Soft-gated accelerated Cartesian 4D flow imaging with intrinsic navigation

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PURPOSE: Time-resolved phase contrast MRI (4D flow) can quantify cardiac function and flow. Modern acceleration methods enable clinically practical scan times of 3-10 min. Furthermore, 4D flow may even permit complex anatomical assessment, thus comprising a comprehensive exam in a single scan. However, artifacts from respiratory motion may compromise this ability. We develop a motion-compensated approach to improve the reliability and resolution of 4D flow imaging.

METHOD: *Data acquisition:* Two modifications are made to a standard cardiac-gated 3D Cartesian spoiled GRE sequence with unbalanced minimum echo time flow encodings[1]. First, butterfly[2] navigators are readily available simply by extending the readout window to include the flow-encoding gradients. Since the flow encodings are repeated throughout the scan, these flow-encoding gradients provide sufficient data to monitor motion intrinsically without any alteration to the gradient waveforms (Fig 1a).

Second, the Variable-Density sampling & Radial view-ordering (VDRad[3]) scheme is incorporated and modified to be synchronized to the cardiac cycle (Fig 1b & 1c). VDRad achieves variable-density subsampling with unique sampling patterns for each temporal phase – beneficial for compressed-sensing[4] reconstructions. The golden-ratio ordering[5] and the re-sampling of the k-space center make the acquisition even more robust to motion.

Reconstruction: Motion estimated from Butterfly flow navigators are incorporated as soft-gating weights[3,6] in an ESPIRiT[7,8] parallel imaging & compressed sensing framework:

$$m = \text{argmin}_m \frac{1}{2}\|W(Am - y)\|_2^2 + \lambda_x\|\Psi_x m\|_1 + \lambda_t\|D_t m\|_1,$$

where m are the recovered images, W soft-gates the data based on the degree of respiratory motion as provided by the navigators, A is a linear model that includes coil sensitivity ESPIRiT eigen maps and subsampling (with reduction factor R), and y is the acquired k-space data. For compressed sensing, Ψ_x is a spatial wavelet operator that favors spatial sparsity, and D_t is a finite difference operator in the temporal cardiac cycle dimension that favors temporal sparsity. Regularization parameters λ_x and λ_t are experimentally tuned.

Experiment: With IRB approval and informed consent, subjects were scanned on a 3T GE MR750 scanner using a 32ch cardiac coil and ferumoxytol enhancement. Scan parameters include TE of 1.8 ms, TR of 9.1 ms with fat saturation pulse, flip angle of 15°, resolution of 0.8×0.8×1.4 mm^3, FOV of 26x18x17 cm^3, bandwidth of ±83.33 kHz, and scan time of 9-11 min.

RESULTS: The Butterfly flow navigators capture the respiratory motion waveforms and provide accurate 3D motion estimates. This is demonstrated through improved image quality when these motion estimates were applied for a simple motion correction (Fig. 2). VDRad was able to reduce motion artifacts and to limit ghosting typically seen in Cartesian sequences (Figs. 2 & 3). Finally, soft-gating reduced residual motion artifacts, sharpened the blood and myocardial boundaries, recovered minute hepatic vessels and bronchial vessels (Fig. 3).

DISCUSSION: VDRad facilitates compressed sensing with the use of spatio-temporal sparsity. Subsequently, the compressed sensing elements enable soft-gating to suppress motion corrupt data to improve the reliability of 4D flow. Respiratory motion, particularly of the liver and pulmonary vessels, is nonrigid (Fig. 3). For more robustness and to enable depiction of finer vessels, all motion-compensation components are needed. Furthermore, the motion estimated from Butterfly flow navigators allow for more advance nonrigid motion correction[2] by exploiting the localized sensitivity of elements in a coil array.

REFERENCES: **[1]** MA Bernstein et al. JMRI, 2:583-588 (1992). **[2]** JY Cheng et al. MRM, 68:1785-1797 (2012). **[3]** JY Cheng et al. JMRI doi: 10.1002/jmri.24785 (2014). **[4]** M Lustig et al. MRM, 58:1182-1195 (2007). **[5]** S Winkelmann et al. IEEE, 26:68-76 (2007). **[6]** KM Johnson et al. MRM, 67: 1600-1608 (2012). **[7]** M Uecker et al. MRM, 71:990-1001 (2014). **[8]** bart. version 0.2.04. (2014) doi: 10.5281/zenodo.12495

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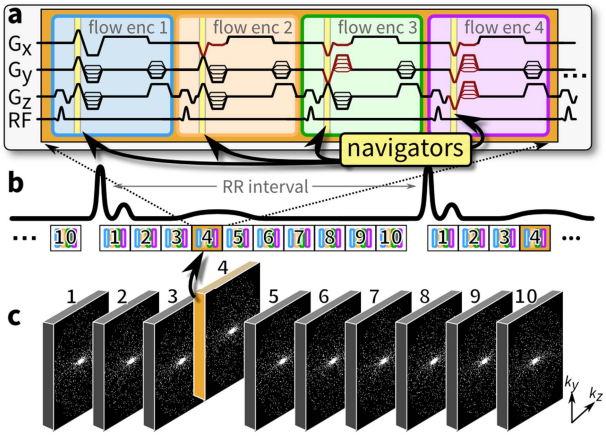

FIG. 1: *Data acquisition for 4D flow.* **a:** One flow-encoding unit consisting of 4 different flow encoding configurations with built-in Butterfly[2] flow navigators acquired during the flow-encoding gradients. **b:** 10 cardiac phases resolved with a flow-encoding unit per phase – for longer RR intervals, patterns are repeated before the next RR interval. **c:** Sampling and view-ordering determined using VDRad[3] that is synchronized to the cardiac triggering.

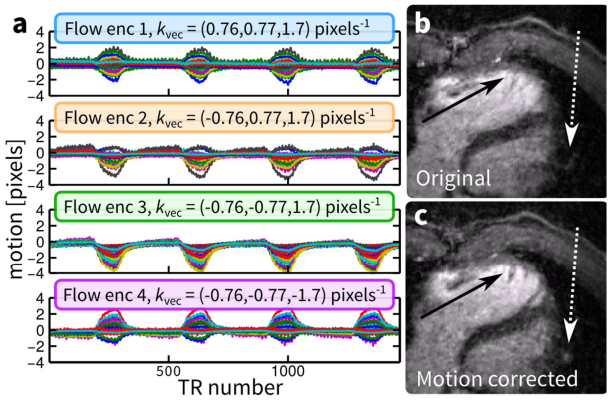

FIG. 2: *Motion estimated with Butterfly flow navigators.* **a:** Motion estimated (cardiac motion suppressed with a stop-band filter) from different flow-encodings --- each color is from a different channel in a 32ch receiver. **b:** 4D flow scan (9.1 min, R=23) of a 22.1-yr-old male. **c:** Corrected using a linear motion estimate selected from (a). In (c), the right ventricular trabeculae are sharpened (*black arrow*); fine vessels are recovered (*dotted white*).

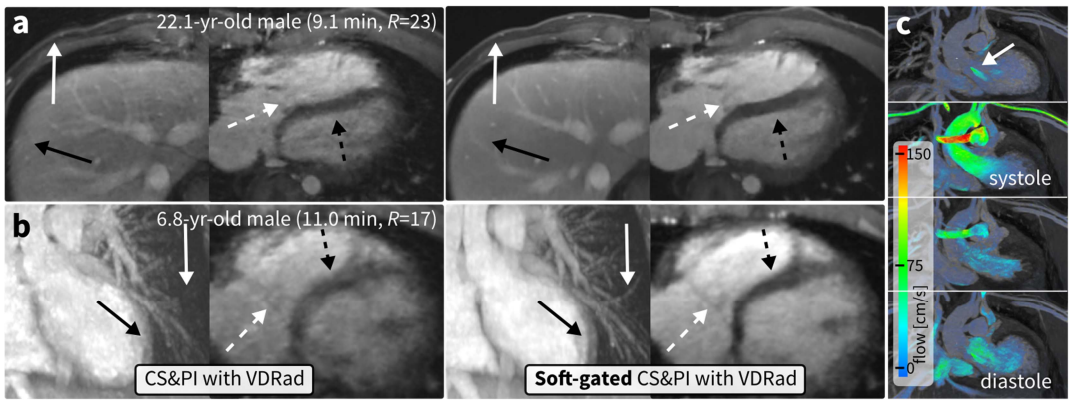

FIG. 3: *Results for soft-gated 4D flow imaging.* **a:** Axial slices depicting sharpened chest wall (*white arrow*) and hepatic vessels (*black arrow*), recovered tricupsid valve septal leaflet (*dashed white*), and sharpened septum (*dashed black*). **b:** Coronal MIP (left) and axial slice (*right*) demonstrating recovered bronchial vessels (*white arrow*), sharpened cardiac wall (*black arrow*), recovered ventricular valve (*dashed white*), and enhanced septum (*dashed black*). **c:** Flow rendering for the soft-gated recon of a 14.4-yr-old female (11.7 min, R=11) highlighting aortic regurgitation (*arrow*).