.g., SENSE [5].

For spin warp imaging, parallel imaging permits subsampling along the phase encoding direction, which means that N fewer lines are collected. This means that the parallel image reconstruction is largely a one-dimensional problem, which permits efficient computational methods of image reconstruction. Both SENSE and GRAPPA have been implemented commercially and are widely used. In spiral scanning, however, reducing the number of spiral interleaves leads to subsampling in two dimensions, and the resulting spatial aliasing effects are more complicated. Because of this, the image reconstruction problem is more difficult. Pruessmann *et al*. introduced an iterative method of extending the SENSE method to non-Cartesian trajectories, including spiral scans [6]. Here we will discuss two non-iterative techniques for reconstructing parallel spiral data: PILS and BOSCO.

2. SPIRAL PILS

Griswold *et al*. introduced partially parallel imaging with localized sensitivities (PILS), which exploits the idea that individual RF coils in a coil array often have localized sensitivity profiles [7]. By considering the data from each coil individually, it is possible to reconstruct a reduced FOV image with fewer readouts. The reduced FOV images can then be combined into one full FOV image, for example using the square root of the sum of the squares of the images. The original demonstration of PILS was for spin warp imaging, where the image combination is then along one dimension. However, the technique has also been applied to spiral scanning, where two-dimensional acceleration is possible if the coils have approximately circular FOV profiles [8–11].

Spiral scanning has an impulse response that consists of a main lobe surrounded by a series of sidelobes. The first sidelobe is a series of spiral arcs that can be approximated as a circle with a radius equal to the acquired FOV. Thus, if the object is larger than the FOV, then a circular aliasing artifact appears superimposed at the opposite side of the image. In spiral PILS, we intentionally use fewer interleaves than would be needed to support the full FOV of the object, so that aliasing would occur if we used body coil reception. However, a spatially-localized coil sensitivity profile effectively results in a smaller object, because the effective object is the product of the coil sensitivity and the object. Thus, aliasing can be prevented for images reconstructed from each individual coil, as long as no coil sensitivity profile is larger than the acquired FOV.

In our implementation of spiral PILS, we use a variable-density spiral trajectory, so that we can reconstruct a low-resolution image at the full FOV. We then automatically detect the center and extent of the coil sensitivity profile for each coil using a Gaussian fit to one-dimensional (1D) projections of these low-resolution images along two orthogonal directions. We reconstruct full-resolution images for each coil and apply a properly-centered Fermi window mask to each image so that the aliasing energy is suppressed. We then combine the resulting unaliased images using square root of sum of squares. We have applied this method to MR coronary angiography and coronary vessel wall imaging. The technique has a number of advantages, including rapid image reconstruction, ease of implementation, and high signal-to-noise ratio (SNR). However, it is restricted to spatially-localized coil sensitivities and does not allow the highest-possible acceleration factors.

3. BOSCO

Spiral PILS is an image domain technique. It is also possible to think about the spiral parallel image reconstruction problem in the k-space domain, where the goal is to fill in the missing k-space data between spiral interleaves. BOSCO is a new auto-calibrating non-Cartesian parallel image reconstruction technique that is in some sense a 2D generalization of the GRAPPA technique [12]. Other recent non-Cartesian GRAPPA implementations have used segmenting techniques to map the 2D problem onto a series of 1D problems [13–16]. The acronym BOSCO stands for parallel image reconstruction **B**ased **O**n **S**uccessive **C**onvolution **O**perations.

GRAPPA fits sampled data points from multiple coils to fill in a missing data point. This operation is effectively a 1D convolution operation (over multiple source channels). For the inherently 2D problem of spiral parallel image reconstruction, a 2D convolution is needed. One option is to perform this 2D convolution directly on the spiral data before gridding. However, the spiral data samples are at arbitrary distances from the desired grid points, which makes this approach unwieldy. Fortunately, convolution is commutative, so it is possible to perform the desired 2D convolution *after* gridding. This is the basis of BOSCO: a gridding convolution, followed by a BOSCO convolution on the gridded data itself. The BOSCO kernels are calculated using a 2D fit from multiple coils to a particular target coil. A separate set of BOSCO kernels is needed for each target. A 2D FFT is then performed for each target, and then the target images are combined using square root of sum of squares.

We have applied BOSCO to phantom, cardiac and brain imaging, with scan time reduction factors ranging from 2 to 4. The resulting images are free from visible aliasing artifacts. The BOSCO convolutions typically use a 5x5 kernel and thus require a reasonable amount of computation. The BOSCO kernel calculation is an overdetermined linear optimization problem, and improved image SNR can be achieved through regularization. BOSCO is a non-iterative technique that shows promise as a rapid and accurate method for parallel image reconstruction of arbitrary trajectories.

4. CONCLUSION

Spiral k-space scanning and parallel imaging each provide substantial MRI scan time reduction. The combination of the two can lead to very fast MR image acquisition. The resulting image reconstruction problem is an area of active research. Spiral PILS is one solution to this problem, which requires little additional computation and produces high SNR, although it requires spatially-localized RF coil sensitivity profiles and somewhat limits the achievable scan time reduction factor. BOSCO is a non-iterative method for parallel image reconstruction that permits higher acceleration factors.

5. REFERENCES

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