Measuring changes in morphology, hemodynamics, and mechanical function by controlling ventricular preload using an MRI-compatible lower body negative pressure chamber

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Introduction: Cardiac performance is modulated in part by ventricular preload, with larger preloads resulting in greater stroke volume. Variations in preload are determined by venous return to the heart as well as ventricular compliance. Previously, the effects of ventricular unloading have been studied by varying lower body pressure[1-3]. Reducing lower body pressure reduces central blood volume by retaining blood in the lower body, thus decreasing venous return and preload. These previous studies have measured indices of cardiac function and their relationship to preload using echocardiography or invasively; however, there remain many aspects of cardiac function that have not been studied with variable preload. MRI is the gold standard for measuring heart chamber volumes and has the ability to measure tissue and blood dynamics, but has not previously been used in conjunction with lower body pressure modulation.

Purpose: To measure systolic and diastolic functional parameters at negative lower body pressure. In this study we include measures of volumes, hemodynamics and tissue mechanics.

Methods: A custom, MRI-compatible, lower body pressure chamber was built using a wood frame covered by a waterbed mattress. A kayak water skirt was attached to the opening of the chamber to make a seal around the subject's waist. A 20 HP vacuum pressurizes the chamber. For experiments, the chamber is placed on the MRI patient bed with the subject's lower body inside the chamber while lying supine. The system has been tested for pressures ranging from -30 mmHg to +15 mmHg relative to atmospheric pressure.

10 healthy volunteers participated in this study. All experiments were performed on a 1.5 T Siemens Sonata MRI scanner (Erlangen, Germany). Short axis cines covering the left ventricle were used to measure ventricular volumes: end systolic (ESV) and end diastolic (EDV) volumes, stroke volume (SV), and ejection fraction (EF). Long axis and short axis phase contrast cines were acquired to measure hemodynamics and tissue velocities: early and atrial filling blood velocities (E and A) and volume filling rates (E_{vol} and A_{vol}), intra-ventricular (IVPG) and -atrial (IAPG) pressure gradients, and peak systolic (S′) and diastolic (E′) annular velocities. Short axis and long axis tissue tagging was used to measure tissue mechanics: peak torsion and untwisting rate, and average radial velocity and circumferential strain rate. All image acquisitions were ECG gated and acquired during breath holds. The experimental protocol is approximately 20 minutes for each loading condition.

Results: Table 1 summarizes the physiological parameters measured. A paired t-test was used to determine if changes between loading conditions were significant (p values < 0.05 are denoted with * and p values < 0.001 are denoted with **).

Table 1: Average measured parameters

Loading conditions	Heart Rate, Volumes and Function					
	HR*	EDV (mL)**	ESV (mL)	SV (mL)**	EF (%)*	
0 mmHg	60.6 ± 10.7	177.6 ± 28.6	68.7 ± 16.3	109.0 ±14.8	61.6 ± 3.7	
-30 mmHg	63.5 ± 9.7	153.1 ± 25.6	65.8 ± 17.1	87.2 ± 10.6	57.5 ± 4.4	
Loading conditions	**Hemodynamics**					
	E (cm/s)**	A (cm/s)*	E_{vol} (mL/s)**	A_{vol} (mL/s)*	IVPG (mmHg)**	IAPG (mmHg)**
0 mmHg	61.6 ± 7.7	34.0 ± 9.4	567 ± 109	258 ± 50	2.9 ± 1.2	1.9 ± 0.4
-30 mmHg	46.5 ± 10.4	25.9 ± 11.6	371 ± 57	208 ± 47	1.8 ± 0.7	1.3 ± 0.4
Loading conditions	**Tissue Mechanics**					
	E′ (cm/s)**	S′ (cm/s)	Peak Torsion (°)*	Peak untwisting rate (°/s)	Radial velocity (cm/s)**	Circumferential strain rate (s^{-1})**
0 mmHg	14.7 ± 3.1	8.3 ± 3.0	11.1 ± 2.1	157 ± 28	4.4 ± 0.9	1.60 ± 0.24
-30 mmHg	9.7 ± 2.0	8.8 ± 2.0	13.4 ± 2.8	162 ± 32	3.5 ± 0.7	1.37 ± 0.21

Conclusions: We have shown that applying -30 mmHg lower body pressure significantly reduces preload (EDV), modulating both systolic and diastolic function and that a comprehensive functional study is feasible using a pressurized chamber in conjunction with MRI. Changes in EDV, SV and standard measures of early filling (E, A and E') are found to be comparable to unloading studies using echocardiography[1-3] while significantly larger decreases in pressure gradients were found here[1]. We show an increase in torsion with unloading and decreases in radial velocity and circumferential strain. In the future, this type of quantitative functional imaging using MRI in combination with variable lower body pressure will allow detailed physiological studies in controls or cardiac patients.

References: 1. Popovic ZB, *et al*. Relationship among diastolic intraventricular pressure gradients, relaxation, and preload: impact of age and fitness. *Am J Physiol Heart Circ Physiol*, 2006. 290(4):H1454-9. **2.** Firstenberg MS, *et al*. Relationship of echocardiographic indices to pulmonary capillary wedge pressures in healthy volunteers. *J Am Coll Cardiol*, 2000. 36(5):1664-9. **3.** Levine BD, *et al*. Left ventricular pressure-volume and Frank-Starling relations in endurance athletes. Implications of orthostatic tolerance and exercise performance. *Circulation*, 1991. 84(3):1016-23.