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THREE-DIMENSIONAL FINITE ELEMENT MODELING OF BLOOD FLOW IN THE CORONARY ARTERIES

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ABSTRACT

Introduction: Coronary artery blood flow is low in systole when the ventricles contract and compress the downstream vessels and maximal in diastole when the ventricles relax, despite the fact that the driving aortic pressure is highest in systole and lowest in diastole. To simulate coronary artery blood flow, the aortic pressure, intra-myocardial pressure and the downstream coronary vessels must be modeled. Intramyocardial pressure can be approximated by left ventricular pressure. Left ventricular pressure is coupled to the aortic pressure and flow in systole (when the aortic valve is open) and thus should be determined by considering the interactions between models of the heart and the systemic circulation. We previously developed a method to couple a lumped parameter heart model to a three-dimensional aortic model [1]. In the present study, we use this lumped parameter heart model, a three-dimensional finite element model of the aorta and coronary arteries and a lumped-parameter model of the distal coronary vascular bed to model blood flow in the coronary arteries.

Methods: The coronary outflow boundary condition strongly couples a lumped parameter coronary vascular model to each coronary outlet [2,3]. A lumped parameter heart model [4] is coupled to the inflow of a three-dimensional thoracic aorta model to compute left ventricular pressure and aortic pressure and flow [1]. Left ventricular pressure and volume are related using a time varying elastance function scaled from a normalized elastance function [5]. Left ventricular pressure approximates the intramyocardial pressure in the lumped coronary model. Parameter values for the lumped coronary and heart models were set to approximate subject-specific heart rate, cardiac output, and pulse pressure data. An augmented Lagrangian method was used to enforce a shape of the velocity profiles of the inlet and the outlets with retrograde flow [6]. A stabilized finite element method was used to compute pressure and velocity fields in the three-dimensional model of the thoracic aorta, coronary arteries and major upper branch vessels. Figure 1 provides an overview of the methods implemented.

Results and Discussion: Figure 2 shows results from a simulation utilizing this new method to model coronary artery blood flow. Using this method, coronary pressure and flow as well as the ventricular and aortic pressure and flow arise naturally through the interactions between the three-dimensional thoracic aorta model, the lumped parameter heart model, and the lumped parameter models of the downstream coronary and peripheral vessels. This is the first three-dimensional simulation of blood flow in patient-specific coronary artery model with realistic flow and pressure.

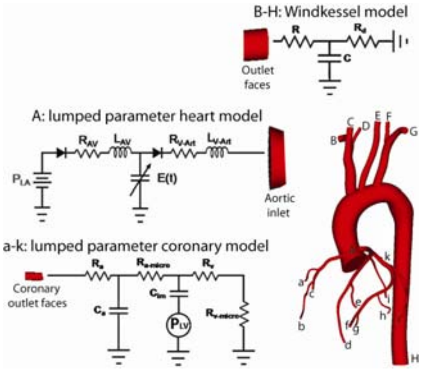

Figure 1. Method to couple 3D aorta and coronary model to lumped models of heart and distal coronary arteries. Coronary boundary condition model includes time-varying intramyocardial pressure obtained from heart model.

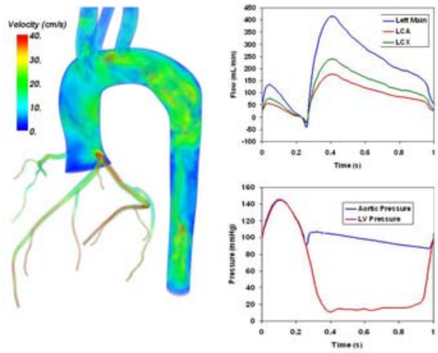

Figure 2. Three-dimensional simulation of flow in aorta and coronary arteries. Velocity magnitude is shown at time of peak coronary artery flow. Coronary flow waveforms demonstrate maximal left coronary artery flow during diastole. Computed left ventricular and aortic pressures are physiologic.

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