Parallel Reconstruction for Cartesian Golden Step MRI with Arbitrary Temporal Resolution, Field-of-view and Acceleration Rate.

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Introduction: Real-time MRI mostly involves single or multiple 2D slices in which spatial resolution is compromised for higher temporal resolution. Typically, images can only be reconstructed for a fixed set of initially prescribed parameters, such as spatial resolution, FOV, and temporal resolution. Acquisition schemes based on the principle of acquiring k-space by recursively sub-sampling the support region in the ratio of the Golden section have been proposed for a radial [1] and, recently, Cartesian MRI [2]. These methods provided an almost uniform distribution of projections after any arbitrary number of phase encoding steps. With more acquisitions, the k-space becomes more densely sampled, eventually becoming massively oversampled. No projection is ever exactly repeated, and at no point does the sampling ever become exactly uniform. These conditions permit real-time imaging with retrospective selection of temporal resolution, field-of-view, parallel imaging acceleration rate, but also necessitate a parallel imaging reconstruction for non-uniform data that varies in its sampling pattern from one time-frame to the next. We are currently investigating several approaches to reconstructing these data. In this work, we propose a fully auto-calibrated reconstruction method based on the GRAPPA [3] approach for golden-step Cartesian imaging. Golden-step data are mapped onto a Cartesian grid using 1D SC-GROG [4], and then GRAPPA is applied to estimate missing lines prior to FFT.

Methods: MRI was performed on a 1.5T Siemens Avanto scanner (Siemens, Erlangen, Germany) with a 32 channel array coil (Rapid Biomedical, Rimpar, Germany). Balanced SSFP and RF-spoiled GRE (SPGR) sequences were modified so that the phase encoding gradients were advanced by the Golden fraction ($(\sqrt{5}-1)/2$) of the k-space. Typical acquisition parameters were: TE/TR=1.15/2.3ms (bSSFP) and TE/TR=2.12/4.26ms (SPGR), ~4500 TR acquisitions, and 2.5×2.5×7mm resolution.

Images were reconstructed offline using Matlab (The Mathworks, Natick, MA). The gridding problem was solved by applying 1D SC-GROG. Following the FOV selection, 1D SC-GROG shifting weights were calculated using whole golden-step acquisition data. The whole golden-step dataset was then gridded using newly calculated shifting weights to obtain a fully sampled, averaged, reference Cartesian k-space data to calibrate GRAPPA weights. Multiple GRAPPA weights (for different acceleration rates) were required for a single frame reconstruction due to non-uniform gaps on the gridded golden-step k-space data. Once GRAPPA weights were calculated, multiple sets of images were reconstructed retrospectively from the same dataset by applying SC-GROG gridding followed by GRAPPA using different imaging parameters. Calibration and reconstruction processes are depicted in Figure 1.

The proposed reconstruction method was tested on phantom data. Method validation was performed with prior written informed consent and local IRB approval in two healthy volunteers. The normal volunteer acquisitions comprised real-time, free-breathing, ungated scans of the cardiac long and short axes.

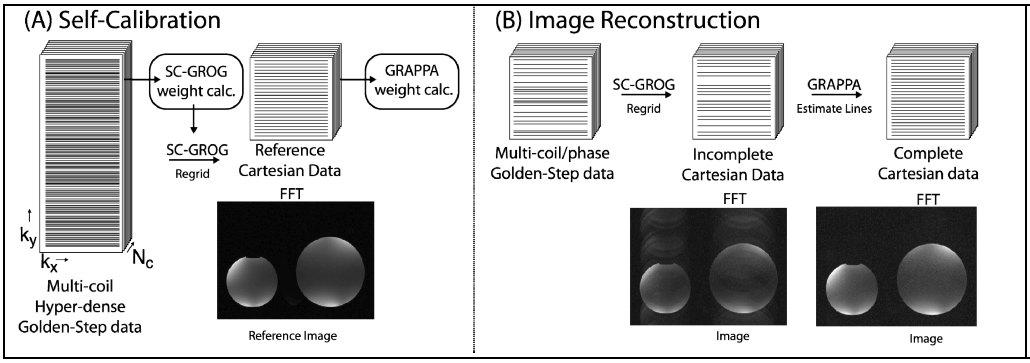

Figure 1: Image reconstruction scheme

(A) Calibration: multi-coil golden-step data is sorted, and 1D SC-GROG shifting weights are calculated. Whole data are then gridded to obtain reference Cartesian data, and GRAPPA weights for different acceleration rates are calculated.

(B) Reconstruction: multi-coil/phase data is gridded using 1D SC-GROG shifting weights. GRAPPA is then applied to fill in the gaps in the gridded Cartesian data. Final image is obtained by FFT.

Results: Figure 2 shows short axis SSFP (top row) and long axis SPGR (bottom row) cardiac images (matrix size 144×128, and 128×128 respectively) reconstructed with different temporal resolutions and acceleration rates R=1:4 are shown in Figure 2. Image quality decreases with increased acceleration rates, as expected.

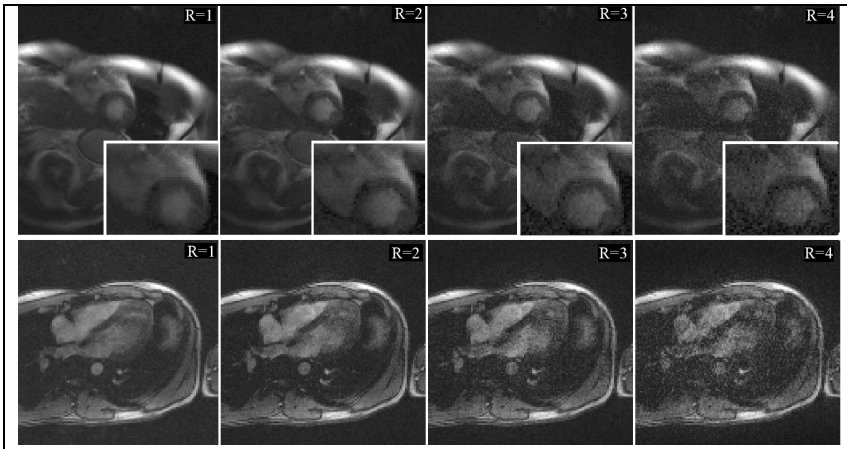

Figure 2: Ungated Cardiac Imaging

Real-time, short and long axis healthy volunteer cardiac images reconstructed with different acceleration rates are represented. For a given matrix size *yres-by-xres*, acceleration rate of R implies *yres/R* golden step lines to reconstruct images. For example, if *yres* is 128, and R is 4, only 32 golden-step lines will be used to reconstruct one frame.

Top row: SSFP short-axis images, with acceleration rates of 1, 2, 3 and 4 (from left to right). Matrix size: 144×128, temporal resolution: 330ms (R=1), 165ms (R=2), 110ms (R=3), and 83ms (R=4). Septal wall is zoomed in at the right hand corner of each images.

Bottom row: SPGR long-axis images, with acceleration rates of 1, 2, 3 and 4 (from left to right). Matrix size: 128×128., temporal resolution: 545ms (R=1), 273ms (R=2), 182ms (R=3), and 136ms (R=4).

Conclusions: Golden-step imaging permits almost uniform k-space sampling from an arbitrary number of acquisitions, and thus provides high flexibility for temporal window width and position, and acceleration rate selection. In this way, temporal resolution can be retrospectively traded for SNR and image quality from a given dataset. In this work, we proposed and demonstrated a fully auto-calibrated GRAPPA based reconstruction scheme for real-time, free breathing, ungated golden-step Cartesian imaging. Our scheme permits the reconstruction of different sets of images each with different FOV, temporal resolution and acceleration rate from the same data set in a completely auto-calibrated manner. We found out that the highest achievable acceleration rate with acceptable image quality with our method was R=3. In general, SSFP images were sharper than the SPGR images for the same acceleration rate, as expected.

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[3] Griswold et al. Magn Reson Med. 2002;**47**(6):1202-10. **[4]** Seiberlich et al. Magn Reson Med. 2008;**59**(4):930-5.