Three-dimensional finite volume modelling of blood flow in simulated angular neck abdominal aortic aneurysm

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Abstract. An abdominal aortic aneurysm (AAA) is considered a deadly cardiovascular disease that defined as a focal dilation of blood artery. The healthy aorta size is between 15 and 24 mm based on gender, bodyweight, and age. When the diameter increased to 30 mm or more, the rupture can occur if it is kept growing or untreated. Moreover, the proximal angular neck of aneurysm is categorized as a significant morphological feature with prime harmful effects on endovascular aneurysm repair (EVAR). Flow pattern in pathological vessel can influence the vascular intervention. The aim of this study is to investigate the blood flow behaviours in angular neck abdominal aortic aneurysm with simulated geometry based on patient’s information using computational fluid dynamics (CFD). The 3D angular neck AAA models have been designed by using SolidWorks Software. Consequently, CFD tools are used for simulating these 3D models of angular neck AAA in ANSYS FLUENT Software. Eventually, based on the results, we summarized that the CFD techniques have shown high performance in explaining and investigating the flow patterns for angular neck abdominal aortic aneurysm.

1. Introduction

Aneurysm is an enlargement or dilation of vessels, in another word, a bulging or ballooning the wall of blood vessel [1]. The aortic aneurysm is commonly occurring at the region of thoracic, thoracoabdominal, and abdominal [2]. Abdominal aortic aneurysm (AAA) forms and grows in the abdominal aorta which usually located between the renal arteries and the iliac bifurcation in the infrarenal abdominal aorta [1]. The healthy abdominal aorta diameter is between 15 and 24 mm in humans based on gender, body weight, and age. The aneurysm results in aorta dilation, typically 50% greater than the normal diameter of healthy abdominal aorta [3]. There are several symptoms that accompany the aneurysm rupture such as sudden abdomen or back pain, sever dizziness, clammy and wet skin, and rapidity of heart rates [3]. The aneurysm rupture is a serious illness with 65% to 85% rate of mortality in many cases where almost half of death cases happened before admitting to the surgery. About 1.3% of deaths amongst men between 60 - 85 years old caused by AAA in developed countries while in USA is considered as 13th of deaths leading cause [3]. Moreover, in Netherlands’s hospitals for period between 1972 and 1992, there were obvious increases of AAA patients due to the detection improvement in ultrasound [4]. Therefore, in many developed countries health care reported this aneurysm is a major health problem. Therefore, it is significant for aneurysm to be treated when it is found before gradually increase widening. Furthermore, endovascular aneurysm repair (EVAR) is considered a less invasive surgical procedure and has become a preferable treatment for many eligible
patients due to minor preoperative risks, lesser mortality, and long-term healing just like open surgery [5,6]. However, some of those eligible patients are not accepted for the EVAR procedure treatment. Due to complicated morphological aneurysm for example short aortic angular neck or highly proximal aortic angulated neck [7]. Shortly, there are few points to be considered when we study on neck angulations of AAA and their measurements such as knowing the exact location where angle occurs, the angle of neck formed in the area beneath the renal artery, proximal neck of an aneurysm and the bifurcation aorta. In contrast, the ideal neck angle of aorta is to be less than 60° if the angle is greater than that it leads to some implantation difficulties, endoleak and as well as the possibility for distal device migration. Computational fluid dynamics (CFD) is increasingly used in cardiovascular medicine that can play an important role in investigating and solving various complicated physiological fluid flows and demonstrating their potentials [8]. The aim of this study is to use CFD technique to investigate the flow pattern in the simulated angular neck abdominal aortic aneurysm.

2. Materials and methods

2.1. Geometry
In this study, we used a geometry which was based on idealized fusiform angular neck abdominal aortic aneurysm (AAA) of patient. The 3-dimensional simulated geometry was constructed by using computer-aided software SolidWorks (Solid Works Corp, Concord, MA) as shown in figure 1. The aneurysm size of 55 mm represented an average risk of rupture [9, 10]. Therefore, the four geometries were designed with the same concepts but the only difference was the neck angle ($\theta$) of aneurysm which was technically set with an increment of 10 degrees as 60°, 70°, 80° and 90° [2].

2.2. Meshing
The four-idealized angular neck AAA geometries were computationally meshed by using ANSYS FLUENT v16.2 (ANSYS Inc., Canonsburg, PA, USA). Tetrahedral meshing and a minimum of 1 mm body element size were applied. Cyclic quality checking and smoothing were done to reach satisfying mesh quality. Five different element numbers were used to determine the mesh quality were 55,304, 71,379, 391,306, 972,832 and 1,029,702. The blood properties and steady-state boundary conditions were applied for all mesh independency simulations. As shown in figure 2, the maximum velocity tended to be plateau when increasing the numbers of elements which indicated for velocity convergence and mesh independence.
2.3. Governing equations

The fluid model solved numerically based on 3-dimensional incompressible Navier-Stokes equations along with the equations of momentum conservation (1) and mass conservation (2).

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} \right) + \rho (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P + \mu \nabla^2 \mathbf{u}, \]  

\[ \nabla \cdot (\mathbf{u}) = 0, \]  

where \( \mathbf{u}, P, \rho, \mu, \) and \( \nabla \) represent velocity, pressure, density, dynamic viscosity, and gradient symbol, respectively.

2.4 Simulation setup

The blood flow through the aorta was assumed to be incompressible and Newtonian fluid [8, 11]. The density and dynamic viscosity were considered constant with value of 1,060 kg/m\(^3\) and 0.0035 Pa·S, respectively [12]. This viscosity was at approximately 45\% of hematocrit value [13]. For all models, the steady-state simulation was performed with an inlet velocity of 0.28 m/s and outlet pressure of zero as well as the aortic wall was assumed to be no-slip and rigid [14]. The Reynolds number at the aorta inlet was calculated as of 1,696 based on inlet velocity and inlet aorta diameter, so flow was treated as laminar model. The CFD simulations were solved by using a commercial finite volume solver, ANSYS FLUENT v16.2 (ANSYS Inc., Canonsburg, PA, USA). All simulations were conducted on workplace computer with 3.40 GHz quad-core processor with 16.0 GB RAM.

3. Results and discussion

3.1. Flow behaviors at proximal aneurysm neck angulation

The flow patterns in angular neck and aneurysm sac were presented as velocity contours with more details in three different areas. The velocity contours on horizontal cross-sectional ZX-plane for the location below proximal aortic aneurysm neck is presented as in figure 3(a). The volume of blood flow was forming a half circular shape of velocity contour with low velocity in angular neck 60 and 70 degrees. Furthermore, it is observed that when the degree of angular neck increases, the velocity gradually increases in the centre of aorta. The chart in figure 3(b) shows the increment of average velocity in the four aortic neck angulations.
3.2. Flow pattern through angular neck AAA model

The flow as illustrated in figure 5 on the longitudinal cross-section YZ-plane presents a fluffy bar of velocity from the proximal aneurysm neck cross the aneurysm sac towards the distal region of abdominal aortic aneurysm. At the same time, the velocity contours showed that the thin strip of high velocity is increasing gradually in the four angular neck aortas based on the change of degree of angular neck AAA.
The velocity streamlines are presented in Figure 6. The different recirculation vortexes were detected at the aneurysm in all aortic angular neck. However, when the angular neck of aorta rises, it is observed that the pattern of vortex inside aneurysm sac is debilitated and the velocity field appears to be more intensive near the middle of aorta.

Even though, this simulation was performed with idealized fusiform models but the simulation was based on realistic patient’s information [15]. As findings in our study, the numerical simulation of the four geometries of highly angular neck AAA using computational fluid dynamics (CFD) has confirmed that the significant influence of aortic neck angles on the velocity flow field because of the degree of angular neck change impacts on the flow downstream [2]. Moreover, we calculated the flow rate \( Q = v_{ave} \cdot A \) at the left and right iliac outlets as shown in figure 7(a) based on the average velocity \( (v_{ave}) \) at the outlets and the cross-sectional area \( (A) \) of each iliac aorta. Since the inlets and outlets of the simulated angular neck AAA geometries were the same with the value of each outlet (left iliac = 11 mm and right iliac = 10 mm), the cross-sectional area of outlet was \( A_{\text{left iliac}} \approx 9.5 \times 10^{-5} \text{m}^2 \) and \( A_{\text{right iliac}} \approx 7.85 \times 10^{-5} \text{m}^2 \). The average velocity values for all angular neck AAA models at both outlets were
presented in table 1. It was found that the average velocity at the left iliac outlet was higher than the average velocity at the right iliac outlet. The plotted chart in figure 7(b) illustrated the difference of flow rates at the outlet of each iliac aorta for each degree of angular neck AAA model. Although, the difference was as shown very minimum but we still can observe the influence of angular neck degrees on the flow rates at the outlet regions for each model. Eventually, it is proper to mention that the findings of this study have some limitations because it was performed under steady-state fluid flow condition, while the blood naturally is transient flow.

| Neck  | Left iliac outlet | Right iliac outlet |
|-------|-------------------|--------------------|
| 60°   | 0.5171            | 0.4921             |
| 70°   | 0.5176            | 0.4923             |
| 80°   | 0.5239            | 0.4904             |
| 90°   | 0.5271            | 0.4913             |

**4. Conclusion**

Four angular neck abdominal aortic aneurysm (AAA) models were simulated by using CFD technique to explain blood flow behaviours. As the results, by applying the steady state and fluid conditions on the three-dimensional angular neck AAA models, we can foresee the behaviours of the blood flow through the angular neck, aneurysm sac and as well the flow rate at the iliac aortas. Moreover, the study found that there was a correlation between the degrees of angular neck AAA and the pattern of the blood flow through the aorta. Therefore, the three-dimensional finite volume modelling and CFD technique can provide better visual details for blood flow in cardiovascular system which is useful for the cardiovascular intervention.
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