IN VIVO ABDOMINAL AORTIC HEMODYNAMIC CONDITIONS AT REST AND DURING CYCLING EXERCISE IN YOUNG HEALTHY SUBJECTS, OLDER HEALTHY SUBJECTS, AND INTERMITTENT CLAUDICATION PATIENTS

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INTRODUCTION

The human abdominal aorta, particularly at the infrarenal level, experiences higher prevalence of atherosclerosic lesions as compared to the thoracic aorta [1]. Localization of atherosclerotic lesions have been correlated with adverse hemodynamic conditions such as low flow, low wall shear stress (WSS), and high flow and shear oscillations [2]. Furthermore, elevated blood flow and WSS, known effects of lower limb exercise, have been shown to trigger atheroprotective biologic responses in the aorta [3]. Quantification of hemodynamic conditions in the human abdominal aorta at rest and during lower limb exercise could improve our understanding of the mechanisms by which exercise protects against atherosclerosis development. Additionally, exercise flow measurement may also provide useful information for the management of lower limb ischemia. We utilized magnetic resonance imaging (MRI), a custom MR-compatible exercise cycle, and custom image processing software to quantify blood flow and WSS at the supraceliac and infrarenal regions of the abdominal aorta in 11 young healthy subjects, 8 older healthy subjects, and 6 claudication patients.

MATERIALS AND METHODS

Each subject, after providing informed consent, was strapped to an upright seat in a 0.5T open magnet (GE Signa SP) such that they could perform full cycling motion while their abdomens were stationary in the center of the magnet. A custom-built MR-compatible exercise cycle was then positioned according to subject size and the pedal resistance was adjusted according to strength. Scans were performed at seated rest and during steady-state cycling exercise (Figure 1), defined for each subject as 150% of resting heart rate. Cine phase-contrast MRI (PC-MRI) was performed to acquire time-resolved anatomic and through-plane velocity maps [4] perpendicular to the abdominal aorta at the supraceliac and infrarenal regions at rest and during cycling exercise [5]. These two image planes were acquired in a single interleaved acquisition with a TR of 25 msec, TE of 9 msec, flip angle of 30º, slice thickness of 10 mm, field of view of 26 by 26 cm, image matrix of 256 by 128, and a through-plane velocity encoding of 150 cm/sec. The cine PC-MRI acquisitions were gated to the cardiac cycle using a plethysmograph placed on the subject's finger, and data was reconstructed to 16 time points for the cardiac cycle. From these time-resolved anatomic and velocity images we computed time-resolved blood flow rate [4] and WSS [6] with custom software. Temporal oscillations of flow and shear were quantified by oscillatory flow index (OFI) [5] and oscillatory shear index (OSI), respectively [2].

Figure 1. 59 y.o. pedaling a custom MR-compatible exercise cycle in a GE 0.5T open magnet.

RESULTS

The young, healthy subjects (23.6+/-2.2 years) experienced a 49+/-4% increase in heart rate from rest to exercise, the older, healthy subjects (57.1+/-3.4 years) experienced a 51+/-3% increase, and the claudication patients (62.3+/-10.3 years) only achieved a 35+/-18% increase in heart rate from rest to exercise. Figure 2 shows the blood velocity surface plots for peak systole (A), end systole (B), and end diastole (C) at the supraceliac and infrarenal levels at rest and during exercise for a healthy 59-year-old subject. Also shown are the time-resolved blood flow rate (top of Figure 2) and wall shear stress (bottom of Figure 2) waveforms for a cardiac cycle. The velocity surface plots show increased blood velocities at points A, B, and C from rest to exercise for both the supraceliac and infrarenal locations. Retrograde and stagnant flow in the infrarenal aorta during diastole at rest were replaced by positive flow during exercise. Infrarenal flow increased more as a result of exercise as compared to supraceliac flow, indicating a lower proportion of blood flow to the digestive and renal systems during exercise. Similarly, WSS not only increased for the entire cardiac cycle for both locations, but regions of negative wall shear stress at the supraceliac and infrarenal levels during diastole were eliminated with exercise. These data are qualitatively similar for the other healthy subjects.

Average hemodynamic quantities for the three groups are shown in Figure 3. While there were no statistical differences in mean flow and OFI between the young and older healthy groups, WSS was lower in the supraceliac aorta of the older subjects at rest as compared to the younger subjects (Young=3.5+/-0.8, Older=2.0+/-0.7 dynes/cm^2, p<0.001). The older population also had higher OSI at the supraceliac (Young=0.01+/-0.01, Older=0.07+/-0.05, p<0.001) and infrarenal (Young=0.13+/-0.09, Older=0.25+/-0.12, p<0.05) levels at rest. During exercise, the older subjects experienced greater WSS in the infrarenal aorta as compared to the younger subjects (Young=5.2+/-1.3, Old=16.5+/-5.1 dynes/cm^2, p<0.05). The claudication patients had less flow at the supraceliac level during exercise as compared to their healthy, age-matched counterparts (Older=6.0+/-1.4, Patients=4.5+/-0.9, p<0.05). The patients also experienced lower OFI at the supraceliac level at rest (Older=0.14+/-0.09, Patients=0.03+/-0.04, p<0.05), and lower OSI at the supraceliac (Older=0.07+/-0.05, Patients=0.02+/-0.03, p<0.05) and infrarenal (Older=0.25+/-0.12, Patients=0.09+/-0.09, p<0.02) levels at rest.

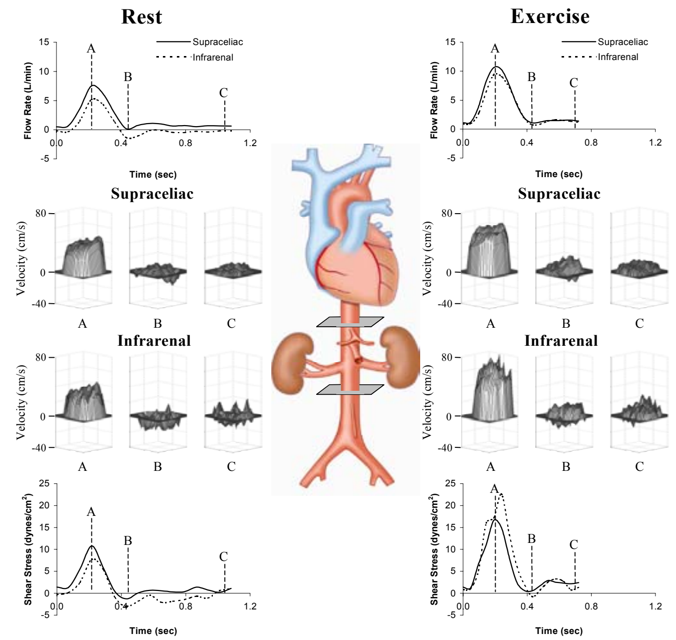

Figure 2. Human aorta with imaging planes at the supraceliac and infrarenal levels, and blood velocity data (middle of figure) from a representative healthy subject, aged 59, at rest (left) and during cycling exercise (right) at peak systole (A), end systole (B), and end diastole (C). Blood flow rate (top) and wall shear stress (bottom) waveforms are also shown.

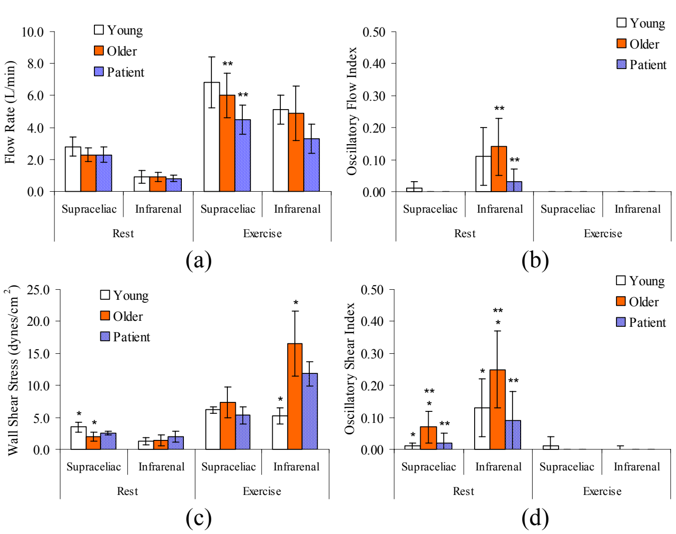

Figure 3. Population averages of rest and exercise (a) blood flow rate, (b) OFI, (c) wall shear stress, and (d) OSI at the supraceliac and infrarenal levels of the aorta. * Indicates significance (p<0.05) between young and older healthy subjects. ** Indicates significance (p<0.05) between older healthy subjects and claudication patients.

DISCUSSION

The increases in flow and wall shear stress, and elimination of flow and shear oscillations in the abdominal aorta as a result of cycling exercise support the hypothesis that lower limb exercise promotes atheroprotective hemodynamic conditions. At rest, the older subjects had lower wall shear stress at the supraceliac level and higher OSI at both the supraceliac and infrarenal levels, however, exercise served to increase the mean wall shear stress more dramatically in the older subjects and eliminate shear oscillations just as in the younger subjects. The claudication patients could not achieve as high an exercise intensity as the healthy subjects, and thus experienced lower supraceliac flow during exercise. Also, probably due to reduced elasticity in distal vessels, the patients experienced less flow storage and reversal and hence lower flow and shear oscillations at rest compared to their age-matched healthy counterparts.

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