Velocity Profile and Wall Shear Measurements in a Model Human Coronary Artery

T.D. Tang, D.P. Giddens, C.K. Zarins* and S. Glagov*

School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA
and
*School of Medicine, The University of Chicago, Chicago, IL

ABSTRACT:

Velocity profiles and wall shear rates were measured with a Laser Doppler Anemometer (LDA) in a large scale model of the human coronary arteries. A pulsatile pump provided physiologic flow waveform, and the model includes the aortic root, left main (LM), left anterior descending (LAD) and left circumflex (LCX) coronary arteries. The axial velocity profiles at the proximal parts of the branches are skewed to the inner wall of the bifurcation as well as to the epicardial surface of the heart. Secondary flow is stronger at regions close to the apex of the flow divider and diminished downstream. Regions of relatively higher or lower wall shear rates were measured at sites in the model, but no flow separation was observed. The measurements provide a fluid dynamic database for studying possible correlations of hemodynamics with atherosclerotic plaque localization in human coronary arteries.

INTRODUCTION:

Hemodynamics has been hypothesized to be associated with atherosclerotic lesion initiation because of localization of plaques at preferred sites such as sharp curvature and branching. The relationship of plaque development to wall shear stress has recently received great attention (1), and strong correlation between early plaque localization and mean wall shear stress has been demonstrated in human carotid arteries (2).

The human left coronary arteries have a complicated and curved branching geometry. The lesions of these vessels has a distinct pattern with high frequency on the outer walls of the bifurcation and at the inner curvature downstream from the bifurcation (3,4). Since the local flow patterns vary in a branching configuration, it is our goal to examine the detailed flow phenomena at this specific bifurcation and investigate whether a correlation exists between plaque localization and any fluid dynamics variables in the coronary arteries and to compare any such correlations with results found in human carotid arteries.

METHODS:

Twelve post-mortem luminal casts of the human left coronary artery trees were prepared by Departments of Pathology and Surgery, The University of Chicago, from the hearts of human subjects who died from non-cardiovascular causes. Dimensions of the arteries, curvature of the bifurcation, and branching angles were measured. An upscaled rigid model, which is four times the average measured dimensions, was constructed and included a segment of the ascending aorta, the sinuses of the Valsalva, the left main coronary artery (LM), and proximal segments of the left anterior descending (LAD) and left circumflex (LCX) coronary arteries. In the process of construction, a clay model was built first and put into a prepared container, and Dow Corning Sylgard 184 elastomer was then poured into the container. After the silicone rubber compound was solidified, the clay core was separated from the sylgard in water of 50 C. The model has a high degree of transparency with index of refraction equal to 1.41.

The experimental setup include a pump, an electrical valve, a magnetic flowmeter,
microcomputer, and Laser Doppler Anemometer (LDA). The upstream pressure head is provided by a Teel pump. A modulating valve which is controlled by the signal from the microcomputer is installed in the flow system to generate the coronary flow waveform. The flow system is arranged to make it feasible to create brief periods of negative flow during the pulsatile cycle by utilizing the pressure difference between different chambers of the downstream tank. A one component LDA system was employed to measure the velocity. The microcomputer acquires and then analyzes the data while sending the signal to control the valve in background.

The generated flow waveform (Fig. 1) in the LM has a mean Reynolds number equal to 240 and a Womersley parameter equal to 2.8. Fluid with index of refraction which matches the model is obtained by a 42% : 58% mixture of water and glycerine. The fluid viscosity is 8.4 cp with density equal to 1.14 gm per cubic cm at fluid temperature of 28 C. Flow division between LAD and LCX is 58:42.

Velocity profiles along the curve of the bifurcation plane and the plane perpendicular to the plane of selected cross-section were measured (Fig. 2). Wall shear rate was determined from velocity measurements close to the model boundary. In the LM coronary artery, only axial velocities were measured while in the branches (LAD and LCX) both the axial and circumferential components were measured.

RESULTS:

Figures 3 and 4 illustrate examples of axial velocity data measured in the LCX. In Figure 3 velocity profiles are represented which were taken in the plane of the bifurcation at location 0.83 diameters downstream of the flow divider. Strong skewing toward the inner wall can be seen, particularly during diastole when the flow rates are high. Figure 4 gives velocity data taken at the same station in the plane perpendicular to that of the previous figure, and the results illustrate a slight skewing toward the epicardial surface. The near-wall velocity profiles were employed to determine the wall shear rate and, hence, the wall shear stress. The inner walls can thus be seen to experience generally higher wall shear than the outer walls, and the epicardial surfaces of the model tend to have slightly higher shear than the endocardial surfaces. Negative shear rates occur transiently during the pulsatile cycle in both figures, but these are a consequence of near-wall flow reversal due to the pulse waveform - not flow separation.

DISCUSSION:

Extensive measurements of pulsatile velocity profiles and wall shear rate have been taken in a large scale cast of the human coronary arteries. Secondary flow patterns are strong at the LAD-LCX bifurcation, and velocity profiles are skewed toward the inner walls of the flow divider. Friedman et al (5) have presented data on correlations between wall shear and intimal thickness in a coronary cast at a limited number of points, but did not give results of velocity profiles measurements. The fluid dynamic data obtained in the present experiments will be employed in a correlative study with histological measurements, in human coronary arteries, which are presently being performed. An objective will be to determine whether the same hemodynamic factors which have been shown to relate to atherogenesis in carotid arteries also are associated with lesion localization in the coronary vessels.

ACKNOWLEDGEMENTS:

The authors gratefully acknowledge support of this work provided by NIH Grant HL 15062-19 and a George W. Woodruff endorsement to the School of Mechanical Engineering.

REFERENCES:


Fig. 1. Left main coronary artery flow waveform

Fig. 2 This diagram represents the model configuration of the left main coronary (LM), left anterior descending (LAD), left circumflex (LCX) coronary artery and the sinuses of Valsalva.

Fig. 3. Axial velocity profiles throughout the cycle in the plane of the bifurcation at location 0.83 diameters downstream of the flow divider in the LCX.

Fig. 4. Axial velocity profiles at the same station in the plane perpendicular to the plane of Fig. 3.