CORRELATION OF WALL SHEAR STRESS AND INTIMAL THICKENING IN THE RIGHT CORONARY ARTERY

Anil K. Joshi (1, 2), Richard L. Leask (3), Matadial Ojha (2), Jerry G. Myers (4), Jagdish Butany (5), and C. Ross Ethier (1, 2)

(1) Department of Mechanical and Industrial Engineering
University of Toronto
Toronto, Canada

(2) Institute of Biomaterials & Biomedical Engineering
University of Toronto
Toronto, Canada

(3) Department of Chemical Engineering
McGill University
Montreal, Canada

(4) Glenn Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

(5) Department of Pathology
University of Toronto
Toronto, Canada

INTRODUCTION

Atherosclerosis is a common arterial disorder, and is of particular clinical significance when it occurs in the coronary arteries since it can result in ischemic heart disease and/or myocardial infarction. The development of atherosclerotic lesions is linked to systemic risk factors including hypertension, hypercholesterolemia, heredity, and smoking [1] as well as local biomechanical factors [2, 3]. This study seeks to determine if there is a correlation between biomechanical factors, specifically wall shear stress (WSS), and early lesion development in the human right coronary artery. Here we assess early lesion development by measurement of intimal thickness (IT).

MATERIALS AND METHODS

Artery Casting

Intact human hearts were obtained at autopsy. The geometries of the coronary arteries were characterized by casting, as previously reported in detail [4]. Briefly, for each heart the right coronary artery was injected with Batson's #17 corrosion casting compound at a pressure of 100 mm Hg and held at this pressure until the resin had completely polymerized. The right coronary artery was then excised from the heart. An incision was made along the myocardial surface of the artery and the artery tissue was carefully removed from the cast (Figure 1). Four human right coronary arteries exhibiting early disease (modest intimal thickening) were used for this study.

Intimal Thickness Measurements

After removal of the cast, tissue samples were obtained at approximately 3 mm axial intervals. Samples were fixed, embedded in paraffin, sectioned perpendicular to the axis of the artery, and stained with modified Verhoff elastic-trichrome stain. Each section was analyzed using a LEICA Q500MC system to measure intimal thickness at eight equally-spaced locations around the circumference of the artery lumen (Figure 2). All intimal thickness measurements presented here have been normalized by the mean intimal thickness of the artery. This is designed to account for systemic factors promoting thickening and hence isolate local variations in intimal thickness.

Figure 1: Batson's cast of a right coronary artery

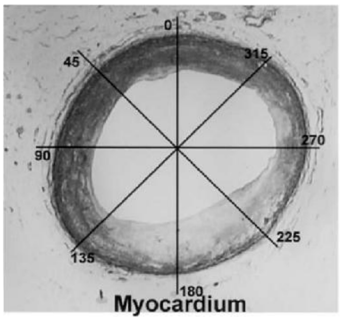


Figure 2: Example of an artery cross-section with measurement locations shown

Model Construction

The artery casts were CT scanned using a procedure described by Moore et al [5]. The resulting three dimensional image volume was segmented using custom MATLAB (MathWorks, Natick, MA) routines to obtain cross-sectional contours of the artery lumen perpendicular to the centroidal path of the artery [4]. These contours were imported into a CAD software package (DDN, ICEM-CFD, Berkeley, CA) and used to reconstruct the artery surface using a procedure described by Moore et al [5]. The Tetra meshing module of ICEM-CFD was used to discretize the geometry into a quadratic tetrahedral mesh.

Flow Simulations

Steady flow simulations on a non-moving mesh were performed at Re=200 on each artery geometry using a well validated, in-house, 3-D incompressible Navier-Stokes flow solver. The inlet velocity profile was assumed to be a fully developed Poiseuille profile. No slip boundary conditions were applied at the vessel wall, and a traction free boundary condition was applied at the vessel outlet. Blood rheology was assumed to be Newtonian and branch flows were neglected. Steps were taken to ensure that results were mesh-independent. Wall shear stresses were obtained following a post-processing step. All wall shear stress values are normalized to the inlet Poiseuille value.

Correlations Between Morphometry and Hemodynamics

Computed wall shear stresses were spatially co-registered with intimal thickness measurements based on landmarks on the cast and tissue sections, including the cut marks on the cast formed when extracting the cast from the artery. The uncertainty in this co-registration process was estimated to be less than 1 mm in the axial direction.

Normalized (local) wall shear stresses were correlated with normalized (local) intimal thicknesses. To minimize noise, wall shear stress data were binned into WSS intervals of 0.2 normalized WSS units.

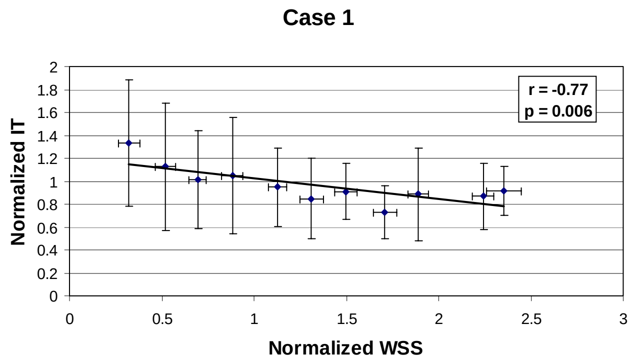
RESULTS

Currently, steady flow simulations have been completed for two artery samples. In case 1 (44 year old male), 208 intimal thickness measurements were obtained. In case 2 (35 year old female), 136 intimal thickness measurements were obtained. For both cases a statistically significant inverse correlation between wall shear stress and intimal thickening was observed, with p values 0.006 and 0.0004 (Figure 3).

DISCUSSION AND CONCLUSIONS

These preliminary results confirm that, on average, intimal thickening is promoted by low wall shear stress. However, the large standard deviations in intimal thickening within a given bin indicate that the intimal thickness depends on factors in addition to WSS magnitude.

In our flow simulations to date, the hemodynamic effects of branch flows, arterial motions and unsteadiness have all been neglected. The first of these two have been shown by our group to have only a small effect on time-average WSS distribution. Flow simulations on additional artery geometries, and including the effects of branch flows and unsteadiness, are ongoing.



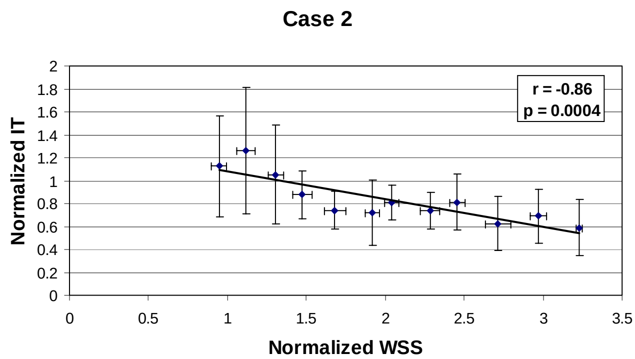


Figure 3: Scatter plot of normalized intimal thickness vs. normalized wall shear stress for 2 human right coronary arteries. Each point represents the mean thickness and mean WSS for a group of points having normalized WSS value lying within a "WSS bin" of size 0.2 normalized WSS units. Error bars indicate the standard deviations in wall shear stress and intimal thickness for each bin. r and p values were obtained from linear regression of mean intimal thickness on mean WSS for each bin.

ACKNOWLEDGEMENTS

This work is supported by an NSERC Operating Grant (CRE).

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