Quantitative Assessment of Blood Flow with 4D Phase-Contrast MRI and Autocalibrating Parallel Imaging Compressed Sensing

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Background: Quantitative evaluation of blood flow is an essential part of the congenital heart MRI examination. While this is generally performed with 2D phase-contrast MRI (PC-MRI), the accuracy of flow measurements can be problematic. Scan prescription is highly operator-dependent, requiring extensive knowledge of congenital heart pathophysiology and treatment. 4D phase-contrast MRI, because of its volumetric nature, has potential for reducing operator-dependence at the time of image acquisition, and allows for retrospective evaluation of blood flow. This pulse sequence however, is time-intensive, as it obtains both anatomic and velocity field data throughout an imaging volume. Parallel imaging techniques and compressed-sensing are therefore ideal to minimize imaging and cardiac anesthesia time while maintaining spatial and temporal resolution necessary for evaluation of pediatric patients. However, given the nonlinear nature of compressed sensing reconstructions, it is not clear whether flow measurements remain accurate when these techniques are applied. We therefore seek to assess the accuracy of flow quantification in a clinical congenital heart population.

Methods: Software for ventricular segmentation and flow assessment from 4D PC data was developed in Java. With IRB approval, patients undergoing 2D PC-MRI and cine SSFP as part of routine clinical MRI evaluation were recruited for a 4D phase contrast scan. Thirteen patients were included in the study, aged 4 months to 10 years, weighing 6-56 kg, and BSA 0.3-1.37 m^2. 4D PC-MRI examinations were performed after intravenous administration of gadofoveset. The undersampled acquisition followed a with Poisson-disc k-space sampling [1] and reconstructed with both parallel imaging alone [2] (ARC, General Electric) and with a GPGPU parallel implementation of compressed-sensing reconstruction, applied separately to each flow encoding (L1-SPIRiT) [3-7]. Representative images are shown in Fig. 1. Examinations were performed with a range of parameters customized to the clinical needs of each patient with flip angle 12-15°, TR 3.74-5.35, TE 1.36-2.16, 2-4 views/segment, V_{enc} 150-300 mm/s, in-plane resolution averaging 0.9 x 1.2 mm and through-plane resolution averaging 2.3 mm. Two-dimensional k_y and k_z outer reduction factors ranged from 1.6-5. Ventricular volumes and 2D PC-MRI flow calculations were performed on a GE Advantage workstation. 4D PC-MRI flow calculations and ventricular segmentations were performed with our homebrewed software.

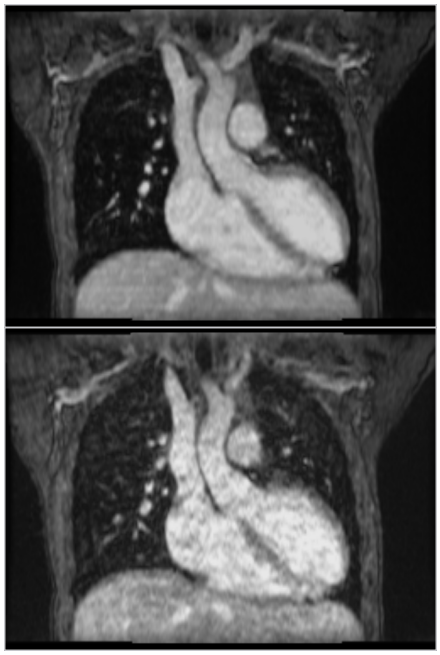

Fig. 1. Coronal magnitude images of an image volume using SPIR-iT (top) and ARC (bottom) reconstruction methods.

Results: Volumetric flow rates from 4D PC obtained at the level of the aortic and pulmonary valves were tightly-correlated with and without the use of compressed-sensing (Q_s: ρ=0.97, Q_p: ρ=1.00), spanning volumetric flow rates from 0.85-5.79 L/min, shown in Fig. 2. Using the SPIR-iT reconstructed data, volumetric flow rates by 4D PC-MRI also correlated well with 2D PC-MRI measurements (Q_s: ρ=0.94, Q_p: ρ=0.98), slightly underestimated relative to 2D PC-MRI by a mean of 0.6 L/min or 24% of the flow rate. In addition, despite the presence of valvular regurgitation, these flow rates correlated well with computed cardiac outputs obtained from cine SSFP ventricular volumes (Q_s: ρ=0.87, Q_p: ρ=0.87), slightly underestimated by a mean of 0.7 L/min or 25% of the flow rate, shown in figure 3. Finally, excluding patients with aortic or mitral valve insufficiency, aortic flow rates correlated strongly with cardiac outputs derived from ventricular segmentations of 4D PC-MRI magnitude data, (Q_s, ρ=0.86), shown in figure 4, with no mean difference on Bland-Altman analysis.

Conclusions: We demonstrate that nearly identical quantitative blood flow measurements can be obtained from 4D PC-MRI with parallel imaging alone (ARC) and with compressed-sensing (SPIR-iT), despite the nonlinear nature of the compressed sense reconstruction and separate application to each flow-encoding. Measured flow rates also correlate well with 2D PC and volumetric assessments, and in particular, volumetric assessments obtained directly from 4D PC-MRI magnitude images. Future work will be aimed at validation at higher accelerations.

References: [1]: Tulleken et al., *Poisson Disk Sampling Tutorial*, Dev. Mag. Magazine 2008; 21:21-25 (devmag.org.za). [2]: Beatty, et al., ISMRM-ESMRMB, 2007; Berlin, p. 1749. [3]: Lustig et al., ISMRM, 2009; Honolulu, p. 379. [4] Lustig et al., MRM. 2007 Dec;58(6):1182-95. [5]: Lustig et al., MRM 2010 Aug;64(2):457-71. [6]: Vasanawala et al., Radiology. 2010; 256:607-616. [7]: Murphy et al., *Clinically Feasible Reconstruction for L1-SPIRiT Parallel Imaging and Compressed Sensing MRI*, ISMRM, 2010; Stockholm.

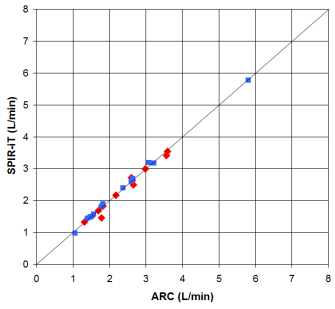

Fig. 2. Flow measurements with (SPIR-iT) and without compressed-sensing (ARC). Flow measurements at the aortic (red) and pulmonary (blue) valves were nearly identical.

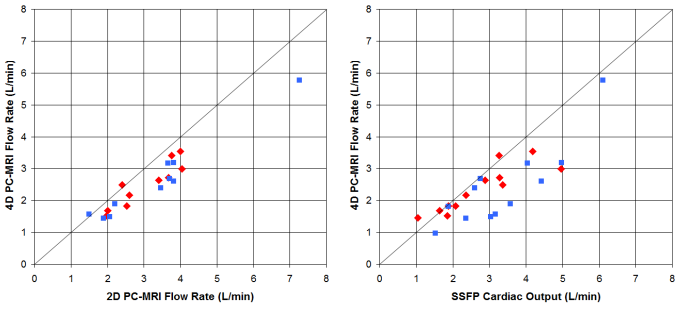

Fig. 3. Flow measurements for SPIR-iT 4D PC-MRI at the aortic (red) and pulmonary (blue) valves correlate well with 2D phase-contrast (left) and SSFP volumetric assessments (right), despite significant inlet and outlet valvular regurgitation in several of our patients.

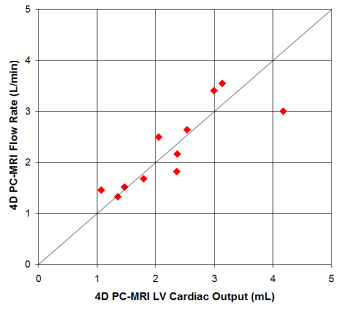

Fig. 4. Flow measurements from SPIR-iT at the aortic valve correlate well with left ventricular cardiac output derived from 4D PC-MRI magnitude images.