RAPID IN-VITRO PHYSIOLOGIC FLOW EXPERIMENTATION USING RAPID PROTOTYPING AND PARTICLE IMAGE VELOCIMETRY

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INTRODUCTION

Cardiovascular disease is the primary cause of death in the United States and most developed countries. Because atherosclerosis begins as highly localized, sparsely distributed lesions, many believe the onset of disease is related to local hemodynamic phenomena in the affected artery. However, a direct correlation between local flow characteristics and plaque formation has yet to be quantified. Our motivation for in-vitro experimentation is to examine local flow characteristics in an attempt to identify potential fluid mechanic causative factors for localized cardiovascular disease. The velocity structure within anatomically accurate cardiovascular system models must be well characterized before a correlation between hemodynamics and the onset of disease can be made. Moreover, hemodynamic studies should be based on accurate, patient-specific anatomy. As such, a fundamental plug and play system capable of taking quick flow field measurements in anatomically accurate models is required.

This study aimed to develop the essential elements of such a system and use it to measure the flow field in a physiologically relevant model. We describe test section development and measurements in physiologically representative flow. An idealized symmetric bypass geometry was selected for system development and demonstration. The experimental data measured within the simplified geometry will provide a basis for comparison with numerical simulations and magnetic resonance velocimetry (MRV) measurements. The flow model was manufactured using rapid prototyping (RP) technology and the velocity structure was measured using particle image velocimetry (PIV). With the system described, RP manufactured anatomically accurate vascular geometry can be inserted into the experimental setup to provide clinically relevant information within reasonable times.

SPECIFIC PROJECT OBJECTIVES

The characterization of the hemodynamics within the symmetric bypass model required development of four elements that comprised the flow simulation and measurement systems: a complex physical model, working fluid, physiologically representative flow system, and the PIV system. Most importantly, these components were incorporated into one comprehensive experimental apparatus. The following includes details of individual components required to meet the overall project objective of rapid in-vitro physiologic flow experimentation.

Model Development

A symmetric bypass physical model shown in Figure 1 was developed based on simplified geometric considerations. The stenosis was modeled as a 75% reduction in cross-sectional area (from 0.750- to 0.375- inch diameter), with a length of 0.125 inches. The reduction profile followed a 5th-order polynomial from the diameter of the main artery to the diameter of the stenosis with zero slope and curvature specified at the beginning and end of the curve. The 0.125-inch section of the stenosis served as a reference for the flow measurement. The anastomosis was modeled as the 45° intersection of two cylinders. The host artery and graft have diameters of 0.750 and 0.625 inches, respectively. The graft was modeled as a flattened arch with a straight, one-inch section offset from the main artery by 1.50 inches. The graft followed a 5th-order polynomial between the offset axis and anastomosis with zero curvature at both ends, zero slope at the end connected to the graft, and a slope of one (or -1) for the end connected to the anastomosis. End connections were included (not shown in the figure) so that one-inch outer-diameter, 0.125 inch wall tubing could be mated to the model.

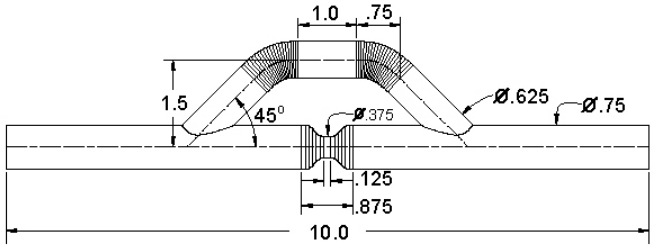

Figure 1. The symmetric bypass model (in inches)

The symmetric bypass was first drafted as a 3-dimensional computational solid (AutoCAD, AutoDesk San Rafael, CA). The CAD file was converted to STL format and processed by the software that controls a fused deposition modeling RP machine (Quickslice and FDM 3000, Stratasys, Inc., Eden Prairie, MN). A positive model, to serve as a mold, was manufactured out of a water-soluble polymer (WaterWorks P-400 Soluble Support, Stratasys, Inc.), polished, and then cast in a transparent polyurethane block. After curing, the mold was dissolved, leaving the flow passages under investigation. The techniques applied to manufacture the bypass have also been applied to anatomical models extracted from Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) data [see 1 and 2 for additional details]. RP molds using WaterWorks allow for the construction of complex, closed-loop flow paths free of the seam lines associated with traditional casting techniques.

Working Fluid

The working fluid required two important properties: 1) the index of refraction must match that of the model material to allow optical accessibility free of distortion, and 2) the kinematic viscosity must be matched for dynamic similarity. Because the model was developed to scale, the fluid's viscosity was matched to that of blood. It was assumed in the experimentation that a Newtonian fluid was acceptable for the examination of relevant flow parameters within the model [3]. A combination of ammonium thiocyanate, glycerol, and water was used to balance requirements for fluid refractive index and viscosity. Equal parts ammonium thiocyanate and water by mass formed a base solution that was mixed with glycerol 70/30 by volume, respectively. The working fluid index of refraction and viscosity were 1.47 and 3.5-centipoise, respectively.

Physiologically Representative Flow System

The flow system as shown in Figure 2 was designed to deliver a range of inlet flow conditions to the test section, including steady or pulsatile flow. Fully adjustable steady flow, delivered via a motor-driven flexible impeller pump (Model 18610-0271, JABSCO, Costa Mesa, CA) was used to qualify the PIV system. A flow development section of seven feet was attached at the model inlet to ensure fully developed flow based on the hydrodynamic entrance length for laminar flow using 7 L/min. A pulsatile pump (Model 1423 Blood Pump, Harvard Apparatus, Holliston, MA) provided flow similar to the ventricular output of the heart. Resistance (1/4 inch stopcock valves) and compliance (aspirator bottles) within the flow loop provided adjustable physiologic flow waveforms to the test section.

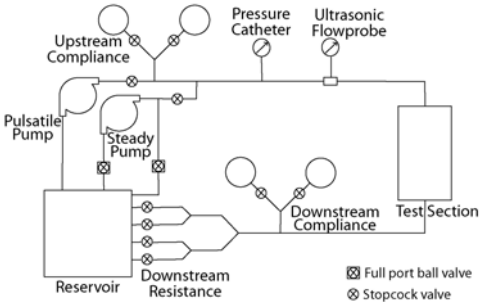

Figure 2. Schematic of the Flow System

Particle Image Velocimetry

A commercially available PIV system (Powerview Stereoscopic PIV, TSI, Inc., Shoreview, MN) including a 200 mJ/pulse Nd:YAG laser (NewWave Research, Inc., Fremont, CA) was the basis of the fluid measurement system. During pulsatile flow, a proximity switch mounted inside the pump synchronized image acquisition. The switch served as the external gate for a pulse generator (Model 500 Programmable Pulse Generator, Berkeley Nucleonics Corporation, San Rafael, CA) capable of delivering a delayed trigger to the PIV synchronizer. Image pairs were acquired at different points along the waveform by varying the delay. The timing separation between images was based on the flow rate at the particular phase of the pulsatile waveform. Flow was seeded with 10μm mean-diameter silver-coated glass spheres (Part # 900875, TSI, Inc.).

FINAL REMARKS

To demonstrate the measurement capabilities of the system, Figure 3 provides an instantaneous vector field acquired at one instant in the physiologic waveform. In addition to using these data for comparison with numerical simulations and other data, the relative speed afforded by RP technology provides a unique opportunity to investigate cardiovascular flow in clinically relevant settings. In addition to providing instantaneous flow-field data, PIV provides the capability to examine flow characteristics such as wall shear stress often associated with cardiovascular disease. Through the use of RP manufacturing, an adaptable flow system, and PIV, we have demonstrated a system by which flow measurements in anatomical models can be taken within reasonable times. This system is highly useful for studying hemodynamics in large patient populations based on patient-specific flow characteristics rather than the flow in a representative average anatomical model.

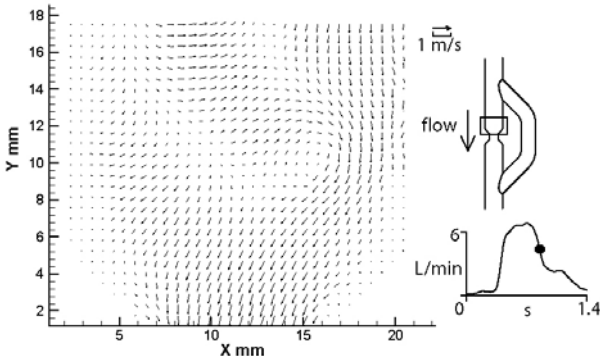

Figure 3. Instantaneous PIV data, Δt = 150 μs

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