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ANALYSIS OF BLOOD FLOW IN A DISSECTED AORTA BY COMPUTATIONAL FLUID DYNAMICS

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Abstract. *Type B Aortic Dissection (TBAD), a tear in the inner wall of the aorta, is a thoracic aortic disease with a high mortality rate. In terms of physiology, an entry tear originates just below the subclavian artery and extends distally to the descending aorta [1]. A new channel termed as the false lumen is created, while the original one constitutes the true lumen. At the lower part of the descending aorta, there may be one or more re-entry tear(s) connecting these lumens [2]. A modern surgical treatment, endovascular repair (EVAR), is to close the entry tear by deploying a stent graft. Thrombus formation may occur since the blood flow in the false lumen becomes sluggish. A higher degree of thrombosis is generally believed to be safer for TBAD patients. The main objective here is to analyze the effect of a critical biomechanical factor, the area ratio of the false lumen to the true lumen, on the blood flow pattern in a dissected aorta after EVAR by Computational Fluid Dynamics (CFD).*

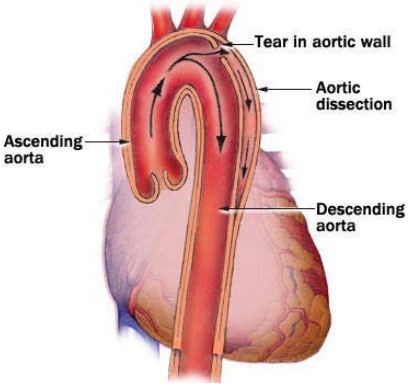
Four models with different area ratios, 2, 3, 4 and 9, are created on the basis of the Computerized Tomography (CT) images of TBAD patients by applying the pre-processor of CFD (GAMBIT 2, Fluent Inc.). The models are then meshed and solved in the post-processor (FLUENT 6, Fluent Inc.). The pulsatile velocity and pressure waveform obtained by experimental measurements are used as inlet and outlet boundary conditions respectively (Fig. 1). The clinical objective is to assess the blood flow configuration after EVAR. The blood may still enter the false lumen through the re-entry tear and flows backward to an upper level in the false lumen. The degree of backwash of blood in the false lumen is generally greater when the area ratio is higher (Fig. 2). If the level the blood can reach in the false lumen is higher, the chance for thrombus formation becomes lower. Consequently, the weakened false lumen is unsteady with a large region of streaming blood. Patients with a larger area ratio will generally suffer a higher risk of vessel rupture. These results will be highly relevant for clinical practitioners in determining the course of treatment.

1 INTRODUCTION

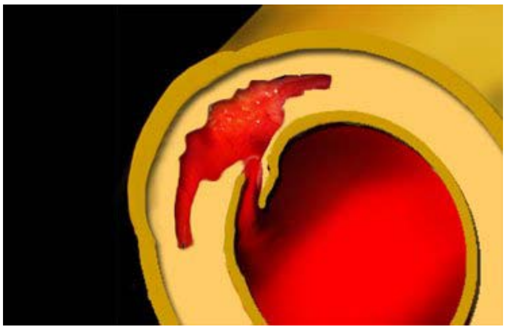
1.1 Background

According to the mortality statistics from the World Health Organization (WHO), cardiovascular diseases have been the leading cause of death in the world. High-fat diets and stressful lifestyle have been the main contributing factors. These causes result in a rising prevalence and incidence of thoracic aortic diseases. Among various disorders of the heart and blood vessels, the focus here will be the ‘Thoracic Aortic Dissection’.

Aorta is an elastic tube which composed three layers of muscles, named as the tunica intima, tunica media and tunica adventitia, to withstand the high blood pressure generated from the heart. Thoracic aorta is part of aorta which located in the chest in front of the spine. An aortic dissection is a tear in the inner layer of the blood vessel wall which leads to blood flow into the layers of vascular wall. The blood enters the media and causes the tear to extend distally (Fig. 1). A new channel termed as ‘false lumen’ (FL) is formed, while the original channel constitutes the ‘true lumen’. The partition between those lumens is known as the intimal flap. There are one or more disruptions, the ‘re-entry tear(s), along this flap which allow(s) the blood to flow back to the true lumen.



(a)



(b)

Fig. 1 (a) Thoracic aortic dissection. (b) Tear in the intima tunica.
(Source (a): http://www.mayoclinic.com, (b): http://www.radiologyassistant.nl/en/441baa8530e86)

According to Stanford Classification, a scheme dividing aortic dissection into two types, Type B Aortic Dissection (TBAD) [1, 2] involves the descending aorta and originates just below the subclavian artery. Untreated dissection might lead to rupture of vessel and death. Patients with uncomplicated TBAD have a 30-day mortality rate of 10% [3].

Endovascular repair, a new technique to treat TBAD, restores the blood flow in the true lumen by covering the entry tear. This technique involves inserting a metal stent and a graft to the aorta with a small incision made in the hip. The graft is sized and the stent is positioned in order to reinforce and hold the layers of aortic wall [4] (Fig. 2).

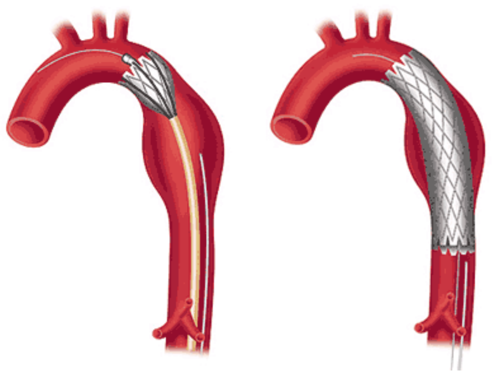


Fig. 2 Endovascular repair with stent-graft placement (Source: http://www.slrctsurgery.com)

The false lumen is the risky location since the wall has been weakened. Due to the coverage of the entry tear, the blood flow in the false lumen is mainly due to the backwash from the re-entry tear(s) at the distal part of the descending aorta. Sluggish flow in the retrograde end of the false lumen results in thrombus formation. A smaller extent of blood flow might reduce the risk of rupture of the vessel. Indeed the degree of thrombus formation in the false lumen is a criterion in determining the risk as the vessel wall has suffered attenuation. A static, thrombosed false lumen is believed to pose a lower risk to the dissection patients [5].

The degree of backwash of blood from the re-entry tear(s) along the intimal flap is an important factor in judging the risk of aortic events. Aortic flow models are created by computational techniques to estimate the effect of the ratio of areas of the lumens on the volume of backwash.

1.2 Literature Review

The effect of some of the biomechanical factors, e.g. vessel internal diameter and the aortic curvature, on the drag force after endovascular repair of aortic aneurysms have been studied [6]. The additional ingredient in patient with aortic dissection is the flow condition in the false lumen. Indeed the tear size and location will affect the fluid pressure in the false lumen [7]. The diastolic pressure in the false lumen will rise significantly after the placement of stent-graft. This increase may indicate a higher risk in vessel events. Some aspects of such studies remain incomplete, e.g. the pressure is measured only at one location, and the velocity profile is not recorded. The objective of the present work is to focus on one biomechanical factor, namely, the effect of the area ratio of the lumens.

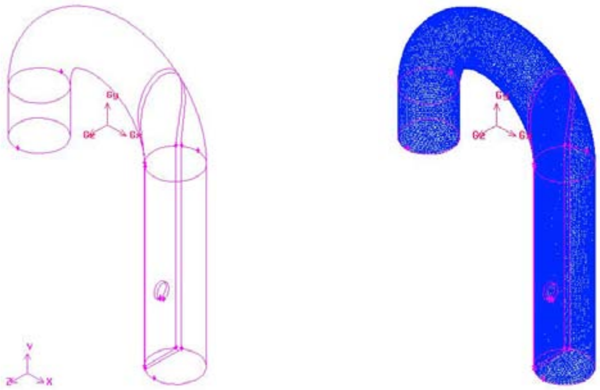
2 METHODOLOGY

Blood flow phenomena are generally very complex, combining the difficulties of irregular geometry, pulsatile pressure gradient and wall elasticity. Simplifying assumptions will be made to obtain realistic estimates, enabling surgeons to make clinical assessment and decision.

2.1 Modeling

Computational Fluid Dynamics (CFD) technique has begun to occupy a more prominent position in biomedical engineering researches. The objective here is to perform an in-depth study of aortic dissection by CFD. Difficulties with *in vivo* experimentation and measurements are avoided to some extent.

Applying a pre-processor tool (GAMBIT 2, Fluent Inc.), an aortic model can be constructed based on the geometry from a contrast-enhanced Computerized Tomography (CT) image of a patient with TBAD. The relevant length scales are the diameter of the aorta, curvature of the aortic arch and the thickness of the intimal flap. An idealized geometry, an aortic arch with constant diameter, consisting of the ascending aorta and the descending aorta, is adopted.



(a) (b)

Fig. 3(a) The geometry of the aortic model; (b) The meshed aortic model

Two channels, the true and false lumens, are created by defining a vertical plane (the intimal flap) perpendicular to the outlet in the descending aorta (Fig. 3(a)). A re-entry tear, modeled by an elliptical hole of the intimal flap near the distal end, links the two lumens. The proximal entry tear is assumed to be covered by the deployment of a stent-graft after the endovascular repair. Several area ratios are obtained by varying the position of the vertical plane. In practice, the false lumen is typically several times larger than the true lumen. In subsequent simulations, four models with area ratios of 2:1, 3:1, 4:1 and 9:1 are employed.

Computations for the discrete cells (Fig. 3(b)) are then performed. About 200,000 elements are created in the flow, enabling the governing equations to be solved in each of the smaller domains.

2.2 Governing equations

The governing equations are the usual continuity equation and the Navier-Stokes (NS) equations. In tensor notations, the continuity equation is

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

and the three-dimensional NS equations are

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_i} \ , \tag{2}$$

where ρ: fluid density
u_i (i=1,2,3): components of velocity vector
τ_{ij} (i, j =1,2,3): normal and shear stress
p: pressure.

The finite volume technique is employed. In the control volume generated by the pre-processor, these governing equations are discretized and solved iteratively.

2.3 Boundary conditions

Several assumptions regarding the rheological properties of blood will be made. Although blood is a suspension of blood cells and blood platelets in the plasma, only plasma will be taken into consideration. The other particles are ignored as they are dynamically unimportant. The blood is thus treated as an incompressible, homogeneous Newtonian fluid. This assumption is reasonable in large arteries like the thoracic aorta [8]. The density of the blood, ρ, is accordingly taken as 1060 kg m^{-3} while the viscosity, μ, is set as 0.0035 N s m^{-2} [9, 10]. The no slip boundary conditions adopted, and the elasticity of the vessel wall is neglected.

Pulsatile velocity and pressure waveforms are applied at the inlet of ascending aorta and the outlet of descending aorta respectively. Parameters for these waveforms are calculated from those profiles obtained experimentally (Fig. 4) [8]. Applying CFD codes (FLUENT 6, Fluent Inc.), the blood flow pattern in the dissected thoracic aorta is simulated. Both velocity and pressure are analyzed for the laminar flow regime at the peak rate.

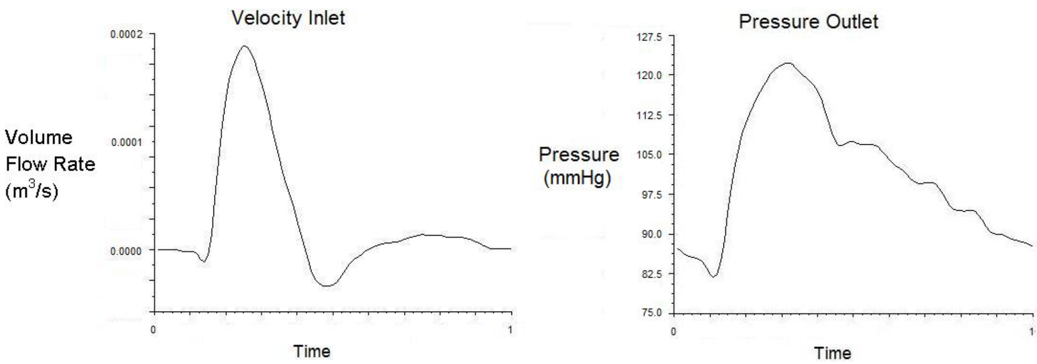


Fig. 4 The waveforms of pulsatile velocity inlet and pulsatile pressure outlet

3 RESULTS & DISCUSSION

3.1 Preliminary analysis

Before presenting computational results on the backflow of blood, a preliminary analysis is carried out on a pre-operative dissected aorta model. This model consists of two connections along the intimal flap, an entry-tear and a re-entry tear. The entry tear is located at the aortic arch while the re-entry one is situated at the distal end of the descending aorta.

The simulation shows the blood flows through the entry tear to the false lumen and flows back to the true lumen again from the re-entry tear before the endovascular repair (Fig. 5). With a patent false lumen, thrombus formation would not occur. The wall there may be further weakened by the circulating blood flow and the high blood pressure. This may increase the chance of severe aortic events. Aortic rupture leads to massive internal bleeding, and almost certain death if left untreated. Endovascular repair is believed to be a viable treatment method for TBAD patients. The blood flow pattern of some post-operative models is discussed in the next section.

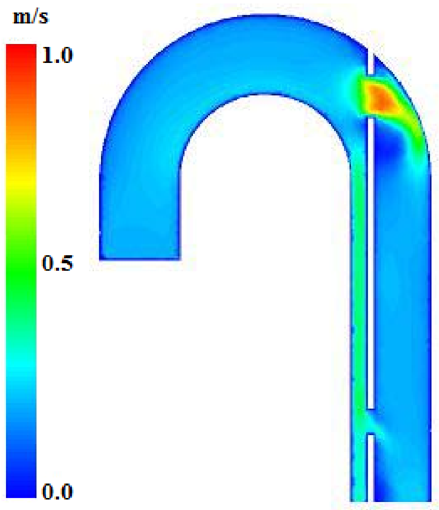


Fig. 5 The velocity plot of the coronal plane of the model at the peak flow rate.

3.2 Effect of area ratio

Four models of dissected aorta, with area ratios (false lumen to true lumen) 2:1, 3:1, 4:1 and 9:1 are created and examined. Blood enters the ascending aorta and exits at the distal end of the descending aorta, where the cross sectional area is diminished due to dissection. The blood velocity there would thus increase. At the distal part of the descending aorta, the re-entry tear, the connection between the true and false lumens, allow the blood to enter the false lumen. The working assumption is that little or negligible blood flow in the proximal portion of false lumen implies thrombus formation. The flow pattern and velocity distribution in the false lumen are analyzed by examining the transversal planes along the descending aorta. Fig. 6 illustrates the velocity magnitude plots of the coronal planes of the four models at the peak flow rate.

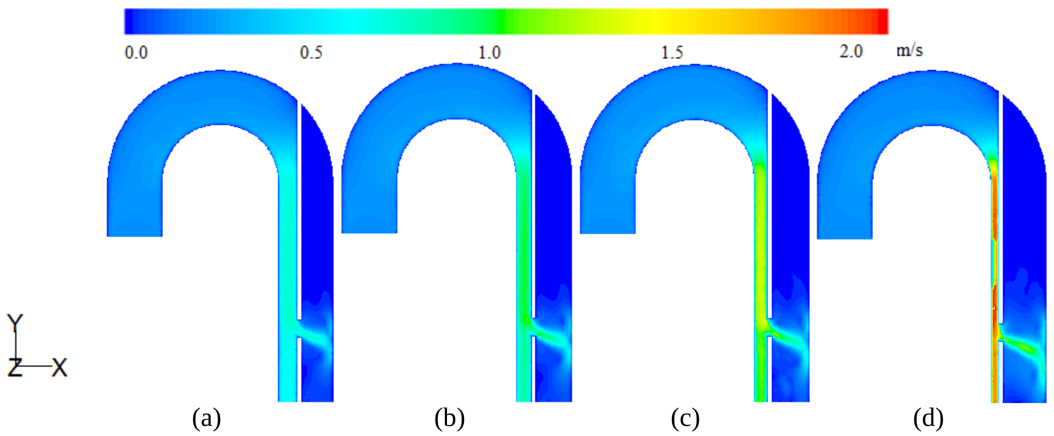


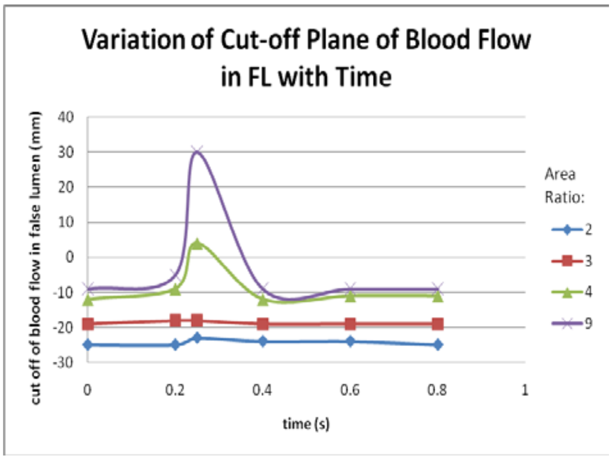
Fig. 6(a)-(d) The snapshots of velocity magnitude of the coronal planes of the aortic models at peak flow rate with different area ratios, form (a) to (d), 2, 3, 4 and 9 respectively.

The snapshots at the peak flow rate demonstrate a gradual increase in the velocity along the true lumen of the descending aorta with increasing area ratio (of false lumen to true lumen). This is consistent with the general principles of mass conservation of fluid flow, i.e. a smaller area of the true lumen implies a larger velocity there. The flow in the false lumen below the re-entry tear displays a balance between the injection of fluid momentum at the tear and the zero velocity boundary condition at the retrograde end.

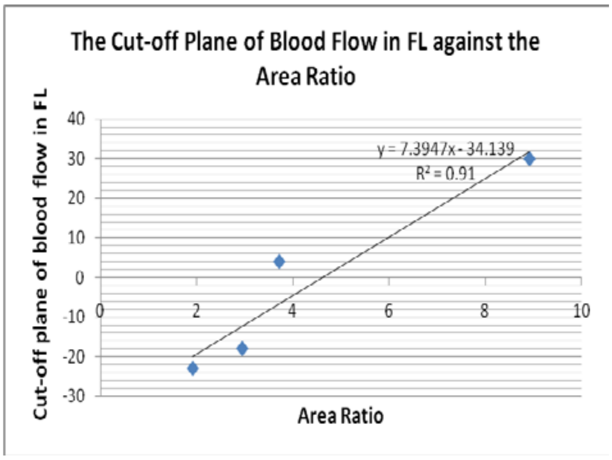
The flow above the re-entry tear is of primary interests from the clinical perspective. A smaller re-entry tear will cause a higher injection velocity, and thus the fluid can intrude further into the otherwise stagnant regions (Fig. 6).

Due to pulsatile inlet and outlet boundary conditions, the flow of blood in the aorta will vary with time. The blood flow pattern is analyzed at every 0.2s interval(s), and only results at the peak flow rate will be reported.

For convenience a vertical coordinate is adopted, where the origin is set at the level where the aortic arch begins. A cut-off transversal plane is defined as the maximum vertical coordinate the blood intrusion into the false lumen can reach. The time dependence of the position of the cut-off transversal plane is shown (Fig. 7(a)). A larger false lumen (or a smaller true lumen) generally leads to a greater degree of backflow from the re-entry site (Fig. 7(b)).



(a)



(b) FL = False Lumen

Fig. 7(a) The graph of the variation of cut-off plane of blood flow in false lumen with time;
(b) The graph of the cut-off plane of blood flow in false lumen against the area ratio at peak flow rate.

4 CONCLUSION

Type B thoracic aortic dissection (TBAD) may lead to rupture of vessels and thus death of the patient. One new treatment is the deployment of endovascular stent graft to cover the entry tear. For physiological reason, the re-entry tear(s) is/are left intact, and blood flow in post-surgical configuration of such TBAD patients is simulated by Computational Fluid Dynamics techniques. Four models of dissected thoracic aorta are created to investigate the effect of the area ratio of false lumen to true lumen on the blood flow pattern according to the CT images of a TBAD patient.

In general, a larger false lumen to true lumen area ratio will result in a larger degree of backflow of the blood from the re-entry tear. Assuming regions of negligible flow or stagnant flows lead to thrombosis. These findings imply that these patients may have a higher risk in aortic events, and thus the simulations will be highly relevant for clinical practitioners in determining the methods of treatment.

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