GPU accelerated iterative SENSE reconstruction of radial phase encoded whole-heart MRI

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Introduction

Isotropic whole-heart imaging has become an important protocol in simplifying cardiac MRI. The acquisition time can however be a limiting factor when acquiring large field-of-views at high spatial resolutions. To reduce acquisition times, a three-dimensional (3D) acquisition scheme combining Cartesian sampling in the readout direction with a radial sampling scheme in the phase encoding plane, was recently suggested [1]. This encoding scheme allows high undersampling factors in the phase encoding plane when obtaining data with a 32-channel coil array and employing non-Cartesian iterative SENSE [2] for reconstruction.

To reconstruct the 3D volume, initially the fast Fourier Transform (FFT) is applied in the fully sampled readout direction, converting the remaining reconstruction problem into a series of two-dimensional radial reconstructions. Unfortunately this reconstruction is a time consuming process; using Matlab a reconstruction time of 3 minutes/slice when using 32 coils for a 256 slice acquisition was reported (the total reconstruction time was over 12 hours) [1]. The purpose of the present abstract is to demonstrate that the reconstruction time can be brought to a clinically acceptable level using commodity graphics hardware (GPUs) and a dedicated parallel implementation of the non-Cartesian SENSE reconstruction. Such an approach was recently demonstrated for real-time iterative SENSE reconstruction of two-dimensional (2D) radial imaging [3].

Theory and Methods

Acquisition: SSFP imaging (90° flip angle, TR/TE=5.0 ms/2.28 ms, 32 receive channels) during free breathing (6 mm navigator window) was used to acquire a 3D dataset in end diastole using a resolution of 1.3^3 mm^3 (scan time would be 8 minutes at 100% navigator efficiency) on a 1.5T system (Philips Achieva). The dataset contained 64*256=16384 lines of *k*-space data using Cartesian sampling in the readout (feet-head) direction. In the phase encoding plane these were laid out as 64 radial profiles of 256 samples each. In this work we define a fully sampled 2D *k*-space for the desired 256x256 matrix as one containing 256^2 samples. Thus for each slice, the current acquisition scheme utilized an angular undersampling factor in $R_\theta = 4$ and radial undersampling factor $R_p = 1$. We subsequently simulated further undersampling of the acquired dataset by leaving out half of the acquired samples in the radial direction (radial undersampling, $R_p = 2$) and by removing every other profile (angular undersampling, $R_\theta = 8$). We consequently reconstructed 3 datasets using the settings $R_\theta = 4,\ R_p = 1;\ R_\theta = 4,\ R_p = 2;\ R_\theta = 8,\ R_p = 2$ with corresponding oversampling factors $R = R_\theta * R_p = \{4, 8, 16\}$ respectively.

Reconstruction: Each 2D radial iterative SENSE reconstruction was performed on the GPU adapting parts of the implementation described in ref. [3] using a target matrix size of 256x256 for 256 slices. As opposed to ref. [3] the coil sensitivity maps were acquired in a separate reference scan. Also, no explicit regularization term was included in the reconstructions since radial undersampling ($R_p > 1$) makes the standard approaches unfeasible. We used 10 iterations of the conjugate gradient solver. For the required gridding steps we used an oversampling factor of 2 and a Kaiser-Bessel kernel of width 5.5. The data was reconstructed on an Nvidia Geforce 280 GTX GPU with 1GB of memory. The host system was a 64bit Windows XP system with 4GB of memory.

Results

Figure 1 shows three reformatted slices (transversal, coronal, and sagittal view) from the three reconstructed, isotropic 3D volumes. Table 1 shows the corresponding reconstruction times per slice. Reconstruction times range from 1.11s to 1.28s per slice. These numbers include data transfers from disc taking roughly 0.5s. In total, the full 3D datasets (256 slices) were each reconstructed in 5-6 minutes.

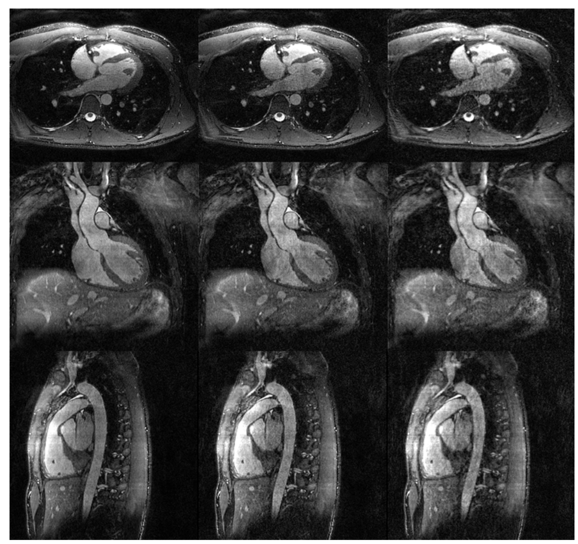

Figure 1. Reformatted transversal (top row), coronal (middle row) and sagittal (bottom row) planes from a 3D whole heart reconstruction with undersampling factors $R = R_\theta * R_p$. Left column: $R = 4 * 1 = 4$. Middle column: $R = 4 * 2 = 8$. Right column: $R = 8 * 2 = 16$.

	$R_\theta = 4$, $R_p = 1$	$R_\theta = 4$, $R_p = 2$	$R_\theta = 8$, $R_p = 2$
Pre-processing (once)	0.7	0.7	0.7
Full reconstruction / slice *	**1.28**	**1.18**	**1.11**
* includes			
Load data (disc → GPU)	0.48	0.48	0.48
Iterative SENSE	0.80	0.70	0.63

Table 1. Reconstruction times in seconds for different undersampling factors $R \in \{4, 8, 16\}$ (see Figure. 1).

Discussion

Using an inexpensive commodity GPU we reduced the reconstruction times for the 3D radial phase encoded datasets from multiple hours to a clinically acceptable level of 5-6 minutes. The three volumes depicted in the three columns in Figure 1 show the obtainable image quality at different undersampling levels – corresponding to scan times of approximately 8, 4, and 2 minutes respectively (assuming 100% navigator efficiency). To achieve these results we used data for which a 1D FFT had already been applied along the readout direction. We do not consider this as a limitation to our results as these FFTs could in fact have been performed immediately after each readout during the acquisition – and before storing the data. I.e. we believe to have demonstrated clinically acceptable reconstruction times. Nonetheless, there is a fairly straightforward approach to reduce reconstruction times further if need be; it is possible to upload data to the GPU asynchronously while a reconstruction takes place. From Table 1 one can see that taking such an approach would result in approximately a 40% reduction in the overall reconstruction time when removing the cost of data transfer completely. Note also, that since the simulated undersampling of datasets 2 and 3 took place on the GPU after upload, the data transfer row in Table 1 is identical for the three datasets.

References

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