High Temporal Resolution Retrospective Real-time Cine Imaging: Shortened Acquisition via Nonlinear Reconstruction

Hui Xue[1], Peter Kellman[2], Andrew E. Arai[2], and Michael Schacht Hansen[2]

[1]*Siemens Corporate Research, Princeton, New Jersey, United States,* [2]*National Institutes of Health, National Heart, Lung and Blood Institute, Bethesda, Maryland, United States*

Introduction While cardiac cine MRI with breath-hold, segmented acquisition has been clinically accepted for function and flow evaluation, it is less robust under imperfect breath holding and arrhythmia [1]. For these cases, real-time free-breathing cine can be a valuable alternative. However, despite the advances in rapid imaging sequences and parallel imaging, real-time cine still has compromised spatio-temporal resolution, compared to the segmented techniques. Furthermore, real-time cine images are not retrospectively gated and affected by respiratory motion, which makes quantitative measurement of cardiac function more difficult. As a result, commercial software for cine image analysis may not take real-time images as input for correct cardiac functional evaluation. One strategy to reconstruct retrospectively gated high temporal resolution cine from real-time acquisition has been proposed in [2], which is based on respiratory motion correction and binning of *k*-space data over multiple heartbeats. The main obstacle to use this method in a clinical setting is the lengthy acquisition needed for sufficient *k*-space coverage (60s acquisition is used in [2]). While the iterative motion correction has been combined into this binning workflow and decreases the acquisition period to ~30s [3], it is still desirable to further shorten the acquisition while maintaining the robustness. Towards this end, we propose to utilize the non-linear reconstruction to fill missing *k*-space lines after the binning. The entire workflow is implemented inline on the scanner. In-vivo studies show robust reconstruction can be achieved with 10s of data. Image quality is comparable to segmented cine.

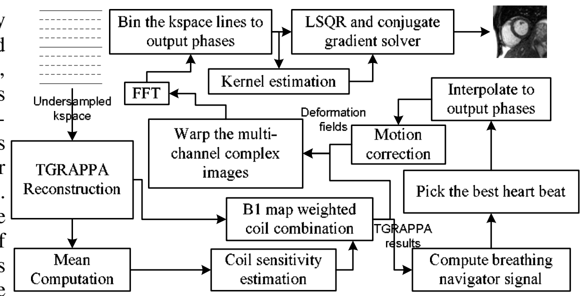

Figure 1. Schematic diagram of proposed reconstruction scheme.

Material and Methods ***Reconstruction workflow:*** As shown in Fig. 1, the real-time acquired temporally interleaved *k*-space data are averaged to generate the auto-calibration signals and a TGRAPPA reconstruction of real-time images is performed. Resulting images are used as input in the non-rigid registration module to estimate an image-based respiratory navigator, as proposed in [2]. The deformation fields are also used to warp multi-channel complex images of TGRAPPA reconstruction for every output phase bin. After complex images are warped to correct respiratory motion, they are converted back to *k*-space. The ECG trigger time of every resulting *k*-space line is interpolated from the recorded ECG time on the acquired lines. The warped *k*-space lines are then binned and averaged according to the output phase bins. The resulting binned *k*-space can have 'holes' (e.g. Fig. 2(k)) when the acquisition is short. To fill these holes and thus stabilize the reconstruction, the TSPRiT reconstruction [4] with spatio-temporal regularization is applied to compute the retro-gated *k*-space. Given the binned *k*-space $\boldsymbol{a}$, the TSPIRiT aims to reconstruct the complex images $\boldsymbol{x}^*$ by solving the following optimization problem: $\boldsymbol{x}^* = \boldsymbol{min}_{\boldsymbol{x}}\{\|(\boldsymbol{G}-\boldsymbol{I})\boldsymbol{F}\boldsymbol{x}\|_2 + \lambda \cdot \|\boldsymbol{\psi}\boldsymbol{C}^H\boldsymbol{x}\|_1 + \beta \cdot \|\boldsymbol{D}\boldsymbol{F}\boldsymbol{x}-\boldsymbol{a}\|_2\}$. Here $\boldsymbol{x}$ is N_c channels of unknown complex image series. $\boldsymbol{G}$ is the concatenated SPIRiT kernels computed on mean *k*-spaces which are binned and warped for every output phase. $\boldsymbol{F}$ is the Fourier transform and $\boldsymbol{C}$ is the coil sensitivity. $\boldsymbol{C}^H\boldsymbol{x}$ represents the coil combination, converting the multi-channel complex image to the coil combined image which is then fed into the 2D+T wavelet transform $\boldsymbol{\psi}$. As shown in Fig. 2, this nonlinear reconstruction step is essential for shortened acquisition, as missing lines in binned *k*-space can drastically degrade image quality. ***Inline reconstruction:*** All processing steps were implemented using C++ on the Gadgetron [5] framework, which ran on a PC (Intel Xeon E5620 2.40GHz, 40G RAM, 8 cores) connected to the scanner. While the acquisition is proceeding, every readout line is sent to the Gadgetron computer. Once all readouts for a slice are acquired, the reconstruction starts. Entire reconstruction takes ~150s. TGRAPPA images are reconstructed and displayed before completion of entire process for quick reviewing. Entire process is fully automated and all resulting images are sent back to the scanner from the Gadgetron computer without interrupting the clinical workflow. ***In-vivo study:*** 10 volunteers (4 males; age 19.4‒66.2yrs) underwent free-breathing cine examination with written consent. For each subject, 10s of real-time data from one short-axis slice was used. Typical imaging parameters as: bSSFP readout, acquired matrix 256×144, resolution 1.4×1.9mm^2, R=4 time-interleaved undersampling, BW 930Hz/pixel, acquired temporal resolution 110ms. All data were reconstructed to 30 output phases.

Results Figure 2 shows the comparison of example raw real-time images, direct FFT reconstruction on the binned k-space, linear SPIRiT and the segmented acquisition with identical slice prescription. For all cases, the image quality of nonlinear retro-gated reconstruction is the most comparable to the segmented cine, while FFT reconstruction causes noticeable artifacts in 8 cases due to missing lines. The measured SNR of end-systolic septum is 4.5±0.9/7.3±2.4/7.2±1.6/9.3±2.2/10.0±2.1 for raw/FFT/linear/nonlinear/segmented cine (P<0.05 for nonlinear vs. linear, P=0.51 for nonlinear vs. segmented). With the manually tracing the endo-myocardial boundary, the estimated ejection fraction based on the single short-axis slice has average value 56.5±8.1% for the segmented cine and 57.7±6.8% for the nonlinear reconstruction (P=0.49, paired t-test).

Conclusions The nonlinear reconstruction with spatio-temporal regularization is adopted to shorten the required acquisition time for retrospective reconstruction of real-time cardiac cine images. With the nonlinear reconstruction to fill missing lines in binned *k*-space, good image quality can be achieved with 10s acquisition. The usability of proposed method is further enhanced by integrating entire workflow into the scanner via the Gadgetron framework.

References [1] Kaji, S, et al., JACC 38:527-533 (2001) [2] Kellman P, et al., MRM 62:1557-1564 (2009) [3] Hansen MS, et al., MRM 68:741-750 (2012) [4] Xue H, et al., ISMRM 3846 (2012) [5] Hansen MS, et al., MRM doi: 10.1002/mrm.24389

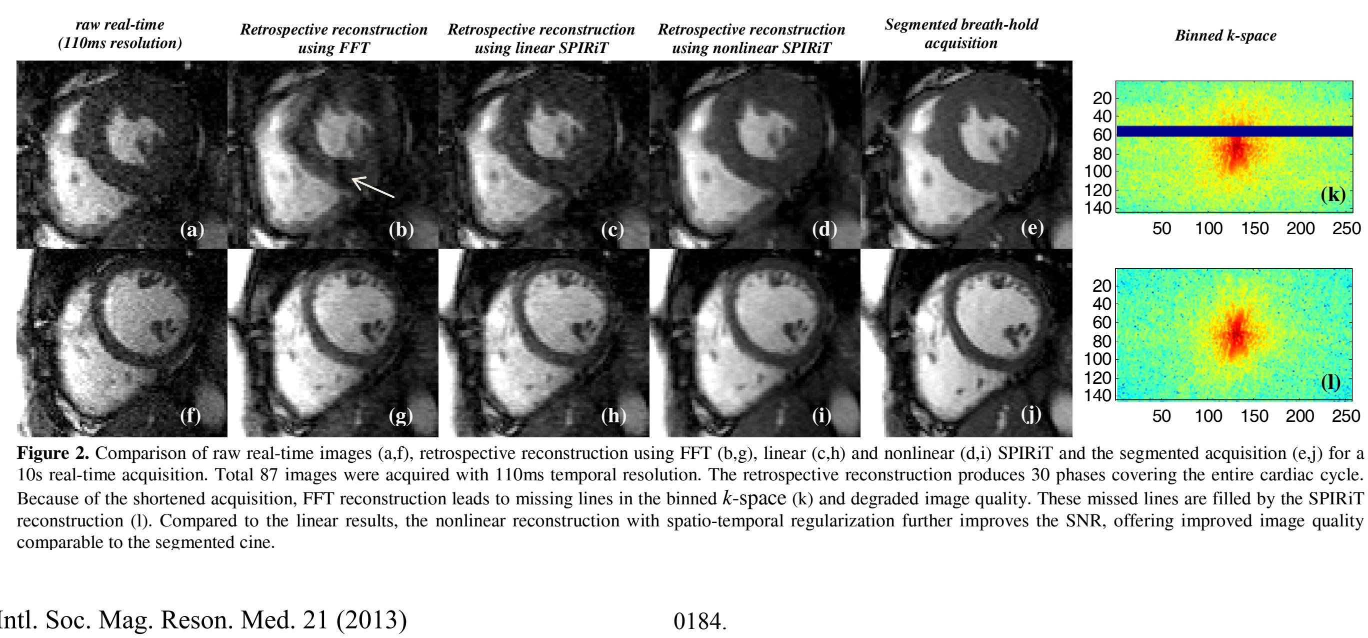

Figure 2. Comparison of raw real-time images (a,f), retrospective reconstruction using FFT (b,g), linear (c,h) and nonlinear (d,i) SPIRiT and the segmented acquisition (e,j) for a 10s real-time acquisition. Total 87 images were acquired with 110ms temporal resolution. The retrospective reconstruction produces 30 phases covering the entire cardiac cycle. Because of the shortened acquisition, FFT reconstruction leads to missing lines in the binned *k*-space (k) and degraded image quality. These missed lines are filled by the SPIRiT reconstruction (l). Compared to the linear results, the nonlinear reconstruction with spatio-temporal regularization further improves the SNR, offering improved image quality comparable to the segmented cine.