4D flow MRI of the Great Vessels during Respiration Plateaus

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TARGET AUDIENCE: Those interested in 4D flow MRI and congenital heart disease (CHD).

PURPOSE: Total cavo-pulmonary connection (TCPC) is a palliative procedure to treat complex CHD and results in a single, systemic ventricle and passive systemic venous return to the lungs. These changes in blood flow result in long-term complications, including arrhythmia, poor exercise capacity, and ventricular failure[1]. Previous studies using 4D flow MRI and complementary computational fluid dynamics modeling assume unchanged flow between respiration phases, yet venous return in a Fontan repair in TCPC is passive by design and has greater respiratory variation than in healthy volunteers based on real-time 2D flow MRI[2]. 4D flow MRI using radial projections (PC-VIPR[3]) allows for flexible retrospectively sorting of data due to intrinsic oversampling of central k-space and pseudo-random sampling trajectories. ***The purpose of this study was*** to measure and establish blood flow waveform patterns in cardiac vessels for inspiration and expiration plateaus in a healthy control (HC) population and in TCPC using 4D flow MRI.

	Measurement Location
Right Side	Inferior Vena Cava (IVC)
	Superior Vena Cava (SVC)
	Main Pulmonary Artery (MPA)
	Left Pulmonary Artery (LPA)
	Right Pulmonary Artery (RPA)
Left Side	Ascending Aorta (AAo)
	Left Superior Pulmonary Vein (LSPV)
	Left Inferior Pulmonary Vein (LIPV)
	Right Superior Pulmonary Vein (RSPV)
	Right Inferior Pulmonary Vein (RIPV)

Table 1. Locations of flow measurement.

METHODS: Eight healthy volunteers (5M/3F, 26.3 +/- 3.8 years old) and one patient with atrio-pulmonary TCPC (F, 32 years old) were imaged on a 3T system (Discovery MR750, GE Healthcare) using PC-VIPR prescribed over a large chest imaging volume (FOV = 32 x 32 x 32 cm^3, TR/TE = 5.5/2.3 ms, α = 15°, Venc = 150 cm/s, projection number ≈ 22000, 16 reconstructed cardiac time frames, scan time: 11 minutes 30 seconds). In recent work, we developed a scheme that allows for double gating to the ECG and respiratory cycles based on the bellows signal to provide cardiac series of flow data for separate respiratory phases[4]. Here we adapted that scheme with a modified sorting scheme to target the plateau phases of respiration. After a moving average filter was applied to the respiratory waveform to subdivide data above (inspiration) and below (expiration) the moving average, a 40% acceptance threshold was applied to mitigate potential motion during active respiration. This window was chosen to mimic our standard prospective expiration respiratory gating in which data is only acquired during the lower 40-50% of the bellows signal. The image sets were exported to an advanced visualization software package (EnSight, CEI). Metrics of total flow (mL/beat) and peak flow (mL/s) were computed for both respiration plateaus. Table 1 lists all measurement locations. Between-plateau differences at each measurement location were assessed using Student's paired t-tests and were considered significant at the 5% level ($p < 0.05$).

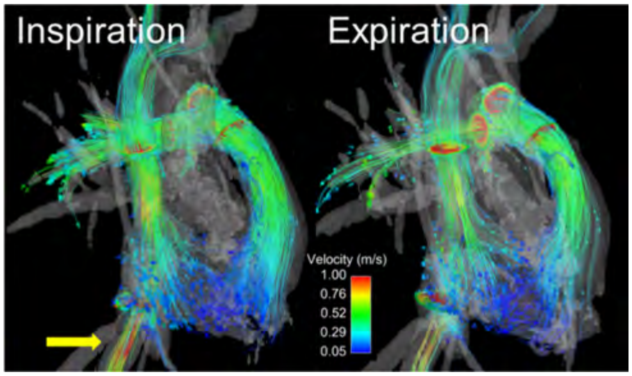

Figure 1. Example velocity streamline visualization emitted from right side vessels for respiration plateau phases in a healthy volunteer. Local areas of velocity difference are qualitatively observed (yellow arrow).

Total Flow (mL/cardiac cycle)	Healthy Controls					TCPC				
	IVC	SVC	LPA	RPA	AAo	IVC	SVC	LPA	RPA	AAo
Inspiration	53.9 ± 15.7	25.5 ± 4.0	42.6 ± 13.0	38.5 ± 6.7	77.2 ± 22.3	46.8	18.8	24.5	24.1	46.8
Expiration	47.9 ± 19.2	27.7 ± 8.0	38.6 ± 7.9	39.7 ± 7.8	78.8 ± 18.2	29.5	19.0	24.7	28.6	55.4
p	.075	.223	.097	.297	.428	--	--	--	--	--

Table 2. Left: Total flow measurements (average ± std dev) in healthy controls in major vessels. Right: Measurements in the TCPC patient.

RESULTS: High-quality angiograms as well as flow distribution visualizations were achieved in all subjects (Figure 1). Table 2 – left summarizes measurements of total flow in selected vessels for healthy controls: IVC, SVC, LPA, RPA, and AAo. Table 2 – right displays results for the single TCPC patient. Figure 2 shows blood flow waveforms for selected vessels averaged (± standard error shading) over all HCs.

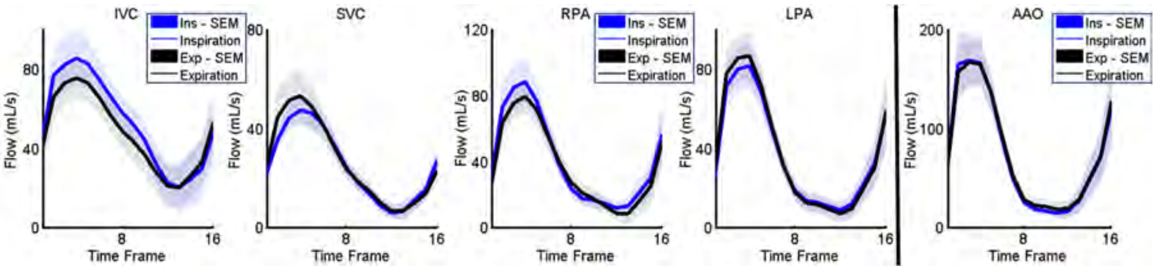

Figure 2. Average (± standard error of the mean, SEM) flow waveforms in selected right- and left-side vessels in HCs. Inspiration increase in IVC and decrease in SVC are apparent.

DISCUSSION and CONCLUSION: Though no statistical differences were found in HCs, clear trends toward higher peak and total flow in inspiration for the IVC and expiration in the SVC are evident. In more muscular arteries less susceptible to intrathoracic pressure changes, these respiratory-induced changes are not evident. The respiratory variation in the TCPC subject was greater than that in the healthy control subjects, consistent with recently published data using real-time 2D PC[2]. We expect the addition of more TCPC subjects into this data to strengthen these results. In conclusion, future studies using 4D flow MRI and computational fluid dynamics simulations in TCPC subjects must take into account these respiratory variations.

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REFERENCES: **1**. Khairy et al. *Circulation* 2008. **2.** Körperich et al *Eur Heart J 2014.* **3.** Johnson et al. *JMRI* 2008. **4.** Schrauben et al. *JMRI* 2014.