Cardiac Function and Myocardial Perfusion Immediately following In-Room Maximal Treadmill Exercise

M. Jekic[1,2], E. L. Foster[2,3], S. V. Raman[2,4], and O. P. Simonetti[2,5]

[1]Biomedical Engineering, The Ohio State University, Columbus, Ohio, United States, [2]Davis Heart and Lung Research Institute, The Ohio State University, Columbus, Ohio, United States, [3]Mechanical Engineering, The Ohio State University, Ohio, [4]Internal Medicine, The Ohio State University, Ohio, [5]Internal Medicine and Radiology, Ohio State University, Ohio

Introduction: Over 70 million Americans have one or more types of cardiovascular disease (CVD), the underlying cause of over 37% of all deaths. Approximately 500,000 (53%) of those deaths are specifically due to coronary artery disease (CAD). CAD is often only evident under stress (induced by exercise or a pharmacologic agent), resulting in increased myocardial oxygen demand which cannot be fulfilled by obstructed coronary arteries. Exercise testing is preferred to pharmacologic stress because it links physical activity to symptoms of ischemia, and offers additional important information such as exercise capacity, blood pressure response, development of arrhythmias, and the presence or absence of chest pain during exercise. Treadmill exercise is preferred to bicycle ergometry because of quadriceps fatigue that typically allows subjects to achieve only 80% - 90% of their treadmill O_2max on a bicycle ergometer. Imaging modalities typically used with exercise testing (echocardiography and nuclear scintigraphy) have limitations in signal-to-noise and resolution, and image quality can be highly dependent on both operator and patient. Cardiac magnetic resonance (CMR) has the potential to rapidly acquire both cardiac function and myocardial perfusion images immediately post-exercise, and could provide significant benefits in CAD diagnosis. However, the treadmill must be in proximity to the MRI table to minimize the distance a fatigued subject must travel after exercise and reduce the time between exercise and imaging.

Purpose: To develop a protocol for real-time non-breathhold MRI of cardiac function and myocardial perfusion following maximal exercise on a treadmill positioned inside the MRI room, and test its feasibility in healthy volunteers.

Materials and Methods: Seven healthy subjects performed maximal exercise following the standard Bruce protocol on a treadmill positioned in the corner of the MRI room (Siemens 1.5T Avanto). The treadmill was modified by replacing most ferromagnetic components with non-ferromagnetic stainless steel and aluminum. All remaining ferromagnetic components, including the motor, were situated outside of the 0.0005 Tesla (5 Gauss) safety line. The experimental setup is displayed in Figure 1. Slice localization and resting function images were acquired first, prior to exercise. Vacuum mattresses were used to form a rigid mold around the subject and ensure that rest and stress images would be acquired at the same location. After baseline imaging, the subjects were connected to a 12-lead ECG system and began treadmill exercise following the standard Bruce protocol. Blood pressure was recorded at the midpoint of each Bruce protocol stage. 12-lead ECG monitoring was performed throughout exercise, with the ECG monitor placed at the entrance to the MRI room. At the end of exercise, the patient was disconnected from the 12-lead ECG system, but heart-rate was monitored continuously using the 3-lead wireless MRI patient monitor unit. The subject was quickly escorted from the treadmill to the MRI table, a surface coil was placed on the chest, the contrast injector was connected to the previously inserted IV in the subject's arm, and the scan was started from within the MRI room. The time from end of exercise to start of imaging (Tstart), and from end of exercise to completion of function imaging (Tend) was recorded. The goal was to complete function imaging within 60 seconds post-exercise to avoid resolution of exercise-induced wall motion abnormalities; which is the same target defined for exercise echocardiography. Perfusion imaging immediately followed, with the goal to complete within 90 seconds post-exercise. After image acquisition, the MRI table was immediately pulled out, and ECG and blood pressure were recorded for 6-8 minutes while the subject recovered on the MRI table. Resting function and delayed enhancement (viability) images were captured following recovery.

A real-time SSFP sequence with TSENSE acceleration factor of 3 was used for cine function imaging. Temporal resolution of 56.8±2.2 msec and spatial resolution of 3.7±0.1mm x 2.9±0.1mm x 8mm were achieved with no breath-hold and no ECG gating. 0.1 mmol/kg gadolinium-DTPA was administered intravenously as a contrast agent for perfusion imaging. GRE-EPI with TSENSE acceleration rate of 2 was used to obtain three short-axis slices each cardiac cycle. Siemens Argus software was used to compute the ratio of cardiac output (CO) at stress and rest by manually defining the endocardial and epicardial borders in end diastolic and end systolic images, and also to compute the myocardial perfusion reserve index (MPRI) for one mid-ventricular slice.

Results: The entire procedure took an average of one hour. All function studies were completed successfully; one perfusion scan was unsuccessful due to IV failure. Results are displayed in Table 1. Heart rate at peak exercise and at start of imaging is expressed as percent of maximum predicted heart rate (MPHR) based on age (220-age). For these six healthy volunteers, cardiac output increased by a factor of 3.3±0.4 from rest to stress. Increased contractility is clearly depicted in the end-systolic images at rest and stress displayed in Figure 2. Figure 3 shows the myocardial signal intensity curves during the first pass of the contrast agent through the heart. The increase in slope from rest to stress due to the increased cardiac output is clearly depicted, which is in agreement with quantitative perfusion analysis that yielded MPRI of 1.9±0.3. MRI scan commenced within 28±5 seconds after exercise, and function imaging was completed within 45±5 seconds after exercise. Image quality was sufficient for visual assessment of wall motion and perfusion in all left ventricular segments, and no subject had ischemic abnormality.

Table 1: Results

		Bruce	Max HR	Start Img HR	Stress CO /	MPRI	Tstart	Tend*	Temporal Res	ΔX	ΔY
	Age	Stage	(%MPHR)	(%MPHR)	Rest CO		(sec)	(sec)	(msec)	(mm)	(mm)
1	20	5	92	73	3.5	2.1	25	44	59.1	3.6	2.8
2	35	6	92	69	3.5	1.8	27	45	59.1	3.7	3.0
3	35	4	102	98	2.5	1.8	25	41	55.6	3.5	2.7
4	25	5	102	95	3.1	2.1	24	40	54.9	3.8	3.0
5	25	5	87	65	3.8	1.4	37	53	54.9	3.8	3.0
6	25	5	85	63	3.5	2.0	33	51	54.9	3.8	3.0
7	20	5	90	85	3.0	N/A	27	43	59.1	3.8	3.0

*From end of exercise to completion of the stress function scan

Conclusions: This study demonstrates the feasibility of exercise testing inside the MRI room, and the ability to capture function and perfusion at stress with real-time MRI. Efforts are being made to develop a totally magnet-safe treadmill that can be placed next to the MRI table in order to further reduce the time between exercise and imaging and improve patient comfort.

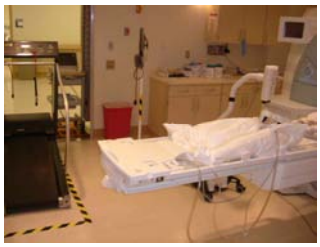

Figure 1: Experimental setup

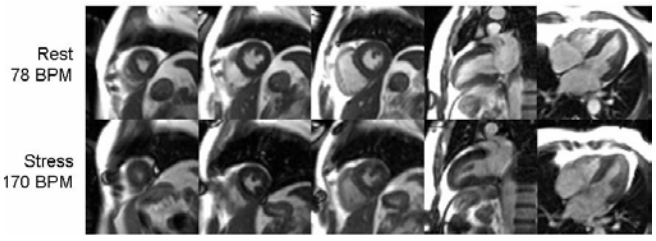

Figure 2: Increased contractility from rest to stress at end systole for one subject

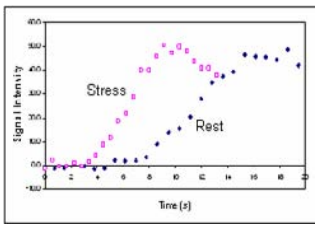

Figure 3: Changes in signal intensity of myocardium at stress and rest