MRI Assessment of Cardiac Function in Response to Exercise

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TARGET AUDIENCE: Scientists and clinicians interested in the use of MRI-compatible exercise equipment.

PURPOSE: It is well known that stress tests of cardiac function can reveal important diagnostic information beyond function tests performed at rest[1]. This is commonly explored with ultrasound studies using exercise equipment. In contrast, MR studies rely on pharmacologically induced stress because of the difficulties of exercise due to limited space in the bore, the supine position of the subject, and patient safety. However, the use of exercise equipment is preferred as it more closely resembles cardiovascular stress experienced during daily life and is better tolerated by patients than pharmacological agents[2]. An MR compatible ergometer can be used next to the magnet[3], but this allows for an unavoidable time delay between exercising and scanning, which can reduce the measured physiological changes. Recent work has addressed this shortcoming with a custom-made MRI-compatible stepping device that allows subjects to exercise in a supine position in the bore of the scanner (Figure 1)[4]. In this pilot study, we investigated the effect of exercise on left ventricular function and aortic flow with this device. The consistency in stroke volume measurements between volumetric measurements in the left ventricle and phase contrast measurements in the aorta was also examined.

METHODS: Twelve healthy volunteers were imaged on one of two clinical 1.5 T systems (HDx (Ø = 60 cm) or Discovery 450w (Ø = 70 cm), GE Healthcare, Waukesha, WI). The subjects exercised in three successive, incremental exercise stages with workloads of 36±7, 43±6, and 50±8 W. Each exercise stage was 3 minutes long and followed immediately by a gated 2D cine phase contrast (PC) acquisition (TR/TE = 6.1/3.7 ms; FA = 30°; ASSET = 2; VENC = 150 cm/s) in the ascending aorta across a 15 s breath hold. The subject's heart rate was recorded during this scan. For a subset of six volunteers, this scan was immediately followed by an additional minute of exercise (to compensate for the rest during scanning) and a subsequent single 18 s breath hold cardiac function scan with whole heart coverage. This was accomplished with a kat-ARC short-axis multi-slice 2D cine balanced SSFP acquisition with parallel imaging and Cartesian undersampling exploiting spatiotemporal correlations[5] (TR/TE = 3.4/1.3 ms; FA = 45°; slice thickness = 8 mm; # slices = 12; net acceleration = 8x). Stroke volume (SV), cardiac output (CO), relative area change (RAC), and pulse wave velocity (PWV) (using the QA method[6]) were analyzed for each exercise stage in the aorta, while stroke volume, cardiac output, ejection fraction (EF), and fractional shortening (FS) were analyzed in the left ventricle. A paired student's t-test was used to determine the statistical significance of any changes between exercise and baseline ($p<0.05$).

Figure 1: MRI-compatible exercise equipment. The subject follows a dynamic stepping motion to the beat of a metronome. Workload is determined by the cadence, step length, and the amount of removable weights added to the end of each lever arm.

Aorta	**HR [hb/min]**	**SV [mL/hb]**	**CO [L/min]**	**PWV [m/s]**	**RAC**
Rest	**67 ± 6**	89 ± 8	**6.3 ± 1.2**	**1.4 ± 1.0**	0.32 ± 0.12
Stress	**98 ± 13**	103 ± 23	**11.1 ± 3.8**	**2.3 ± 1.2**	0.36 ± 0.14
LV	**HR [hb/min]**	**SV [mL/hb]**	**CO [L/min]**	**EF**	**FS**
Rest	**71 ± 9**	72 ± 14	**5.1 ± 1.4**	**0.46 ± 0.07**	0.35 ± 0.07
Stress	**101 ± 13**	77 ± 16	**7.6 ± 0.9**	**0.55 ± 0.07**	0.37 ± 0.02

Table 1: Comparison of various hemodynamic parameters at rest and exercise in the aorta (second exercise stage) and left ventricle. Statistically significant differences are bolded. All LV parameters are from a subset of four subjects.

RESULTS: For the aortic flow measurements, results are presented for the second exercise stage, as it had the smallest intrasubject variation in work load. Of the six volunteers who received the short-axis scan, only four had acceptable image quality to properly measure LV volume in at least one exercise stage. Table 1 shows the values obtained for the measured hemodynamic parameters in both the aorta and left ventricle. For the PC analysis, heart rate, cardiac output, and pulse wave velocity showed statistically significant increases under exercise conditions. In the left ventricle, heart rate, cardiac output, and ejection fraction at stress showed statistical significance over baseline measurements.

DISCUSSION: Patient motion during exercise was the major limiting factor in acquiring acceptable image quality for the cardiac function sequence. To allow for immediate scanning following exercise, scan volumes had to be prescribed before exercise, which allowed for the patient to move out of the scan volume during exercise without being noticed until after scan completion. These effects were most prominent in the LV scans, as the scan volumes were kept small to reduce scan time, so small movements could move some of the ventricle out of the volume. Pulse wave velocity and cardiac output in the aorta, as well as ejection fraction and cardiac output in the left ventricle, were all sensitive to changes in hemodynamic function brought on by exercise. Measured stroke volume in the left ventricle was consistently lower than that measured in the aorta from PC scans, which is worthy of investigation in future studies. The difference was greater under stress conditions, which may be due to the brief rest during the phase contrast scan, but the heart rate data suggests that the extra minute of exercise in between the two scans did an adequate job of correcting for this rest period. For this initial study, workloads were kept relatively low to test the feasibility of measuring these hemodynamic parameters with the exercise equipment. It would be interesting to investigate whether higher workloads would improve the statistical significance of some hemodynamic parameters. Future studies will also investigate whether these hemodynamic parameters hold diagnostic or prognostic value in diseased and healthy patient populations, respectively.

CONCLUSIONS: This feasibility study demonstrates the use of MRI to measure the effect of exercise on left ventricular function and aortic flow using a customized exercise device that allows for the immediate measurement of hemodynamic parameters following exercise in the bore. Cardiac function measurements in the left ventricle and aortic flow were both measured within single breath holds. Measures of pulse wave velocity, cardiac output, and ejection fraction showed sensitivity to exercise stress. In future studies, the diagnostic values of these parameters will be investigated in a patient population, specifically in subjects with diastolic dysfunction.

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