ENTRANCE FLOW PATTERNS IN THE CORONARY ARTERIES: A COMPUTATIONAL STUDY

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ABSTRACT

Blood flow in the coronary arteries is of fundamental hemodynamic interest in the study of atherosclerosis, and coronary entrance flow patterns are expected to be affected strongly by flow in the aorta root. We investigated entrance flow patterns in both coronary arteries with a combination of magnetic resonance imaging (MRI) and computational fluid dynamics (CFD) techniques. We found that the aortic flow drives two strong axial vortices in the entrance sections of both coronary arteries at systole. The vortices disappear as the coronary artery inflows increase during diastole. The vortices have different rotational directions that produce low and oscillating shear stress on the myocardial side in the right coronary but on epicardial side in the left coronary. If this predicted phenomenon is verified *in vivo*, it may explain earlier observations [1] that show differences in the distribution of atherosclerotic plaques in proximal segments of the right and left coronary arteries in humans.

INTRODUCTION

Blood flow is thought to play a key role in the development, diagnosis and treatment of coronary disease. Coronary arteries receive blood flow from directly from the aorta. The right and left coronaries can be thought of as smaller branches of the aorta, since the diameter of the coronary is about 4mm but the aortic root is about 30mm and the total flow in the coronaries occupies only approximately 5% of the aortic flow. That implies that aortic flow patterns are less affected by the coronaries while, in turn, the entrance flows of the coronaries are controlled by the aortic flow.

Although there have been numerous investigations of coronary flow, the affects of aortic flow on the details of coronary flow are not well known [2-4]. A main reason is the complexity of aortic flow, especially in the aorta root where the flow contains dynamic helical flow patterns that arise not only from geometric curvature of the ascending aorta, compliance of the aortic wall, and the inflow created by ejection from the ventricle and through the aortic valve, but also from the motion of the aorta resulting from its attachment to the beating heart [5]. Thus, a question of interest is how to consider aortic flow in the investigation of coronary flow. As Figure 1(a) shows, if the coronaries are unique outlets and the aorta is taken to be a passive inlet, the coronaries will have a smooth entry flow depending mainly on the geometry of the aorta and aortic valve. In this case, the effects of the inherent flow patterns in the ascending aorta are neglected. On the other hand, the special aortic flow pattern that is formed by the heart, aortic valve and ascending aorta [5] may play an important role in filling the coronaries. Thus, a more realistic modeling approach is to consider that coronary flow is not only affected by the aortic geometry but also strongly controlled by flow patterns in the aorta, as depicted in Figure 1(b).

With recent developments in MRI, it is possible to image coronary artery anatomy and entrance flow non-invasively. Although in principle capable of measuring blood velocity profiles as well, current imaging resolution makes accurate routine extraction of detailed hemodynamic factors difficult in the coronary arteries, if not impossible. CFD, however, has the advantage of expressing all hemodynamic factors to a high resolution if the boundary and input conditions are well defined. Combining MRI and CFD has advanced to a stage where it is now possible to model pulsatile hemodynamics faithfully in realistic arterial models with a high resolution.

This research investigated the entrance flow patterns in the right and left coronary arteries by combining MRI and CFD techniques.

METHODS

<u>MRI</u>

The MRI slices that provided geometry information for the aorta and coronary lumens came from volunteers. A model of the aorta, including the ascending aorta from above the aortic valve, aortic arch and a segment of descending aorta, together with the connected left and right coronary arteries, was been developed. The small branches off the coronary arteries were neglected - only LAD, LCX and RCA were retained.

The aorta and the left and right coronary vessels were reconstructed from their MRI slices and were combined by a computer aided design method to form one CFD model as Figure 2 shows.

Phase contrast velocity MRI scanning was taken above the aortic valve and perpendicular to the local aortic axis. The scanning has three groups of velocity slices that corresponded to three velocity orthogonal components and span a cardiac cycle. The velocity data serve as the aorta inlet conditions in the CFD model. Phase contrast velocity MR scanning was also performed in the entrance orifices of the left and right coronary trees, where only axial velocity was recorded and from which average section velocities and flow rates were calculated.

CFD

Computations were performed with the commercial CFD-ACE code assuming a Newtonian, incompressible fluid and laminar flow. The calculations accounted for changes in geometry of the aorta due to wall motion resulting from compliance and attachment to the beating heart. The coronary artery geometry and inflow were obtained from a different individual, and the geometry was "attached" to the aortic model, as shown in Figure 2. There is small net flow in the coronary arteries during systole, with the bulk of coronary flow occurring during diastole. The inflow waveforms were modeled from measured MR data.

RESULTS AND DISCUSSION

Figure 3 shows the entrance axial velocity profiles of the right and left coronary arteries at times representing 0.2 to 0.6 fractions of one cardiac cycle. Two strong axial vortices develop in the entrances of the right and left coronaries, but, interestingly, their rotational directions are opposite.

The entrance axial vortices reached the greatest intensity during systole (the aortic valve closes at time 0.4), and then they become weaker as the average flow in the aorta diminishes in diastole. As Figure 3 shows, the vortex patterns create a low and oscillatory wall shear stress region on the myocardial side in the right coronary entrance, but on the epicardial for the left coronary entrance.

At this stage of the study we have investigated only one case, and we are collecting data on additional subjects to determine whether the phenomena observed represent general characteristics of coronary artery entrance flows. Additionally, it is important to test the CFD predictions by carefully interrogating the velocity patterns in the coronary artery entrance regions with MR. However, the results to date demonstrate that flow phenomena in the aorta can greatly affect entrance flow details in the proximal segments of the left and right coronary arteries.

ACKNOWLEDGEMENTS

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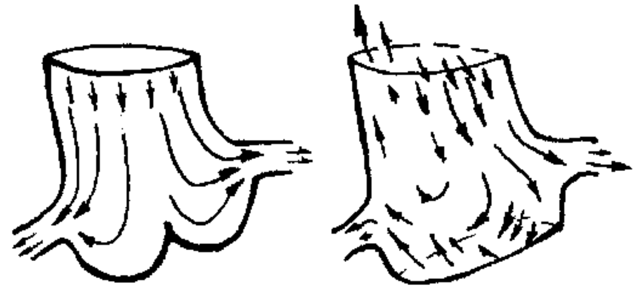


(a) **(b)**

Figure 1.

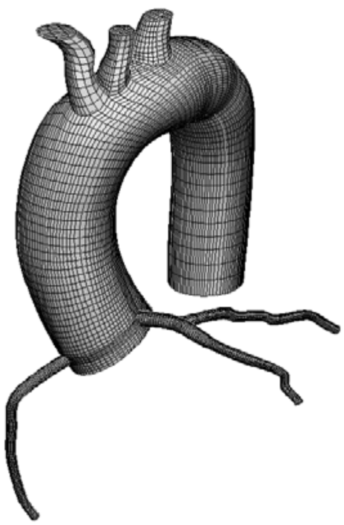
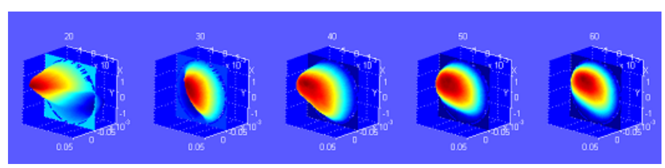
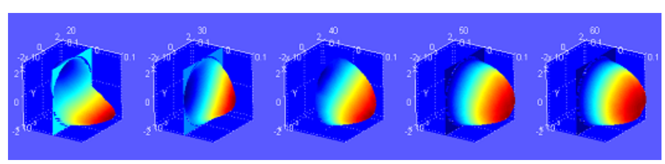


Figure 2.



Right coronary



Left coronary

Figure 3.