SUBJECT-SPECIFIC FINITE ELEMENT MODELING OF THREE-DIMENSIONAL PULSATILE FLOW IN THE HUMAN ABDOMINAL AORTA: COMPARISON OF RESTING AND SIMULATED EXERCISE CONDITIONS

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INTRODUCTION

Adverse hemodynamic conditions, such as complex, recirculating flow, low mean wall shear stress, high spatial gradients in shear stress, and high particle residence times, are hypothesized to explain the localization of atherosclerotic plaque in the infrarenal abdominal aorta [1]. Conversely, elevated blood flow associated with exercise has been hypothesized to result in hemodynamic conditions that inhibit atherosclerosis, such as unidirectional laminar flow, increased wall shear stress, and enhanced transport of cholesterol from the vessel wall. Furthermore, it has been shown in vascular endothelial cell culture that exposure to high shear stress (10 dynes/cm^2) results in an atheroprotective phenotype [2]. Although it is known that high shear environments are able to induce a positive transcriptional effect on endothelial cells in culture, the inability to quantify physiologic flow and shear stress patterns throughout the vascular system has hampered the use of more physiologic flow conditions in *in vitro* biological experiments.

Previous *in vivo* studies using noninvasive medical imaging techniques to quantify blood flow and wall shear stress during resting and exercise conditions has been limited to localized image planes [3]. The results obtained from these analyses provide wall shear stress information at particular locations in the aorta but do not fully describe the three-dimensional distribution.

Computational flow simulations, using finite element methods to solve the Navier-Stokes equations, provide a means to quantify and visualize complex hemodynamic conditions along the entire abdominal aorta. While this analysis has previously been completed on idealized models [4], recent advances enable the construction of more anatomically representative models from three-dimensional magnetic resonance angiography (MRA) data. Furthermore, *in vivo*, pulsatile velocity profiles obtained from cine phase contrast magnetic resonance imaging (PC-MRI) can be used to specify inlet and outlet boundary conditions. The results from these flow simulations provide a subject-specific, three-dimensional description of the flow patterns present in the human abdominal aorta.

METHODS

Magnetic resonance angiography (MRA) scans of two healthy subjects (age 20-30) were obtained in a 1.5T GE Signa (GE Medical Systems, Milwaukee, WI). Coronal slices of 4 mm thickness were obtained in a 40 cm x 40 cm field of view. Three-dimensional, subject-specific solid models were created from the MRA images using custom software [5] and discretized using a commercially available mesh generation program (MeshSim, Simmetrix, Clifton Park, NY).

Cine phase contrast images (PC-MRI) taken perpendicular to the vessels of interest were used to calculate *in vivo*, time-varying volumetric flow. The periodic flow waveforms were then used to compute analytic velocity profiles using pulsatile flow theory, which served as inlet and outlet boundary conditions. The remaining outlets were specified with zero-pressure boundary conditions.

To simulate light exercise for one of the two subjects, the total volumetric flow under resting conditions at the supraceliac and infrarenal levels of the aorta were increased 3-fold and 6-fold, respectively. In addition, the cardiac cycle was shortened to represent a 50% increase in resting heart rate. These values were derived from average increases measured *in vivo* at the supraceliac and infrarenal levels in 11 young, healthy subjects pedaling on an MR-compatible exercise cycle [3]. Furthermore, average exercise flow waveforms at these levels were computed using data from the same 11 subjects. The average exercise flow waveforms were then scaled to represent the total increased volumetric flow at each level for this subject. Figure 1 shows the resting and simulated exercise flow waveforms that were prescribed to each outlet for this subject. The second subject in this study also participated in the study that obtained flow data during exercise on the MR-compatible cycle, so the subject-specific exercise flow waveform and increase in blood flow were used to prescribe inlet and outlet boundary conditions for this case.

Once the boundary conditions were applied at each inlet and outlet, the flow solution for each subject-specific mesh was obtained using a finite element method to solve the incompressible Navier-Stokes equations [6].

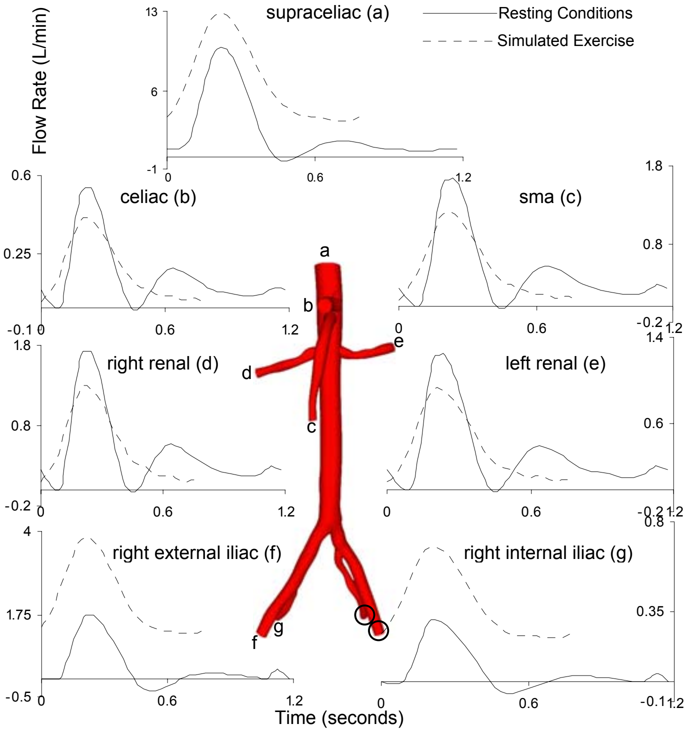

Figure 1. Solid model generated from MRA data and boundary condition specification for one representative subject. Lettered inlets/outlets indicate the prescription of Womersley velocity profiles for the shown periodic volumetric flow waveforms. Circled outlets represent the prescription of a zero-pressure boundary condition.

RESULTS AND DISCUSSION

The flow solutions computed with resting conditions for each subject demonstrated low, recirculating flow in the infrarenal portion of the abdominal aorta during the diastolic portion of the cardiac cycle. Furthermore, reverse flow was observed along the posterior wall at the level of the celiac and superior mesenteric branches during diastole. Results from previous computational flow simulations completed on idealized models indicated the formation of a single vortex along the posterior wall [4] whereas multiple vortices could be observed in each of these subject-specific simulations. The vortices were localized to the celiac branching, renal branching, and supra-iliac bifurcation levels.

Under simulated light exercise conditions, higher velocity, more unidirectional flow was observed throughout the cardiac cycle. The retrograde flow observed under resting conditions in the infrarenal aorta during diastole was eliminated during simulated exercise conditions. Reverse flow along the posterior wall at the celiac and superior mesenteric branches was significantly reduced, but still present. Figure 2 illustrates the flow simulation results under resting and simulated light exercise conditions for the subject in which subject-specific flow waveforms and flow increases were used to prescribe the exercise boundary conditions.

In the simulation results obtained from the use of both rest and exercise boundary conditions, velocity magnitude was observed to be non-periodic over two cardiac cycles in specific domains of the mesh, even though periodic boundary conditions were imposed. It is hypothesized that phenomena such as vortex shedding, which may have periods greater than a single cardiac cycle, were causing local areas of aperiodicity.

The results obtained from this study suggest that the increase in blood flow associated with light exercise can reduce the adverse hemodynamic conditions found at rest. The complexity of the flow features present in the human abdominal aorta may require more refined experimental techniques to emulate these phenomena *in vitro* in order to study the effect of physiologically relevant mechanical forces on the endothelium.

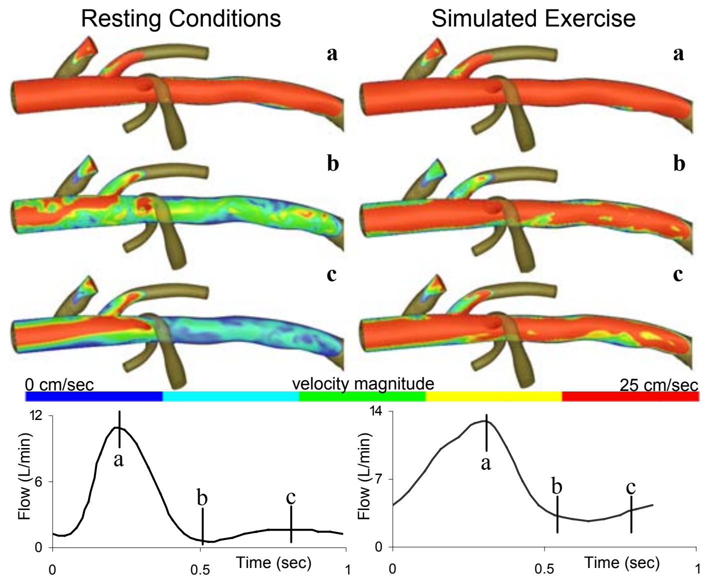

Figure 2. Flow simulation results for resting and simulated exercise conditions for subject with subject-specific exercise waveform and flow increase. A contour slice of velocity magnitude is displayed in the midsagittal plane during three time points in the cardiac cycle.

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