Pulsatile blood flow-split in aortic arch dissection

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Abstract

Abnormalities of the aortic arch, as the most proximal site of the cardiovascular system, are of great interest due to its major role in blood distribution to all downstream members. Wall dissection is one of the disorders that an aorta may suffer due to hypertension or degradation of aortic wall properties. A geometrical change of the aortic arch caused by the dissected wall, and consequently the blood flow path, makes the time-varying flow curves to be different in comparison to the healthy aortic arch. This phenomenon modifies wall shear stress (WSS) history during the cardiac cycle. In the current work, the pulsatile blood flow in a typical Stanford A (DeBakey II) dissected aorta is simulated by CFD technique, STAR-CCM+ [1]. The boundary conditions are calculated based on a combination of the impedance boundary condition and the auto-regulation concept in the cardiovascular system.

1. Introduction

The blood flow pumped by the heart enters the cardiovascular system through the aortic arch. A relatively higher blood pressure and velocity of this site makes the arch prone to several cardiovascular disorders. Weakened arterial walls as a result of improper life habits or congenital problems may result in a laminated arterial wall or a dissection. In comparison with other arterial disorders, a dissection can change considerably the blood paths, due its position which is in the middle of the lumen. An abnormal variation of the geometry at proximal sites modifies the flow patterns of the distal arteries, and consequently, changes their time-varying flow curves during the cardiac cycle. These flow curves are highly related to the wall shear stresses (WSS) and timing of blood irrigation of downstream members. Simulation of a more realistic blood flow patterns in the cardiovascular system is of great interest in biomechanical references due to its clinical application and pre-surgery decisions [2, 3 and 4].

Because the final objective of the investigation is not concentrated on patient-specific cases, a canonical model of the aortic arch is analyzed in the current work. The geometry, as well as inlet flow boundary conditions, are typical of a healthy individual [2, 5 and 6], while the dissected wall is introduced to the healthy canonical model.

The boundary condition at outlets is a concern in many references [3 and 4]. Here, a methodology based on a combination of the impedance concept and the auto-regulation of the cardiovascular system is adopted, which is described in section 3.

1.1. Impedance boundary condition

By an analogy with the electrical systems, impedance of a cardiovascular site can be defined as opposition of the downstream arterial bed to receive and pass the blood through it. Considering an arterial site with one inlet and several outlets, the blood tends to flow to the outlet with lower impedance or resistance. Therefore, there is a reversal correlation of impedance and the blood demand of the downstream beds of an outlet. Referring back to the electrical analogy, the pressure and the flow correspond to the voltage and the current, respectively:

$$Z = P / Q$$

Where, Z is the impedance, and P and Q are the pressure and the blood flow in frequency domain.

1.2. Auto-regulation in cardiovascular system

The cardiovascular system regulates automatically the blood demand of each member by dilatation and contraction of the arterioles [6 and 7]. When they dilate, by increasing their diameter the proximal blood flow is deviated to that bed; vice versa for the case of contraction. The dilated arterioles decrease their resistance, and therefore, the blood tends to flow through the outlet with less flow opposition.

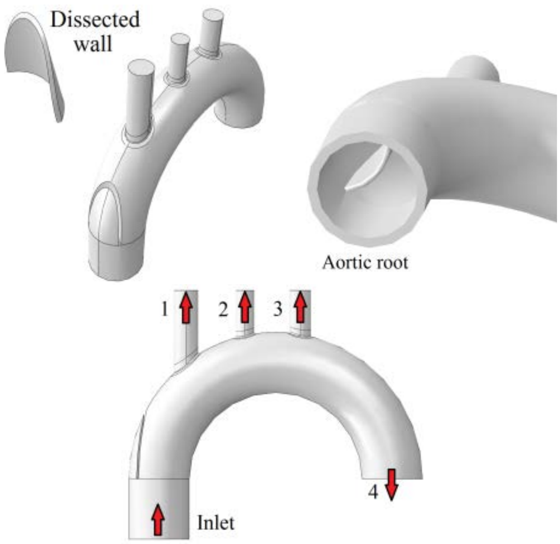

Figure 1. *Dissected aortic arch*

2. Geometry

In order to evaluate qualitatively the fluid mechanic effects of a dissected ascending aorta, a canonical geometry of the aortic arch is adopted in this research. The diameters, lengths and other dimensional values are based on the data reported in different references, e.g. [2 and 5]. Figure 1 shows the reconstructed canonical geometry of the aortic arch which suffers of a dissection in its ascending aorta. In this figure three uprising outlet arteries, brachiocephalic (1), left common carotid (2) and subclavian (3) are shown in addition to the aortic root and descending aorta (4). The dissected wall and its position in the ascending aorta are depicted in the figure, as well.

3. Methodology

As inlet boundary condition, a mass flow history is applied at inlet of the CFD model, where the aortic arch connects to the heart. As the objective concentrates on a canonical simulation, a typical inlet flow may suffice for the current investigation. The inlet mass flow is based on the data presented in [2], which is depicted in Figure 2.

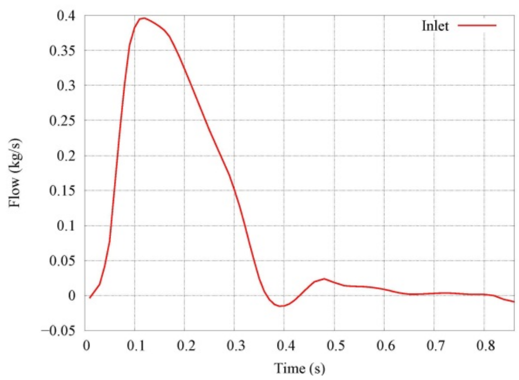

Figure 2. *Typical pulsatile inlet flow at aortic root (SUO)*

As the outlet boundary condition, Auto-regulation plus Impedance Boundary Condition or A+IPBC method is adopted, which is a methodology based on a combination of impedance boundary condition and auto-regulation phenomenon in the cardiovascular system. The A+IPBC method is developed by the authors of the current article. Through the process of this methodology, physiologically realistic and pulsatile pressure time-varying curves are calculated and applied at all outlets. The relation between the flow and pressure outlets satisfy the impedance values of each outlet. The proposed boundary condition is a general method and is applicable on every cardiovascular site, however in the current work its evaluation only in a typical dissected aortic arch model is discussed. The A+IPBC method has been validated by its application on an abdominal bifurcation model presented by Vignon-Clementel [3].The A+IPBC method is computationally cost effective, and therefore, it can be mentioned as an advantage of this methodology.

In aortic arch of a healthy individual it is considered that 10% of the time-average inlet flow deviates to the brachiocephalic artery [4]. Similarly, the flow-split percentage is 5% for both left common carotid and subclavian arteries. Consequently, 80% of the inlet flow is left to be delivered to the lower extreme members through descending aorta. Same as the canonical geometry, these values are considered as typical flow-splits in an aortic arch. Independently of any disorder in the aortic arch, the cardiovascular system regulates the blood demand of each outlet. Therefore, the flow-split requirement should be fulfilled at the end of the iterations of the proposed method. On the other hand, in the A+IPBC method, the impedance boundary conditions of each outlet, which are based on the reported values in the references [6], define the physiological pulsatile pressure curves.

4. Results

The flow rates of the outlets vary in each A+IPBC iteration until all the requirements are satisfied; flow-split and impedance criteria. Figure 3 depicts the history of time-varying flow curves of Outlet 1 (Brachiocephalic artery) during 7 iterations. The flow curve during the first iterations is not physiologically realistic as the time-average flow is equivalent to a backward blood flow; re-entered blood flow back to the aortic arch. The A+IPBC iterations continue and would stop when the difference in two consecutive iterations are lower than a reasonable tolerance. Depending on the arterial site of the simulation, the tolerance is chosen in a way that the changes in consecutive flow curves are not detectable clinically or they are not important from the point of view of the biofluid values.

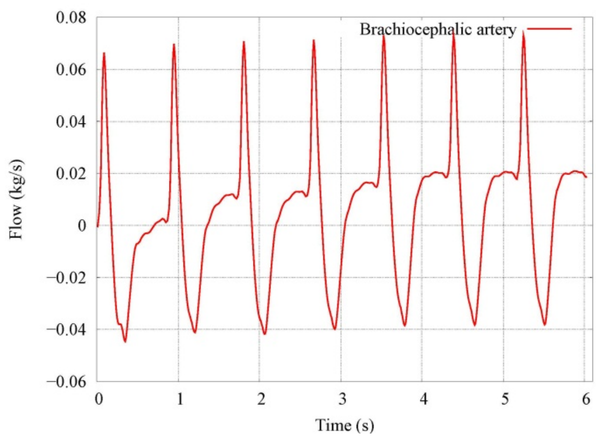

Figure 3. *History of the blood flows during A+IPBC method in a dissected aortic arch*

Figure 4 shows the converged time-varying flow outlets of the A+IPBC method applied on the dissected model. For comparison and evaluation of the effect of the dissected wall on transient flow-splits, the corresponding flow curves of the healthy model are superimposed in the figure. As it can be seen, a considerable variation in the curves is detected in each outlet. The major changes occur in Outlet 1 (Brachiocephalic artery) and Outlet 4 (Descending aorta). It can be deduced from Figure 5 that the change in time-varying blood flow of Outlet 1 is due to its proximity to the dissected wall, which makes the flow deviates to the inner curvature of the aortic arch. Therefore, during the systole when the inertia forces are dominant and the auto-regulation plays a weak role in flow distribution, the brachiocephalic artery receives less blood in comparison to the healthy aortic arch. The lack of blood flow is compensated during diastole as the auto-regulation of the cardiovascular system acts, whose effect is considered in the A+IPBC method. The same blood deviation phenomenon which delivers less flow to the brachiocephalic artery makes the descending aorta receive more blood flow during the systolic phase of the cardiac cycle.

These variations in flow curves will affect directly to the wall shear stresses (WSS) patterns exerted on the endothelial. In long term, the change of WSS history will have a negative impact on the distal cardiovascular arterial sites of the dissected zone. On the other hand, a dissected aorta, apart from weakening the arterial walls which may end in an aneurysm, may destroy or misalign the local endothelial cells due to the formation of the local turbulent eddies around the dissected zone. Consequently, this may cause accumulation of undesired substances and finally the formation of a plaque. Referring back to the Figure 5, a higher local blood velocity, and therefore WSS, are the other source of endothelial damages. On the other hand it can be mentioned that although the auto-regulation phenomenon regulates the blood demand in distal members but the variation in timing of blood delivery (due to the dissection) may affect on efficient member irrigation; the irrigation in a higher blood pressure is more effective to the members. Based on the auto-regulation of the cardiovascular system, the lack of blood in the systole is compensating during the diastolic pahse, when the blood pressure is relatively lower.

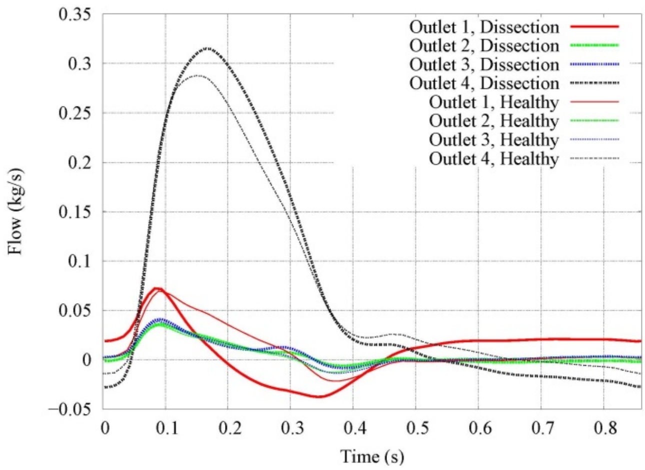

Figure 4. *Comparison of outlet flow in the healthy and dissected aortic arch*

5. Discussion

Considerable variations in blood flow patterns on downstream of an abnormal site have been detected. The proximal outlet to the ascending dissected wall suffers more of these variations, which consequently affects directly on the WSS history of that outlet. Physiological realistic pressure boundary conditions are applied at outlets, based on the A+IPBC method. The proposed methodology is applicable on all cardiovascular sites, when the impedance and flow-split of that site is known.

In the current work the objective was the evaluation of the proposed boundary condition (A+IPBC) on a typical

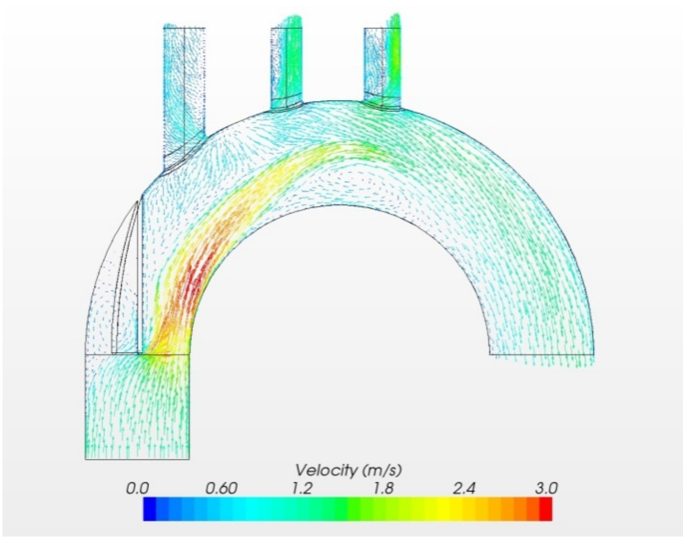

Figure 5. *Deviation of blood flow during systolic phase of the cardiac cycle*

aortic arch when suffers from a dissection in the ascending aorta. The arterial and dissected walls are considered as rigid, but in order to capture more fluid mechanics details around the dissected area, as a future goal, a FSI simulation of a dissected aorta is under development by the authors. However, it is worth mentioning that the major objective was to introduce a disturbance in the blood flow path to the outlets, in order to evaluate the A+IPBC method functionality. A FSI may cause a more realistic oscillation of the dissected flap, but is not aimed at this stage of the investigation. On the other hand, it must be added that incorporation of elastic walls in the models do not affect considerably on flow histories of the outlets which are located relatively far from the cardiovascular disorder.

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