An MRI-compatible lower-leg exercising device for assessing pulmonary arterial pressure

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Abstract

Our client plans to use magnetic resonance imaging (MRI) to study pulmonary blood flow before and during exercise in patients with pulmonary vascular disease. Our goal is to design an MRI-compatible exercise device that increases pulmonary artery blood flow during exercise. To do so, we performed exercise testing and motion capture analysis to determine the best motion. A leg-press type device was then manufactured to match that motion. Initial data showed that use of the device to exercise in the MRI scanner raised heart rate by 36 BPM and increased arterial cross-sectional by 60 mm^2. In the future, our client hopes to use scan data such as these to determine whether moderate exercise will benefit patients with pulmonary vascular diseases.

Keywords: pulmonary artery pressure, MRI, exercise

1. Introduction

Pulmonary Hypertension (PH) is a condition in which the blood vessels of the lungs constrict or stiffen, thickening the vessel walls and causing a rise in pulmonary vascular resistance (PVR) that leads to unsafe pressure increases in the pulmonary arteries. Pulmonary pressure cannot be measured with a simple pressure cuff, as systemic pressure is commonly found. It is commonly estimated invasively with right heart catheterization or non-invasively with Doppler ultrasound measurement of the tricuspid regurgitant jet velocity. The tricuspid regurgitant jet is formed from an insufficiency of the tricuspid valve separating the right atrium and right ventricle of the heart. As the ventricle contracts, a stream of blood leaks back through the valve into the atrium and the velocity of this jet can be used with the modified Bernoulli equation to estimate the blood pressure of the pulmonary artery (Yock and Popp, 1984). PH can be of unknown cause, called Primary PH, but is more commonly a result of emphysema, Chronic Obstructive Pulmonary Disease (COPD), HIV, heart defects, or only appears with exercise (Primary Pulmonary Hypertension News, 2009). A PH patient's quality of life is often severely compromised as side effects of PH may include fatigue, weight changes, shortness of breath, dizziness, heart palpitations, and many need oxygen tanks at all times. There is no cure for PH, but the goal is to reduce the high pulmonary pressures these patients experience as well as treating these symptoms.

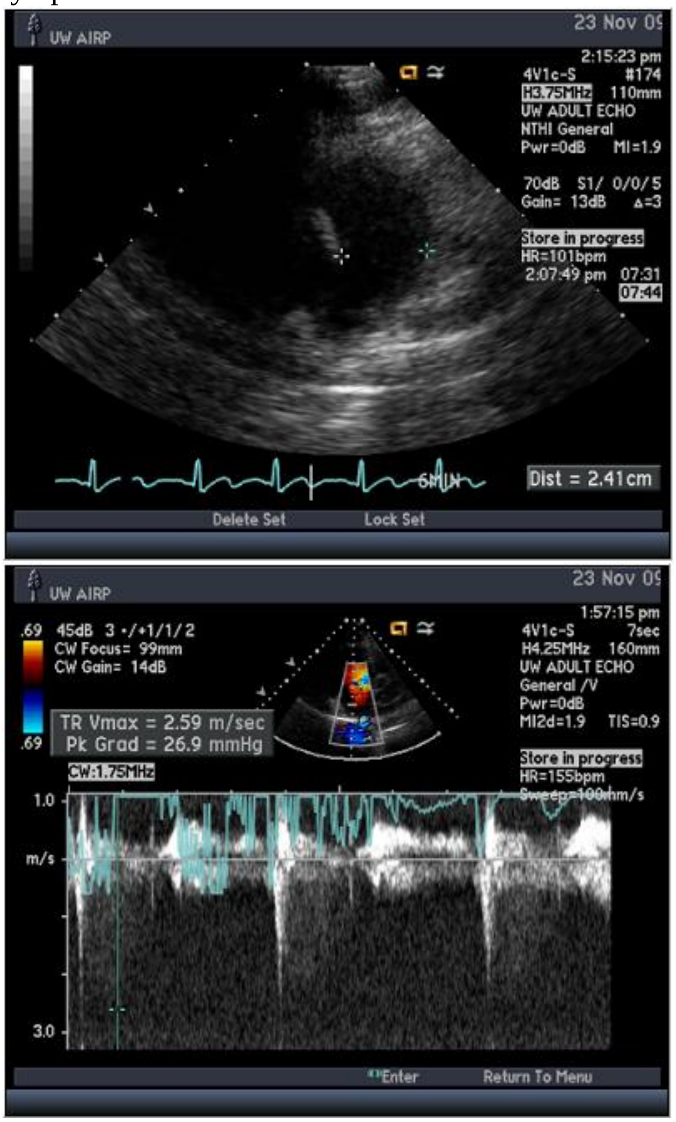


Figure 1: Tricuspid Regurgitant jet. The top image shows the tricuspid valve. The bottom image shows the tricuspid jet velocity. The white waveform along the bottom half of the image charts the magnitude of the jet velocity against time (Ultrasound acquired image).

Previous studies have exercised subjects outside of the Magnetic Resonance Imaging (MRI) bore. In Holverda et al. patients completed 3 minutes of cycling in supine position at 40% of maximal workload (2009).When the exercise is complete the subject must be positioned for proper imaging of the heart. Correct subject placement can take up to 5 minutes, in which time the effects of the exercise can decrease as the subject lies still. This loss of hemodynamic changes decreases the effectiveness of the study. Often researchers use a 6 minute walk to exercise hypertensive patients (Mereles et al., 2006). However, limitations of the 6-minute walk test as a measure of exercise capacity have been identified and has led to MR imaging becoming the standard for assessment of right heart structure and function (McCullagh, B. 2010). It has also been established that resting pulmonary hemodynamics may not reflect exercise capacity and that the response of vasculature is very different at rest compared to exercise; however, the hemodynamics during exercise are much more clinically significant.

The focus of this study was to design a device to allow a subject to exercise while positioned within the MRI bore and be immediately scanned following exercise. The goal is to determine the effectiveness of an MRI-compatible exercise device for increasing pulmonary artery blood flow.

Flaws of Competitive Devices and Previous Studies

The MRI compatible products made by Lode BV are the main competition to our device. The Lode Ergometers are utilized by many studies (Niezen et al., 1998, O'Connor et al., 2004), but there are several short comings of these products. Pricing for these ergometers are near $50,000, limiting availability to many investigators. Often these ergometers are not compatible with all brands of MR scanners. For example, the MRI Ergometer Pedal is not compatible with any GE scanners, and the MRI Ergometer Push/Pull is not compatible with GE's new scanners, the Signa® HDx 3.0T and Signa® HDxt 3.0T. The devices are not compatible because the bore size of GE scanners is smaller than Phillips and Siemens, thus decreasing the range of movement necessary to operate the device.

In an early study utilizing the Lode Ergometer cycling motion and a Phillips NT 15 MRI scanner, the subject's thorax was immobilized by straps, shoulder pads, and sand bags that were placed beside the subjects (Niezen, 1998). This study also required the patient to be brought out of the scanner after baseline imaging to strap their feet into the ergometer and then move them back into the bore for exercise. Other studies have demonstrated in their study limitations that doing a supine exercise test was not feasible during an MRI (Holverda et al., 2009).

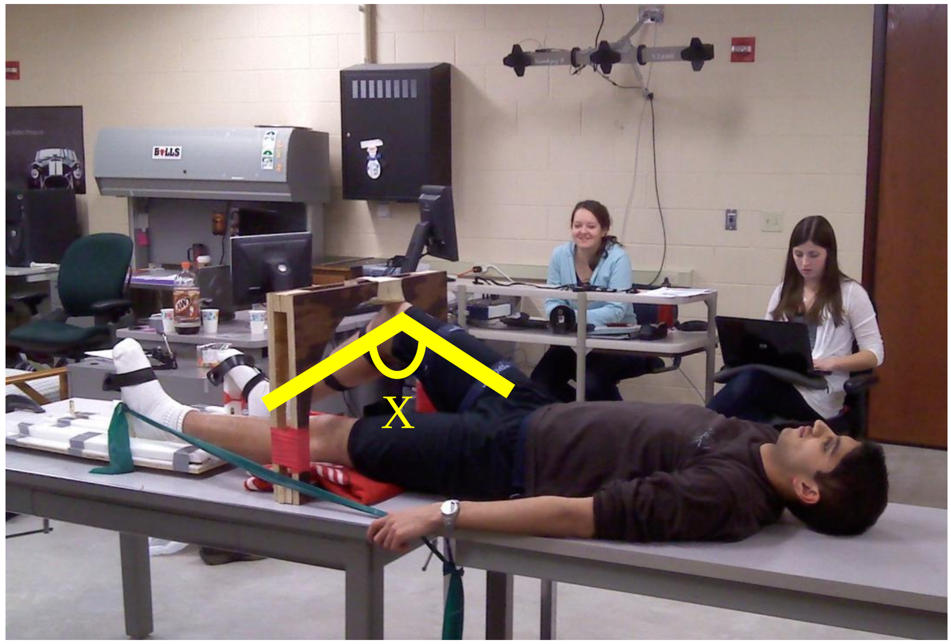


Figure 2: Motion Capture Setup. Motion capture markers were placed at the foot, shank, and thigh to track movement of the lower extremity. Tibial femoral joint angle was measured.

Due to previous flaws and holes of research, we wanted to build a device to collect high quality data on right ventricular and pulmonary vascular function in patients during exercise. This device could be used with any MRI scanner and would allow the radiologist to scan the patient during exercise.

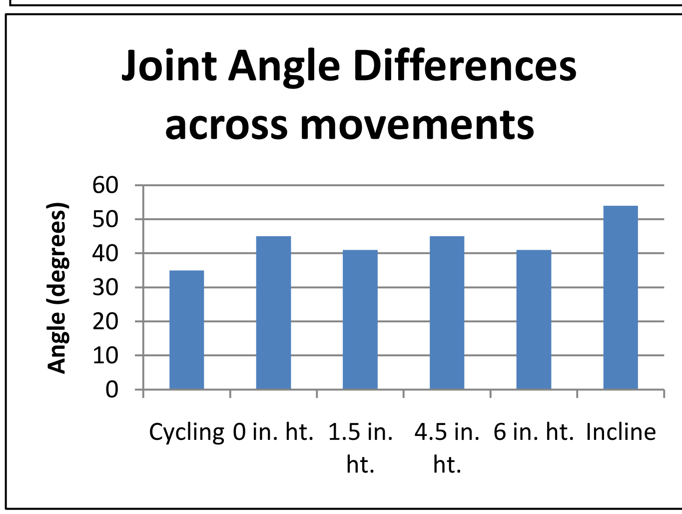
2. Methods

Device Design

Initial exercise testing was done to determine what exercises raise heart rate and blood pressure the most. It was initially determined that a cycling motion would provide the greatest increases but the design of such device would not allow the subject to be scanned while in the MR bore. This is because the cycling motion locked the subject's legs into a certain path, causing their knees to hit the top of the bore. The next exercise chosen had the second greatest increases in heart rate and vitals, originally named the "bicycle kick." (See Figure 8 in Appendix A)

During the design process, motion capture analysis was used to validate the design dimensions (University of Wisconsin-Madison Neuromuscular Biomechanics Lab). Due to limited space for exercise within the MRI bore, exact knee flexion/extension capabilities were documented. In order to determine optimal dimensions, motion capture markers were placed at the foot, shank and thigh to track the movement of the lower extremity (Phoenix Technologies Model 4000 motion capture system was used). The tibial femoral joint angle was measured. A mock MRI bore was placed at the location where exercise motion is normally limited when the subject is located with their heart at the center of the bore. With the end of the bore located approximately mid thigh, the subject was instructed to exercise using the device to cycle or pump/pull their legs. A comparison between the cycling motion and pump/pull motion was performed in Matlab to

Figure 3: Measurement of Joint Angle Differences across movements. Using the leg press motion caused joint angles to increase from the cycling motion. Positioning the device at a 5° upwards incline increased the possible range of motion.



determine the greatest knee range of motion with the restricted space of the MRI. When designing the device, optimum knee range of motion was desired (largest difference in tibial femoral joint angle) because greater knee motion causes more muscle fiber recruitment during exercise. If the hamstrings, quadriceps, and calf muscles can all be used during exercise, the subject will show signs of exercise more quickly. The goal of the device was to perform aerobic exercise.

Device Fabrication

The device, seen in Figure 4, is a nonferrous exercising device which is designed to alter pulmonary hemodynamics by using a translating motion of the lower legs. The device was self fabricated with high density polyethylene, aluminum, brass fittings and screws. The device is easily sanitized with 70% ethanol over polymer and brass surfaces. Specified force resistance is determined by the strength of resistance bands installed in the device. Subjects may have varying fitness levels; therefore the workload can be varied by installing various strengths of resistance bands, from 10, 15, and 20 lbs (Fitness Gear ®Adjustable Resistance Tubes). Adjustable handles provide torso stability, comfort, and ease of use for the subject. The device is approximately 1.5 feet wide by 3 feet long and weighs less than 15 pounds.

Tensile Testing

A Sintech MTS GL10 Tensile Tester device (University of Wisconsin-Madison Department of Mechanical Engineering) was used to determine the spring constant of our resistance bands. The bands had to be tied into knots because the tensile testing clamp could cause a stress concentration in the band, altering the mechanical properties. Figure eight knots were tied into the bands and looped around bar pegs on the machine. Many trials were performed to observe hysteresis. Spring constants for the 10 pound rated and the 20 pound rated Fitness Gear ®Adjustable Resistance Tubes are .72 lbf/inch and 1.42 lbf/in respectively (See Figure 9 in Appendix B).

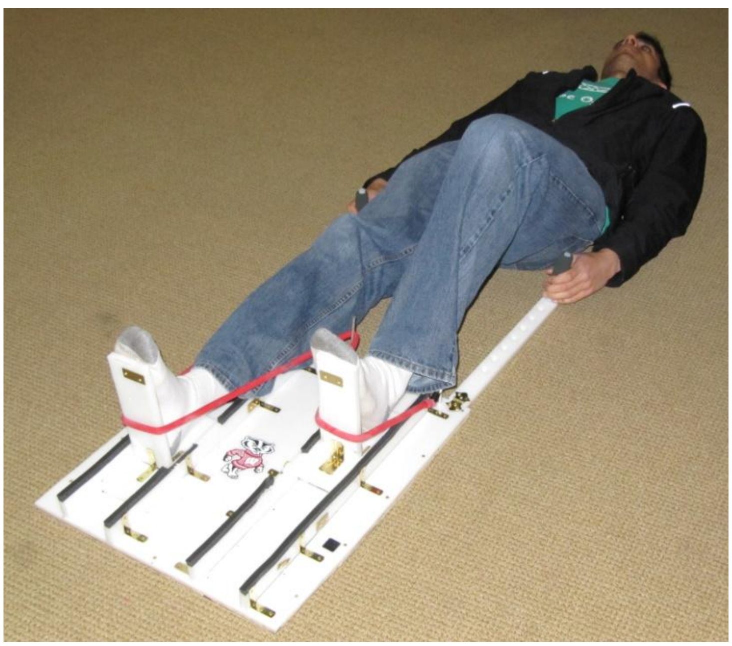


Figure 4: MRI-Compatible Exercise Device. Above: Subject is placed in the device. Handles provide both torso stability and device stability.

Right: Device shown alone.

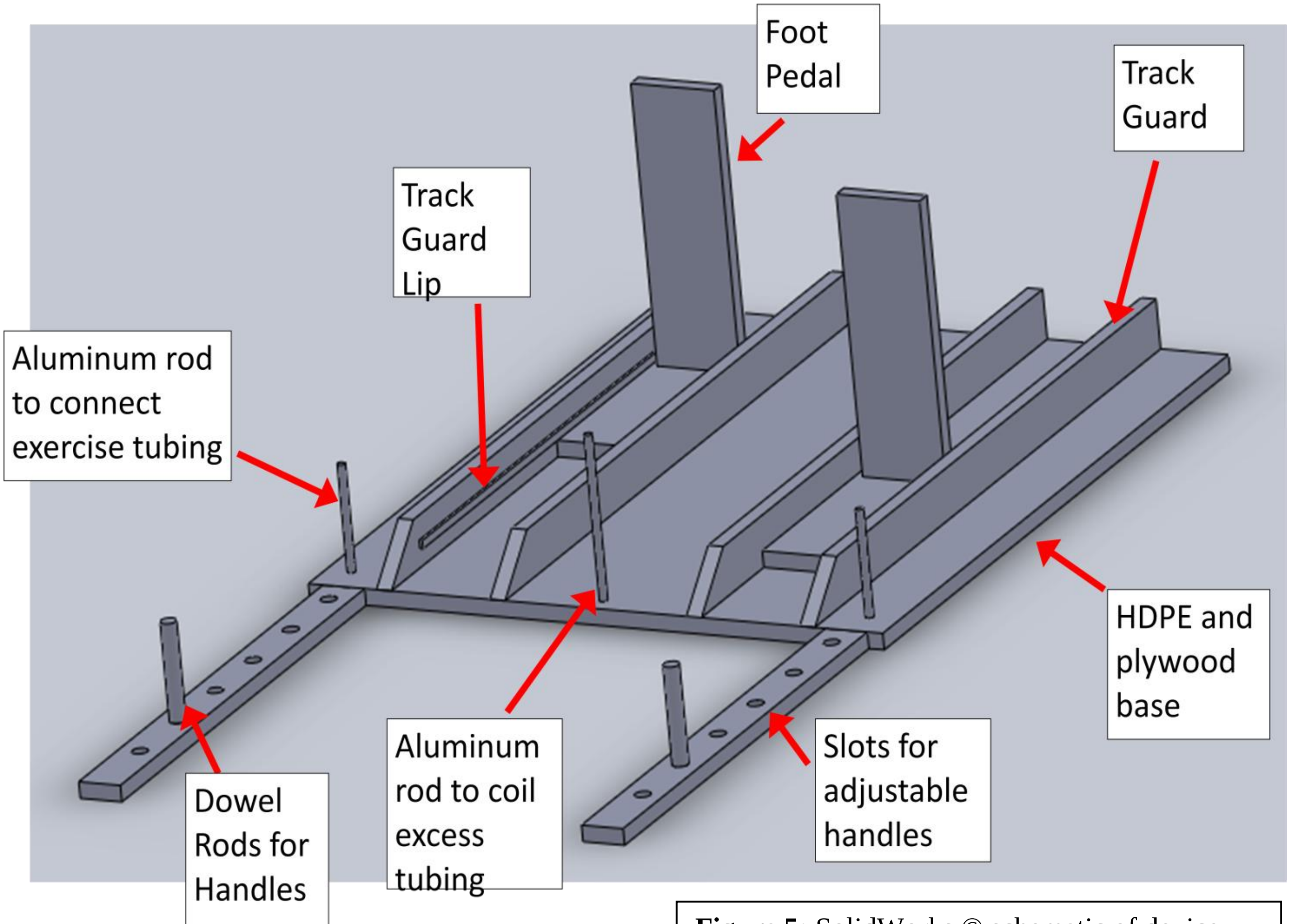


Figure 5: SolidWorks © schematic of device.

Workload Calculations

The study performed by Niezen et al. demonstrated using a Lode Ergometer between 50 and 100 watts. Using various combinations of resistance bands, our device can reach workload capacities of 52 W (however, testing done in this study used a workload capacity of 23 W), comparable to the Niezen study (see Appendix C for calculations). More resistance bands can be purchased and added to the device to increase the workload even further.

3. Testing

This research study included one MRI scan (Wisconsin Institutes for Medical Research) and three ultrasound scans (University of Wisconsin-Madison Hospital) during exercise with the device with normal subjects in good health. This study was designed and conducted in accordance with all Health Insurance Portability and Accountability Act (HIPAA) and University of Wisconsin Institutional Review Board (IRB) standards, for more information please see Appendix D.

This study will use MRI to determine the change in right heart function and vasculature in healthy subjects as a result of exercise. Exercise is used as a means to study the heart because it causes changes in heart rate and systemic and pulmonary blood pressures, and flows. Exercise induces higher pulmonary pressures in normal subjects similar to people with mild PH. However, the body is able to regulate this increase in pressure due to the distensibility of the pulmonary arteries. During exercise, patients with PH see an even higher rise in pulmonary artery pressures due to the increase or maintenance of the PVR, which restricts any escalation in cardiac output (Holverda et al., 2009).

In order to study the changes in right heart function, one important measure is pulmonary systolic blood pressure. This requires the presence of a tricuspid regurgitant (TR) jet, the backflow of blood through the tricuspid valve separating the right atrium and right ventricle during contraction, seen in Figure 1. A minor regurgitation can be found in over 70% of the general population (Singh et al., 1999). The TR jet velocity can be used in the modified Bernoulli equation ($\Delta P = 4V^2$) to approximate the pulmonary systolic blood pressure (Yock and Popp, 1984).

During the MRI scan, the subject was positioned in the scanner with his legs extending out of the bore. The exercise device was positioned on the patient table. An initial scan was performed to estimate a baseline systemic blood pressure, heart rate, aortic flow and diameter, and anatomy and physiology of the heart and lungs. The subject exercised for three minutes using the device positioned on the scanner bed. The subject began pushing the pedals at 120 repetitions per minute (rpm) and increased to approximately 144 rpm at the two minute mark. The subject remained in the bore so that the imaging reference frame did not change. Once the subject exercised, he remained still for a series of post exercise scans of the chest. The procedure was approximately one hour in duration. A similar procedure was performed with Doppler ultrasound.

The subjects and the device were placed on the bed so proper exercising could occur. The sonographer acquired initial baseline data of the subjects and kept acquiring new data after approximately one minute of exercise, up to five minutes. The data parameters acquired were heart rate, systemic blood pressure, tricuspid regurgitant jet velocity, pulmonary artery diameter, and pulmonary artery velocity.

4. Results

A summary of the Doppler Ultrasound Results, focusing on pulmonary measures during exercise at 23W, can be seen in Table 1. Note the increase in heart rate and systemic blood pressure across all subjects. In subjects 1 and 2 the TR Jet velocity decreased, but in subject 3 it increased. Reasons for this parameter's variability are covered in the Discussion.

MRI measurements focused on aortic measurements during exercise at 23W. Heart rate values, seen in Figure 12 and 14 in Appendix E, were similar to the 1998 Niezen study where at rest the

Table 1: Summary of Ultrasound Scan Results

		Heart Rate (bpm)	Systemic BP	TR Jet Velocity (m/s)	PA diameter (cm)	PA Velocity (m/s)
Subject1 (Mar 1, male age 22)	Baseline	56	119/61	2.18	2.32	1.03
	2:30	84	125/71	2.19		
	3:30	88				0.96
	4:30	86	125/72	2.19	2.36	0.98
Subject2 (Apr 28, female age 22)	Baseline	63	116/66	1.77	2.16	0.85
	1:45	90	139/83			
	3:00			1.7	2	1.06
	5:00	91	135/78	1.64	1.84	1.1
Subject3 (May 3, male age 30)	Baseline	56	126/68	1.8	2	1.06
	1:00	75	127/76			
	2:30	86	134/76			
	3:00			2	2.1	1.17
	5:00	80	133/73			

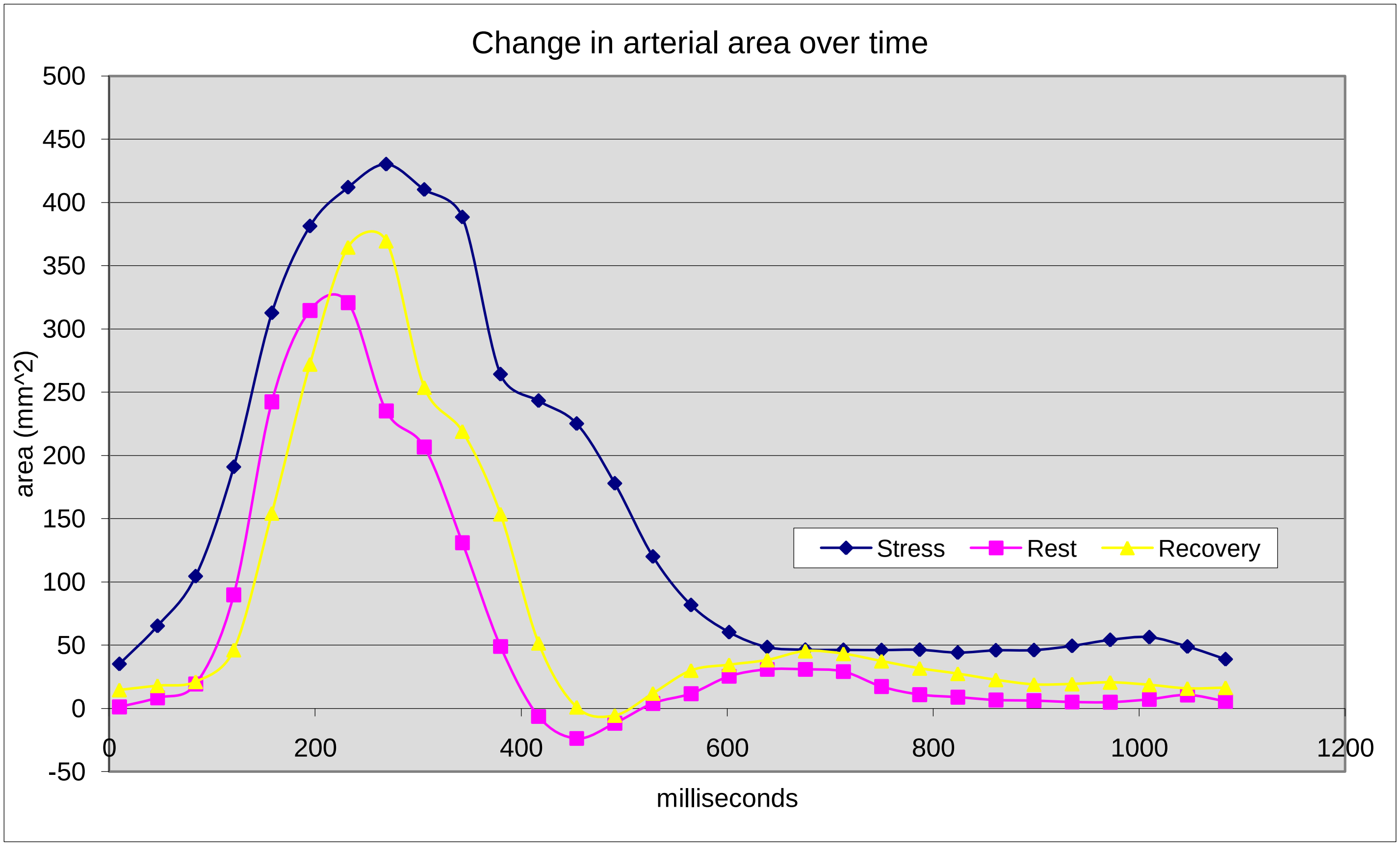


Figure 6: Change in aorta cross-sectional area over time. Three scans were done: one scan during rest, pre exercise for baseline measurement, one scan post exercise to measure recovery, and one scan during exercise to measure stress. Pre and post exercise scans showed a marginal difference in arterial area, but the scan during exercise showed a large increase in arterial area over baseline.

average measure was 63±8 beats per minute (bpm), increasing to 90±14 bpm at 50W, and 106±21bpm at 100W exercise levels.

Figure 6 shows the change in arterial area over time. Scans during exercise demonstrated a larger arterial area compared to scans at rest and recovery.

5. Discussion

In our study, normals exercised at the same workload for all volunteers. We realize, however, that for each individual, these workloads may have a different effect, depending on age, body size, and exercise tolerance. A possible solution for this problem would be to use a target heart rate instead of a target workload. If our method is to be used in patient studies, we would recommend the use of a predetermined subject-specific workload (Niezen et al., 1998).

The ultrasound data from during exercise shown in Table 1 indicates that the exercise device is successful in raising the heart rate of healthy subjects. There was a heart rate increase for all three subjects between 24-30 bpm over the course of the 5 minute exercise duration. The change in aortic area from MRI data shown in Figure 6 compared at rest, stress, and recovery show the decrease in effects of exercise are almost immediate in the subject. This indicates the importance of scanning during exercise to accurately determine the effects of exercise on hemodynamics. This MRI data also shows the successful measurement of aortic flow and change in diameter before, during, and after exercise and indicates that the device design allows for the collection of data during motion with minimal motion artifact (Figures 6 and 7).

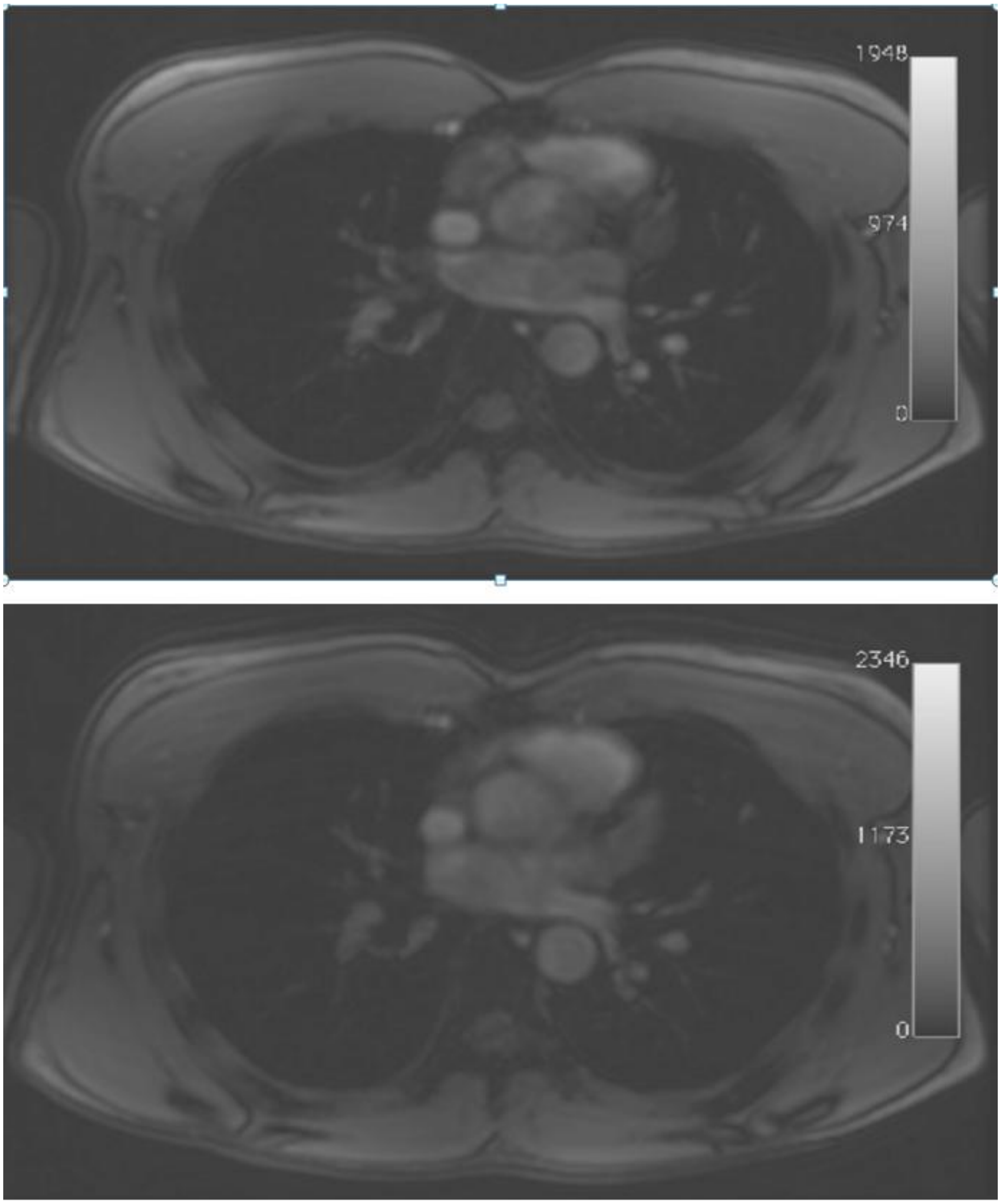


Figure 7: Images acquired during MRI scan. Top shows image quality while subject is at rest, and bottom shows image quality while subject is exercising in bore (images acquired during MRI scan). It is clear in the bottom image that exercise caused more noise and other artifacts to appear in the image. Nevertheless, data from this image was successfully obtained and analyzed.

There are, however, some inconsistencies with the ultrasound measurement of the tricuspid regurgitant jet velocity. Two of the subjects experienced a decrease or no change in the TR velocity during exercise while one of the subjects showed an increase in the TR velocity, Table 1. The increases of the TR jet velocity with the third subject correlate with previous ultrasound studies (Himelman et al., 1989). The inconsistencies with the other two subjects could be an indication of limitations of ultrasound scanning. The ultrasound scanning was done with the subject lying supine on the table which is not the ideal scanning position for the sonographer. This position makes finding and measuring the TR jet more difficult (normally subjects lay on their slide to allow for a better angle). Also, this study did not use intravenous agitated saline solution to strengthen the ultrasound TR signal as other studies have done (Himelman et al., 1989). This may indicate that the ultrasound measurements were not always accurately measured due to weak signaling.

Our device was only operated at a workload of approximately 25 W for all imaging scans, far too low for testing on healthy patients. However, in the condition that many patients with PH are in, we are confident that this workload amount will be sufficient enough to produce good results. Future testing of this theory would be needed.

While there are some limitations of the collected data, the initial trials of the device show promising results for the increase in heart rate and effect of exercise on hemodynamics. This device shows promise over existing ergometers that are not compatible with all types of MR scanners, or may cost too much. Work to improve this system is worthwhile because test results support use for exercise testing. Further use of this device may be applied to stress testing, primarily stress testing of the pulmonary arteries.

Study Limitations

Often our team had trouble setting up scan times, especially for MR scans. Conflicts with existing classes and meetings and the limited availability of our cooperating radiology technicians prevented us from testing our device across several MR scans.

Conflict of interest

None of the authors of this manuscript have any conflict of interest relevant to this work.

Acknowledgements

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