Free-breathing Motion Corrected Phase Contrast Flow Quantification

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TARGET AUDIENCE: Clinicians and research scientists with an interest in phase contrast flow quantification and respiratory motion correction for cardiac imaging.

PURPOSE: To accelerate and improve free-breathing phase contrast flow quantification studies. Phase contrast flow measurements can be acquired during a breath-hold. However, acquisitions with high spatial and temporal resolution require long breath-holds that are poorly tolerated by patients and susceptible to problems with arrhythmias. Consequently, phase contrast studies are often acquired during free breathing but with multiple averages (long term averaging) to mitigate breathing artifacts. The resulting free breathing acquisitions are long (on the order of minutes) and can suffer from blurring caused by the respiratory motion. The purpose of this work was to incorporate explicit motion correction into the reconstruction algorithm thereby reducing the length of the acquisition and potentially improving image sharpness.

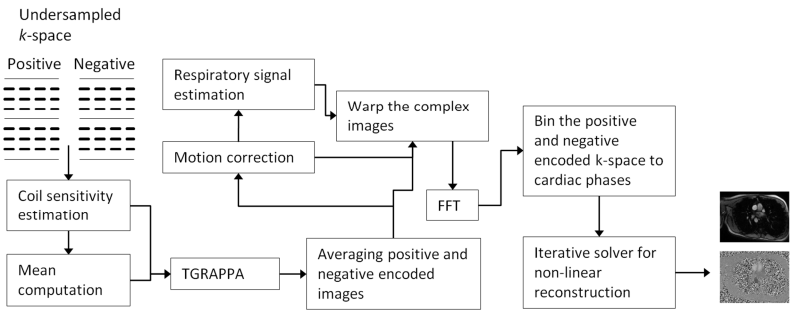

Figure 1. An outline of proposed retrospective flow imaging scheme.

METHODS: To achieve complete free-breathing, retro-gated, high temporal resolution cardiac flow imaging with reduced scan time, we extended a previously developed retrospective motion corrected cardiac cine imaging technique [1, 2] to phase contrast flow measurements. As illustrated in Figure 1, positive and negative velocity encoding gradient were applied to real-time acquired temporally interleaved *k*-space data. Acquired interleaved *k*-spaces were averaged to generate the auto-calibration signal and a TGRAPPA reconstruction was performed. Resulting magnitude images of both encoding directions were averaged and used as input to a non-rigid registration module to estimate an image-based respiratory navigator. The resulting deformation fields were used to warp multi-channel complex images of both flow encoding directions for every retro-gated output phase. After the complex images were warped, they were converted back to two separate *k*-spaces. The ECG trigger time of every resulting *k*-space line was computed from the recorded ECG time of the acquired lines. The warped *k*-space lines were binned and averaged into the output cardiac phase bins. Resulting two binned *k*-spaces were used as input to a TSPRiT reconstruction [2] with spatio-temporal regularization applied to compute the retro-gated *k*-spaces. Given the binned *k*-space $\boldsymbol{a} = [\boldsymbol{p}; \boldsymbol{n}]$ where $\boldsymbol{p}$ and $\boldsymbol{n}$ are positive and negative encoded *k*-space, the algorithm aims to reconstruct the complex images $\boldsymbol{x}^* = [\boldsymbol{x}_p^*; \boldsymbol{x}_n^*]$ by solving the following optimization problem: $\boldsymbol{x}^* = \boldsymbol{min}_x\{\|(\boldsymbol{G}-\boldsymbol{I})\boldsymbol{F}\boldsymbol{x}\|_2 + \boldsymbol{\lambda}\cdot\|\boldsymbol{\psi}\boldsymbol{C}^{\boldsymbol{H}}\boldsymbol{x}\|_1 + \boldsymbol{\beta}\cdot\|\boldsymbol{D}\boldsymbol{F}\boldsymbol{x}-\boldsymbol{a}\|_2\}$. Here $\boldsymbol{x}$ is $\boldsymbol{N_c}$ channels of unknown complex image series. $\boldsymbol{G}$ is the concatenated SPIRiT kernels for both flow directions and temporal phases. $\boldsymbol{F}$ is the Fourier transform and $\boldsymbol{C}$ is the coil sensitivity. $\boldsymbol{\psi}$ is the 2D+T wavelet transform, only within positive or negative encoded flow images. In other words, regularization is not applied across flow encoding directions. The resulting phase images were then subtracted to compute velocity quantities. ***Inline reconstruction:*** All processing steps were implemented using C++ on the Gadgetron [3] platform, which ran on a PC (Dual Intel Xeon E5-2670 2.60GHz, 192G RAM, 16 cores) connected to the scanner. Entire reconstruction took ~1.5mins and all magnitude and phase images were sent back to the scanner from the Gadgetron server. ***In-vivo study:*** One healthy volunteer underwent both breath-hold segmented and free-breathing flow acquisition with written informed consent. 40s of real-time data from pulmonary vessel plane was acquired. Imaging parameters were: Spoiled gradient echo (FLASH) readout, acquired matrix 192×128, resolution 1.8×2.8mm^2, R=4 time-interleaved undersampling, BW 910Hz/pixel, acquired temporal resolution 270ms, TE 2.38ms, flip angle 20^o. All data were reconstructed to output 30 cardiac phases (approx. 33ms temporal resolution for a nominal 1s RR interval). The segmented flow data with matching spatial resolution and slice prescription was acquired with 2x under-sampling in a 14s breath-hold duration and also repeated three times for the averaging purpose.

RESULTS: Figure 2 shows an example comparing the segmented breath-hold (a,d), segmented free-breathing with three averages (b,e) and motion corrected free-breathing flow (c,f). Both magnitude and phase images are plotted and the flow curves were extracted from the pulmonary. While the raw real-time flow images have very low temporal resolution, the retrospective scheme recovers the temporal fidelity of the velocity curve and offers comparable quality to the segmented scan, without the need of breath-holding. The measured cardiac outputs on pulmonary were respectively 5.17, 5.06 and 5.05 L/min for three methods. The motion corrected acquisition took only 40s while the free breathing scheme with three averages took ~1min.

DISCUSSION AND CONCLUSION: A new scheme was proposed for free breathing, motion corrected, retro-gated cardiac flow imaging with high temporal resolution. The key features involve respiratory motion correction, *k*-space rebinning and regularized nonlinear reconstruction within each flow encoding direction. Volunteer study showed comparable image quality can be achieved with a 40s free-breathing acquisition. The clinical deployment of proposed method is achieved by integrating entire workflow into the Gadgetron framework directly linked to the scanner.

References [1] Kellman P, et al. MRM 2009;62:1557-1564. [2] Xue H, et al. JCMR 2013;15:102. [3] Hansen MS, et al. MRM 2013;69(6):1768-1776.

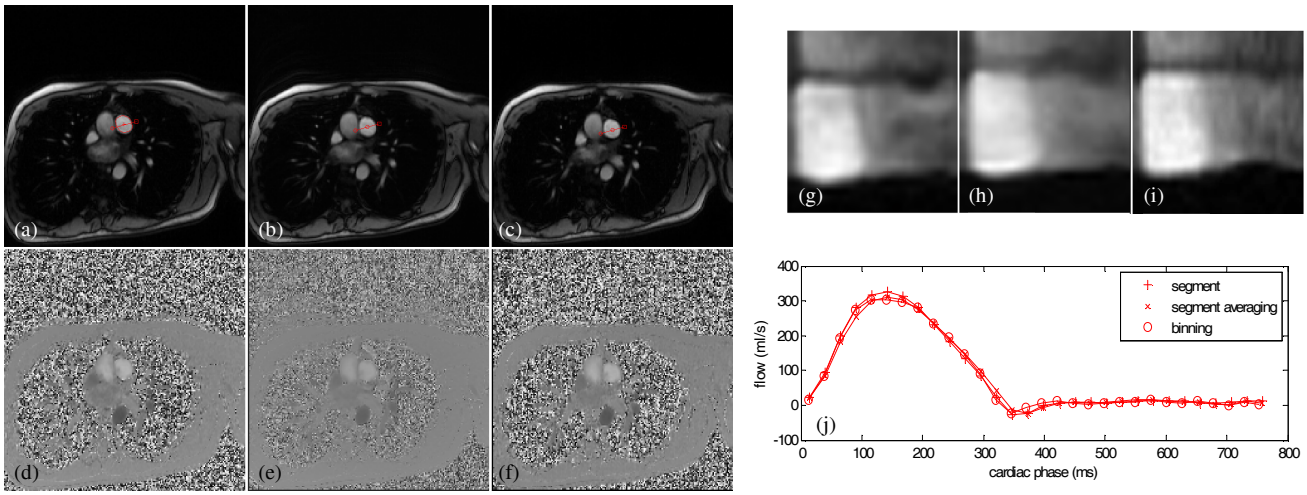

Figure 2. Comparison of segmented breath-hold acquisition (a,d), segmented free-breathing acquisition with three averages (b,e) and proposed free-breathing motion corrected imaging scheme (c,f). Both magnitude (a,b,c) and flow velocity images (d,e,f) are shown. The motion corrected acquisition was acquired in 40s while the segmented acquisition requires breath-hold and took 14s. The segmented acquisition with three averages took ~1min to acquire. The temporal intensity profiles across cardiac phases are plotted for pulmonary (g,h,i). The flow rate (j) was measured by segmenting the pulmonary vessel lumen for 30 cardiac phases, which shows the proposed method well recovers the flow velocity changes; even the acquired raw real-time images have very low temporal resolution.