Low-Latency Radial GRAPPA Reconstruction using Multi-Core CPUs and General Purpose GPU Programming

Haris Saybasili[1,2], Daniel A. Herzka[2], Nicole Seiberlich[3], and Mark Griswold[1,3]

[1]*Department of Radiology, Case Western Reserve University, Cleveland, OH, United States,* [2]*Biomedical Engineering, Johns Hopkins University School of Medicine, Baltimore, MD, United States,* [3]*Biomedical Engineering, Case Western Reserve University, Cleveland, OH, United States*

INTRODUCTION: Real-time imaging using non-Cartesian k-space trajectories can yield images with excellent quality. Very high acceleration rates with parallel imaging are possible when using non-Cartesian strategies due to oversampling of the center of k-space. However, reconstruction methods such as through-time radial generalized autocalibrating partially parallel acquisitions (GRAPPA) [1] and conjugate gradient sensitivity encoding (CG-SENSE)[2] are computationally demanding, leading to long reconstruction times and unacceptable latency for real-time acquisitions. CG-SENSE has been shown to work with low latency by moving from regular computational hardware to graphical processing units GPUs[3]. No such transition has been shown for non-Cartesian GRAPPA. In this work, we present a hybrid (CPU- and GPU-based), fully auto-calibrated, fast reconstruction implementation for through-time radial GRAPPA. The main motivation for using radial GRAPPA was its k-space driven calibration that provides very robust reconstructions from undersampled acquisitions. Unlike CG-SENSE, radial GRAPPA does not involve multiple iterations that may take too long to achieve good image quality for low latency applications.. Results on the performance for both radial GRAPPA weights calculation and image reconstructions are presented for varying rates of acceleration.

METHODS: ***Software Implementation****:* The radial GRAPPA process can be broken down into two separate components: (1) calibration, implemented using multi-threaded CPU programming, and (2) image reconstruction, completely performed on a GPU (Figure 1). Gridding was performed on the GPU using real-time GRAPPA operator gridding (RT-GROG) [4], a parallel imaging based approach with very low latency. A 2x-oversampled grid was used for gridding accuracy [5]. Memory intensive calibration processes were implemented on the CPUs, permitting asynchronous calibration and reconstruction [4,6]. Note that weight calculation processes could be ported to GPUs, if multiple GPUs are present on the system. The Atlas library (http://math-atlas.sourceforge.net/) was used for matrix operations during calibration, and the OpenMP library (http://openmp.org) was used for parallelization. Reconstruction was performed on the GPU, using CUDA 4.0 (http:// http://developer.nvidia.com/cuda-toolkit-40) which includes the CuFFT library used for FFT operations.

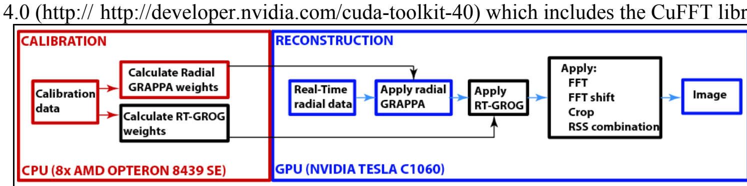

Figure 1. Schematic depiction of calibration (red) and reconstruction (blue) processes. Performances of the operations in black boxes do not depend on acceleration rate.

Processing: First, fully-sampled radial data were acquired to calculate through-time radial GRAPPA and RT-GROG weights. To improve conditioning in the weights calculation, groups of 4 continuous samples in each readout were assumed to have the same weights [1]. Thirty to 80 fully-sampled frames (repetitions through time) and block size 2x3 were used during radial GRAPPA calibration. Weights calculation for (R-1) missing samples and their estimation were computed at once. Hence, lower acceleration rates required more matrix operations on smaller matrices (smaller load, lower resource utilization), while higher acceleration rates used fewer matrix operations but on bigger matrices (bigger load, higher resource utilization) to ensure better performance for higher acceleration rates. Performance was measured separately for both image reconstruction and weight estimation for datasets with varying number of coils, varying number of repetitions through time, and varying acceleration rates.

MRI: MRI was performed on a 1.5T Siemens Espree scanner (Siemens, Erlangen, Germany). Acquisition parameters were: acquisition matrix=144x256, TR=2.64ms, FOV=300mm, BW=1115Hz/px. Imaging was performed with prior written informed consent and local IRB approval in three healthy volunteers, and not breathholding or EKG gating was employed during the acquisition of either the calibration or undersampled datasets.

RESULTS: Figure 2 shows the execution times for calibration and reconstruction. RT-GROG weights were calculated (on average) in 0.098 seconds for a 12 coil dataset, and in 0.120 seconds for a 15 coil dataset. Radial GRAPPA weights calculations were more time consuming, though performance depended significantly on the calibration data size and the acceleration rate. Weights calculated from 30 repetitions through time provided acceptable image quality, while the best image quality was obtained with 80 repetitions. Short-axis full FOV, systolic and diastolic cardiac images (rate 9, 42 ms temporal resolution) are presented in Figure 3.

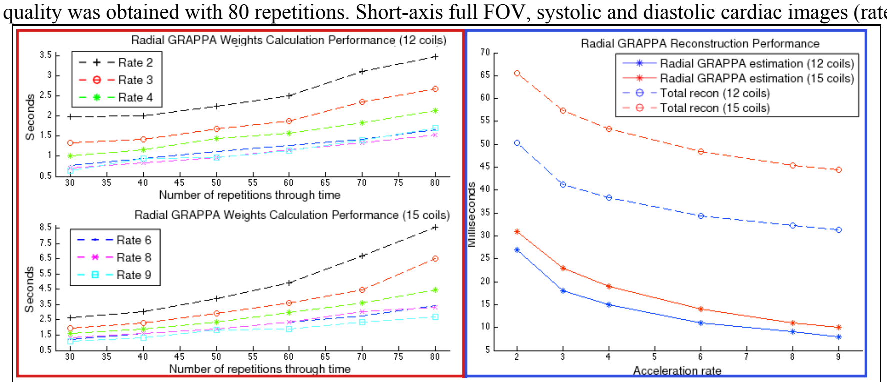

Figure 2. Radial GRAPPA reconstruction and weights calculation performances using 12-15 coils, 144x256 k-space data for different acceleration rates. Temporal resolution was between 190 ms (rate 2) and 42 ms (rate 9). ***Weights calculation:*** Performance values in seconds for different number of repetitions through time. ***Reconstruction:*** Performance values for application of radial GRAPPA and total reconstruction (includes data transfers to/from GPU and RSS combination).

DISCUSSION: We present a low-latency radial GRAPPA reconstruction pipeline using multi-threaded CPU and GPU programming. These results indicate that real-time, online low-latency radial GRAPPA reconstruction is possible. An example application in cardiac imaging is demonstrated. High acceleration rates were achieved with image reconstruction matching data acquisition. Though conventional gridding can be used to map the radial k-space data onto the Cartesian grid for FFT, we chose to use RT-GROG to benefit from data driven calibration with negligible time penalties. Asynchronous calibration and reconstruction processes permit the deployment of our implementation during real-time MRI guided interventional procedures where scan plane changes often.

REFERENCES: **[1]** Seiberlich et al. Magn Reson Med. 2010; 65:492-505. **[2]** Pruessman et al. Magn Reson Med 2001; 46:638-651. **[3]** Sorensen et al. IEEE Trans Med Imag. 2009; 28: 1974-1985. **[4]** Saybasili et al. Magn Reson Med. 2010; 64:306-312. **[5]** Seiberlich et al. Magn Reson Med. 2008; 59:930-5. **[6]** Saybasili et al. Magn Reson Med. 2009; 61:1425-1433.

Figure 3. Radial GRAPPA images reconstructed from 12 coil, 144x256, rate 9 radial acquisition; 16 projections were used during reconstruction of these real-time cardiac imaging examples. From left to right: full FOV image, systolic image (1.6x), diastolic image (1.6x).
Acquisition time: 42 ms
Reconstruction time: 33 ms (includes data transfers to/from GPU and RSS combination).