Quantification of Hemodynamics in Abdominal Aortic Aneurysms During Rest and Exercise Using Magnetic Resonance Imaging and Computational Fluid Dynamics

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Introduction

Abdominal Aortic Aneurysms (AAAs) represent the 13th leading cause of death in the United States. As AAAs enlarge, adverse hemodynamic conditions, including regions of low mean wall shear stress (MWSS) and high particle residence time, are exacerbated under resting conditions. Preliminary rodent studies show that the growth of experimentally-created AAAs was slowed when an arterio-venous fistula (AVF) was created downstream of the aorta to increase blood flow through the aneurysm [1]. Thus, we hypothesize that moderate exercise, which increases infrarenal blood flow and MWSS in healthy aortas [2] may slow or even halt the growth of AAAs. This work combines magnetic resonance imaging with computational fluid dynamics to study blood flow in AAAs under rest and exercise conditions.

Methods

Three male patients (mean age 72.6 ±11.5 years) with known small abdominal aortic aneurysms (<5 cm) were imaged in the supine position using a 1.5T GE Signa MR scanner (GE Medical Systems, Milwaukee WI) and an 8-channel torso or cardiac coil. Imaging studies were conducted under a protocol approved by the institutional review board, and informed consent was obtained from all subjects. A 3D gadolinium-enhanced magnetic resonance angiography (MRA) sequence was used to image the aorta. A cardiac-gated phase contrast sequence (PC-MRI) was used to measure blood flow velocity perpendicular to the aorta at the supraceliac (SC) and infrarenal (IR) levels. Brachial systolic and diastolic blood pressures were acquired immediately after the scan. 3D patient-specific geometric models were constructed from the MRA data using custom software [3] and then discretized into finite-element meshes. The PC-MRI images acquired at the SC and IR levels were segmented at each of 24 reconstructed time-points using a level-set technique and then assembled into volumetric flow waveforms (Figure 1).

The patient-specific SC volumetric flow waveforms were mapped to the inflow faces of the meshes using a Womersley velocity profile. At each outlet, a three-element Windkessel model consisting of a proximal resistance (R_p), capacitance (C), and distal resistance (R_d) was used to represent the resistance and compliance of the vessels downstream of each outlet. The R_p, C, R_d values were determined from the PC-MRI data, literature, and the brachial blood pressures. These values and the inflow waveform were scaled to simulate exercise [4]. The Navier-Stokes equations were then solved on the finite-element meshes using the aforementioned inlet and outlet boundary conditions assuming rigid walls for both rest and exercise. MWSS over the cardiac cycle was quantified in 1-cm strips at the supraceliac, infrarenal, and suprabifurcation levels, and at the largest diameter of the aneurysm, where flow stasis and low MWSS are likely to occur at rest (Figure 2).

Results and Discussion

Simulated pressures at the inlet of the computational model were all within 5% of the measured brachial blood pressures, an agreement found in literature [5], and all flows at every outlet were within 5% of target values. Under resting conditions, the renal arteries lacked backflow, matching literature MR measurements [6], and the MWSS was lowest in the aneurysm (3.0±1.6 dynes/cm²). MWSS increased in all four locations during exercise, including 7.6±4.3-fold in the AAA, eliminating areas of low MWSS (Figure 2). The resting IR flow waveform obtained from simulation compared favorably with the measured PC-MRI flow waveform (Figure 3). Future work includes analyzing additional subjects and examining the influence of wall motion.

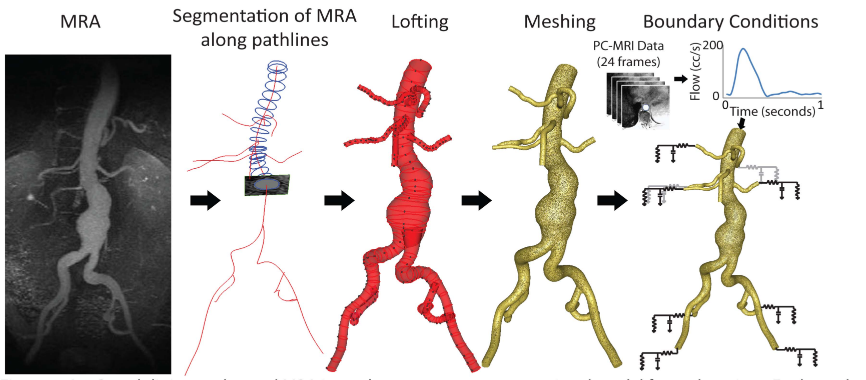

Figure 1: A 3-D gadolinium-enhanced MRA is used to construct a computational model for each patient. For boundary conditions, PC-MRI data is applied at the inlet; a 3-element lumped parameter RCR model is applied at each outlet.

	Patient 1		Patient 2		Patient 3		Average		
Location	Rest	Exercise	Rest	Exercise	Rest	Exercise	Rest	Exercise	Rest-to-Exer. fold increase
Supraceliac (SC)	3.5	7.8	3.5	8.0	2.5	8.3	3.2±0.6	8.1±0.2	2.6±0.6
Infrarenal (IR)	4.9	33.1	5.8	20.7	3.4	26.2	4.7±1.2	26.7±6.2	6.2±2.2
Mid-Aneurysm (MA)	3.1	19.5	1.4	17.5	4.5	18.7	3.0±1.6	18.6±1.0	7.6±4.3
Suprabifurcation (SB)	5.6	27.2	1.6	10.4	9.4	84.8	5.6±3.9	40.8±37.2	8.1±1.5

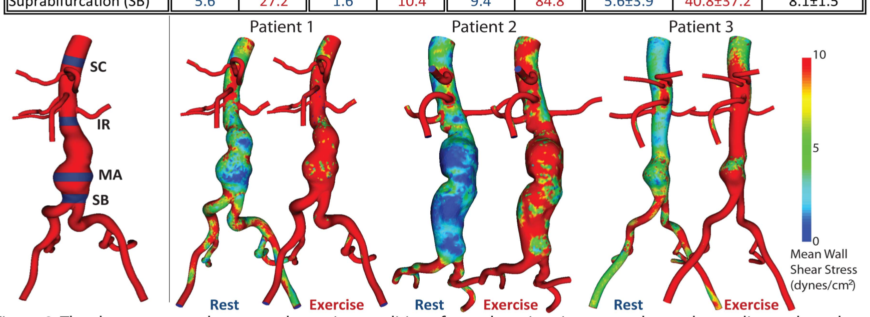

Figure 2: The shear stress under rest and exercise conditions for each patient is averaged over the cardiac cycle and quantified in 1-cm strips at four locations. All MWSS values are in dynes/cm².

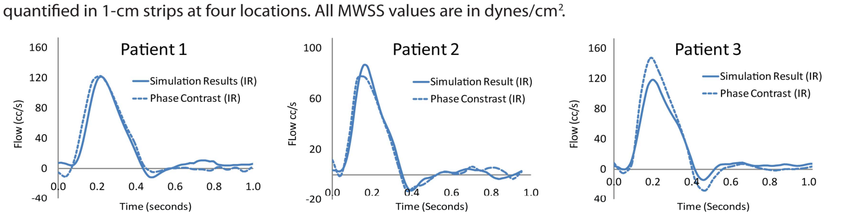

Figure 3: The measured PC-MRI volumetric flow waveforms are compared to the simulated volumetric flow waveforms at the infrarenal (IR) level under resting conditions.

Acknowledgments

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