Interleaved Spiral-in Spiral-out 3D-FSE Reconstruction Using a Fast Field Corrected Iterative Algorithm

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Introduction

Fast Spin Echo (FSE) is a commonly used pulse sequence that saves time over conventional spin echo imaging by generating multiple spin echoes after a single excitation pulse. The initial implementations of this technique acquired a single phase encode line during each echo. The sequence was easily extendable to 3D, but at cost of greatly increased imaging time. When combined with a single-shot acquisition method like EPI or spiral imaging, it is possible to rapidly acquire a full 3D dataset during a single TR, with some resolution restrictions [1]. This has been used for instance to acquire 3D data sets for Arterial Spin Labeling (ASL) sequences, where high spatial resolution is not imperative. For these types of FSE sequences it is preferred that the data be acquired as fast as possible for increased temporal resolution of the time series, e.g., by sampling data for as long as possible between the refocusing pulses. Also, it is desirable to sample the center of k-space at the peak of the echo envelope for true spin echo contrast.

We propose here to acquire the data from a 3D FSE sequence using a stack of 2 interleaved spirals. The interleaves are designed so that one forms a spiral-in and the other a spiral-out trajectory, with the combination of the two making a fully sampled k-space for one phase encode in the 3D FSE. This data is reconstructed using a fast 3D iterative method, including correction for off-resonance effects during readout [2].

Theory

The spatially discrete MR signal equation, including off-resonance effects, can be written as,

$$y(t) = \sum_{n=1}^{N} f(r_n) e^{-t\omega(r_n)} e^{-i2\pi k(t)\cdot r_n} + \varepsilon(t), \tag{1}$$

where r_n is the 3D spatial coordinate, $f(r_n)$ is the magnetization of the object, $\omega(r_n)$ is the field map used for correcting off-resonance effects and $\varepsilon(t)$ is white 0-mean Gaussian noise. Using the model in Eq.(1), we estimate the image using an iterative algorithm to minimize the following penalized least-squares cost function:

$$\hat{\mathbf{f}} = \arg\min_{\mathbf{f}} \|\mathbf{y} - \mathbf{A}\mathbf{f}\| + \beta R(\mathbf{f}). \tag{2}$$

To calculate the forward projection **Af** rapidly, we calculate $\mathbf{A}_i\mathbf{f}_i$ for $i=1,\ldots,N_z$ using a 2D fast algorithm proposed in [2], with i indexing the z position of the image, then we apply 1D FFTs in the z direction. We compute A'y similarly.

The proposed method requires field-map estimates. To estimate the field map, we do 2 acquisitions, with the latter one having its acquisition window shifted by 2ms, assuming there is enough space between the refocusing pulses, and the field map is then calculated from the phase difference of 2 reconstructed 3D images.

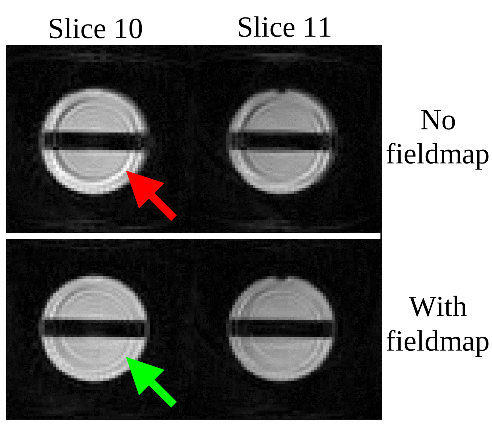

Figure 1: 2 slices of a resolution phantom collected using the 3D FSE. Top two images have no field map in the reconstruction and the bottom 2 include field map.

Results

The data was collected on a 3T GE Signa scanner. Figure 1 shows 2 slices from the 3D FSE proposed here. The top two images are reconstructed with no field map, and the bottom 2 are the same 2 slices, but include now a field map in the reconstruction. The arrows show the artifact reduction in the images when using a field map in the reconstruction. Figure 2 shows 4 slices from an 8 slice 3D FSE acquisition. Here we chose to run a variable flip angle train of pulses approaching 45^o. Some of the artifacts in the image are due to small distortions of the spirals when played in the MRI scanner, e.g., eddy currents, making the k-space subsampled.

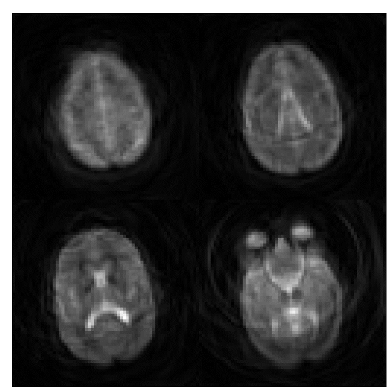

Figure 2: 3D FSE images of a brain

Discussion

We presented a spiral-in spiral-out method, where each spiral is 1 interleave of a 2 interleave spiral trajectory. This acquisition scheme allows for acquisition of the data during the rephasing and dephasing of the echo, with the center of k-space being acquired when the echo is perfectly rephased, improving SNR and eliminating T_2' weighting of the acquired data. Since we merge the data from the two spirals, the method depends on the sampling of the combined data to be adequate; Any skewing of the trajectories when played on the scanner should be minimal to ensure an artifact free image. The artifacts can be reduced by including effects of off-resonance. To further improve image quality one can measure the gradient waveform [3] that is being played on the scanner and correct for any distortions to the spirals due to eddy currents or other possible hardware problems.

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References

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