Numerical analysis of blood flow in abdominal aortic aneurysm using finite volume method

Arif Fatahillah*, Azza Liarista Anggraini, Susi Setiawani

University of Jember, Indonesia

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ABSTRACT

There is a deadly cardiovascular disease that can cause swelling of the Abdominal Aorta. This disease is known as Abdominal Aortic Aneurysm (AAA). AAA is believed to be a degenerative process caused by genetic factors, gender, body weight, and age. Changes in collagen and elastin in the aortic wall are the cause of the degeneration process. Therefore, it will cause dilatation of the aortic wall. Swelling of the aortic blood vessels will affect the blood flow velocity in the aortic blood vessels. This research aims to analyze the velocity of blood flow in the Abdominal Aortic Aneurysm based on swelling diameter, proximal neck length, and aneurysm channel length using Computational Fluids Dynamics (CFD). The blood flow velocity was modeled using mathematical language based on mass continuity equations and momentum equations. Then the finite volume method was one method to solve the mathematical model. MATLAB and ANSYS FLUENT software were used to simulate the velocity of blood flow analysis. The results of the research were shown that the larger the diameter and swelling channel length, the smaller the velocity of blood flow produced. Then, the greater the length of the proximal neck, the faster the resulting blood flow will be.

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INTRODUCTION

Mathematics is a branch of science that has a crucial role in other disciplines such as natural science, economics, and medical science. One of the branches of mathematics namely applied mathematics. Applied mathematics is used to apply mathematics to solve a concrete problem (Permatasari et al., 2020). Medical science is a branch of health science that studies people's health through prevention or treatment (A. Fatahillah et al., 2019; Madinda et al., 2019).

An Abdominal Aortic Aneurysm (AAA) is an artery (blood vessel) swelling in the abdomen(Ulug et al., 2020). The abdominal aorta is an artery originating from the heart. It gets oxygenated blood to the organs of the abdomen, pelvis, and legs. The largest artery in the human body is defined as the aorta (Komutrattananont et al., 2019). When the abdominal aortic wall in the infrarenal artery weakens, it

indicates AAA. Asymptomatic aneurysms have several risks. The risk is progressive expansion leading up to rupture and bleeding until death (Mangarova et al., 2020). The aorta is also defined as the main blood which can supply to the human body. Therefore, the Abdominal Aortic Aneurysm can be life-threatening when the Abdominal Aortic Aneurysm ruptures and bleeding(Kumar & Deoghare, 2018).

AAA generally does not show clinical symptoms. There are several risks of AAA. These factors are smoking habit, genetics, age (> 65 years), gender (male), and white race (Ferda et al., 2019). Aneurysm rupture is a severe disease. **This disease has** a mortality rate **of around 65% to 85%**. Essentially around 50 % of the deaths occur before surgery(Algabri et al., 2017). In Germany, the mortality rate is higher in female patients and older age(Trenner et al., 2018). When the diameter is higher in the amount of 30 mm, it is stated as AAA. The area between the renal artery and the aortic branch to the iliac artery can detect AAA at around 80%(Chaikof et al., 2018). Rupture suddenly can happen. This is caused by the hidden growth of AAA. When an Abdominal Aortic Aneurysm ruptures suddenly, it can have a mortality rate of over 90% if left untreated. Then the survival of patients who can undergo surgery is about 30%–60%(Yazbek et al., 2016). Treatment for aneurysms (aneurysm endovascular [EVAR] or open surgery [OR]) significantly reduced mortality. Generally, a diameter of more than 5.5 cm can carry out such treatment. (Richard et al., 2018). However, not all aneurysms rupture. Small aneurysms can rupture even with a diameter of less than 5.5 cm (Spanos et al., 2020). The diameter of the abdominal aortic aneurysm may not be the only indicator to identify the risk of rupture (Spanos & Eckstein, 2020). One of the factors that can point out the risk of rupture is the length of the proximal neck. A short proximal neck (≤15 mm) will have

high-risk intraoperative complications and type 1a endoleak(Jamtani & Jayadi, 2019).

The numerical method is a technique of solving mathematical model equations used to formulate mathematical, scientific, and engineering problems that can be solved through ordinary arithmetic operations. Numerical methods are suitable for solving mathematical problems whose solutions are difficult to obtain by analytical methods, such as partial differential equations, nonlinear differential, and integral problems (Ritonga & Suryana, 2019).

A finite volume method is a numerical approach that can be used to solve various problems, including fluid flow. This finite volume method is based on the integral form of the law of conservation(Masyhudi et al., 2018).

The Gauss-Seidel method is used to solve a system of linear equations and was developed from the notion of an iterative method for the solution of nonlinear equations(Wiliani & Ikhsan, 2018). One of the advantages of this method is the convergence process to find a solution faster.

Research conducted by Algabri et al. (2017) discussed four models of AAA. The blood flow velocity in four models was simulated with the CFD technique. The models of AAA consist of the neck angle, the aneurysm sac, and the iliac aorta. While in the research ofVinoth et al. (2019) simulated and compared the AAA models and the aorta model of normal subjects. The analysis carried out is stable and transient flow. That analysis has parameters that are predicted during analysis. That parameters are Wall Shear Stress (WSS), pressure, and velocity distribution (Vinoth et al., 2019).

Some researchers focused on the angular neck on the flow patterns of the AAA and compared the blood flow pattern of the healthy aortic model and the aneurysm model. However, none of the

researchers observed the effect of proximal neck length and aneurysm length on the blood flow velocity in abdominal aortic aneurysms. Therefore, this research focuses on the Abdominal Aortic Aneurysm where the aortic model in this research used is the proximal neck, aneurysm sac, and distal neck. The purpose of the research is to build a mathematical model of blood flow in the aortic vessels caused by the Abdominal Aortic Aneurysm and to investigate the blood flow velocity of the AAA with the effect of proximal neck length, swelling channel length, and swelling diameter. The mathematical model in this research refers to previous research by adding physical equations such as Herschel-Bulkley and Poiseuille's equation. Solving the mathematical modeling of the problem is using the finite volume method with the QUICK (Quadratic Upwind Interpolation Convective Kinematics) discretization technique. CFD is a technique used to simulate flow patterns with ANSYS FLUENT and gambit software.

METHOD

Enlargement of the bottom of the aorta in consequence of degradation of the arterial wall causes AAA disease(Chung et al., 2018). One of the treatments that can be done to treat AAA is EVAR. EVAR gives a reduced risk of perioperative mortality than OR. It is based on a literature review and meta-analysis of approximately 267,259 patients from 136 studies (Kontopodis et al., 2020). CT Scan serves to certify the diagnosis and determine the morphology of the aneurysm for the appropriateness of AAA for EVAR. Figure 1(a) and 1(b) are CT scans of the Aorta in humans. It has a different AAA morphology. The difference between RAAA and SAAA is shorter (mean neck length). Based on CT Scan, RAAA is about 15 mm [0e70] and SAAA is about 24 mm [0e63], and P < 0.01(Hollingsworth et al., 2019).

However, some patients were not admitted for EVAR treatment due to the complicated morphological aneurysm, such as the short neck of the aortic angle. In addition,Jamtani & Jayadi (2019) reported that a short proximal neck (<15mm) would have a greater risk of intraoperative complications and type 1a endoleak. The addition of parameters such as proximal neck length, aneurysm length, and aneurysm diameter in this research aims to determine the flow stability in the aneurysm model that can cause aneurysm rupture. These measured parameters can assist surgeons in assessing the severity of aortic aneurysms so that they can be taken into account in making decisions.

The mathematical model in the previous study used the mass conservation equation and the momentum equation. The mathematical model became the basis of this research and was developed by adding several other equations, such as the Poiseuille and Herschel-Bulkley equations. Solving the mathematical modeling of the problem is using the finite volume method with the QUICK (Quadratic Upwind Interpolation Convective Kinematics) discretization technique.
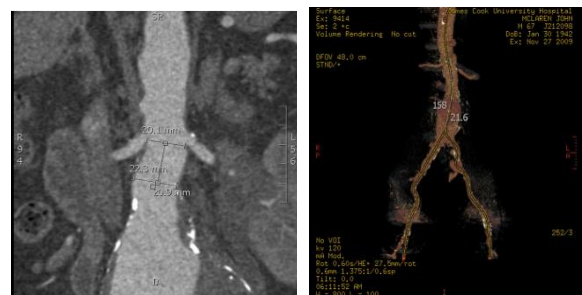

Figure 1(a) and **1(b).** CT Scan of the Aorta in Humans

Simulation research is the type of research that is used in this research. It aims to replicate or visualize the behavior of a system(A. Fatahillah et al., 2021).

The data collection technique used is a literature study. Literature study, namely collecting data by studying books, scientific journals, and data on the internet

related to blood flow in the abdominal aorta blood. After obtaining the data, the next step is to build a blood flow mathematical model in the aortic vessels caused by the Abdominal Aortic Aneurysm numerically using the finite volume method based on the momentum equation and mass continuity equation. The results of the mathematical model with the finite volume method are discretized using the QUICK. The outcome of the QUICK discretization is a matrix that expresses the equations of each control volume control. The discretization method will produce a matrix that states the equation to be solved. The equation is then solved using the MATLAB program.

Numerical calculations from the mathematical model generated in the MATLAB program are analyzed to obtain a convergent numerical solution. This solution approximates the exact solution of the differential equation. Gambit software was used to build the 3-dimensional geometry of the AAA in this research. Then it was simulated using ANSYS FLUENT software. The FLUENT simulation results are analyzed and draw conclusions based on the simulation results.

RESULTS AND DISCUSSION

The blood flow mathematical model in the Abdominal Aortic Aneurysm was used the mass equation and the momentum equation. The momentum equation is a differential equation that contains the forces acting on the control volume and relates the working forces, the forces acting on the pressure, and blood viscosity.
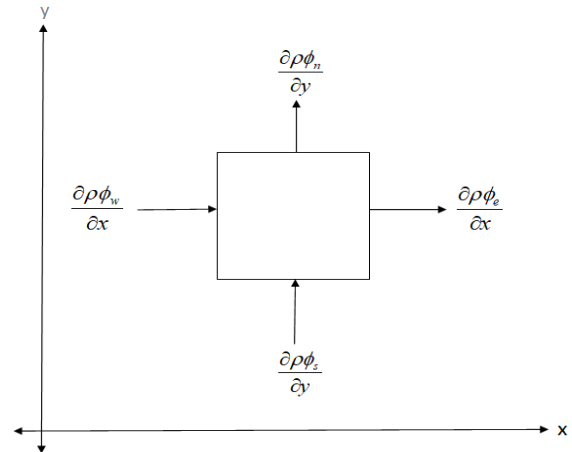

Figure 2. Momentum Equation Control Scheme

Based on Figure 1, the momentum equation obtained is as follows:

$$\frac{\partial \rho \phi_0}{\partial t} + [pure\ rate] = \sum F \qquad (1)$$

$$\frac{\partial \rho \phi_0}{\partial t} + [out - in] = \sum F \qquad (2)$$

$$\frac{\partial \rho \phi_0}{\partial t} + \frac{\partial \rho u \phi_w}{\partial x} - \frac{\partial \rho u \phi_e}{\partial x} + \frac{\partial \rho v \phi_s}{\partial y}$$

$$- \frac{\partial \rho v \phi_n}{\partial y} = -\frac{\partial P}{\partial x} - \frac{\partial P}{\partial x} + \mu \frac{\partial^2 u}{\partial x^2} + \mu \frac{\partial^2 v}{\partial y^2} \ (3)$$

where, $\phi_0, \phi_n, \phi_w, \phi_e, \phi_s$ represent initial velocity, north surface control, west surface control, east surface control, and south surface control, respectively. Moreover, pressure and channel diameter are defined based on Poiseuille's equation and Herschel-Bulkley.

$$P = \frac{128 v \mu L_0}{\pi D^4}$$

$$d_0 = D + \delta \left(1 + \cos \frac{2\pi}{L_0} \left(z - d - \frac{L_0}{2} \right) \right)$$

ρ = blood density (1.06×10^3 kg/m³), P = pressure, μ = blood viscosity (0.0035 Pa·S), v = velocity(0.3 m/s), L_0 = channel length, d_0 = channel diameter, D = aneurysm diameter, δ = aneurysm height(Algabri et al., 2017; Jonuarti, 2013).

Mass equations are also used to build mathematical models of blood flow in the aortic vessels caused by Abdominal Aortic Aneurysms. The mass equation is formed according to the law of conservation of mass. This mass equation is based on the theory that mass can neither be created nor destroyed so that its existence is constant in time.
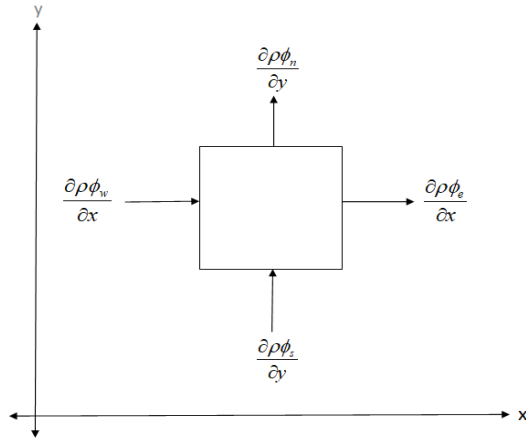

Figure 3. Mass Equation Control Scheme

Based on Figure 2, the mass equation obtained is as follows:

$$\frac{\partial \rho \phi_0}{\partial t} + [pure\ rate] = 0 \qquad (4)$$

$$\frac{\partial \rho \phi_0}{\partial t} + [out - in] = 0 \qquad (5)$$

$$\frac{\partial \rho \phi_0}{\partial t} + \frac{\partial \rho \phi_w}{\partial x} - \frac{\partial \rho \phi_e}{\partial x} + \frac{\partial \rho \phi_s}{\partial y} - \frac{\partial \rho \phi_n}{\partial y} = 0 \qquad (6)$$

Solution of the mathematical model using the finite volume method by integrating momentum equation and mass equation on three variables, namely x, y, and t. The integration of the momentum equation is as follows:

$$\int_t^{t+\Delta t}\int_y^{y+\Delta y}\int_x^{x+\Delta x}\left[\frac{\partial \rho \phi_0}{\partial t} + \frac{\partial \rho u \phi_w}{\partial x} - \frac{\partial \rho u \phi_e}{\partial x} + \frac{\partial \rho v \phi_s}{\partial y} - \frac{\partial \rho v \phi_n}{\partial y}\right] dxdydt =$$
$$\int_t^{t+\Delta t}\int_y^{y+\Delta y}\int_x^{x+\Delta x}\left[-\frac{\partial P}{\partial x} - \frac{\partial P}{\partial x} + \mu \frac{\partial^2 u}{\partial x^2} + \mu \frac{\partial^2 v}{\partial y^2}\right] dxdydt \qquad (7)$$

The final model of the momentum equation for blood flow in the aortic

vessels caused by the Abdominal Aortic Aneurysm is as follows:

$$\rho \phi_0 \Delta y \Delta x + \rho u \phi_w \Delta t \Delta y - \rho u \phi_e \Delta t \Delta y +$$
$$\rho v \phi_s \Delta t \Delta x - \rho v \phi_n \Delta t \Delta x = -P\Delta t \Delta y -$$
$$P\Delta t \Delta x + \mu \frac{\Delta t \Delta y}{\Delta x} + \mu \frac{\Delta t \Delta x}{\Delta y} \qquad (8)$$

Afterward, the integration of the mass equation is

$$\int_t^{t+\Delta t}\int_y^{y+\Delta y}\int_x^{x+\Delta x}\left[\frac{\partial \rho \phi_0}{\partial t} + \frac{\partial \rho \phi_w}{\partial x} - \frac{\partial \rho \phi_e}{\partial x} + \frac{\partial \rho \phi_s}{\partial y} - \frac{\partial \rho \phi_n}{\partial y}\right] dxdydt = 0 \qquad (9)$$

The above integration obtains the mass equation as follows:

$$\rho \phi_0 \Delta y \Delta x + \rho \phi_w \Delta t \Delta y - \rho \phi_e \Delta t \Delta y +$$
$$\rho \phi_s \Delta t \Delta x + \rho \phi_n \Delta t \Delta x = 0 \qquad (10)$$

The next step is to change Equation (10) into the final equation model as in Equation (11)

$$\phi_0 = -\phi_w \frac{\Delta t}{\Delta x} + \phi_e \frac{\Delta t}{\Delta x} - \phi_s \frac{\Delta t}{\Delta y} + \phi_n \frac{\Delta t}{\Delta y} \qquad (11)$$

The blood flow mathematical model in the Abdominal Aortic Aneurysm can be obtained by substituting Equation (11) and Equation (8). Therefore, the mathematical model of blood in the aortic vessels caused by Abdominal Aortic Aneurysm is as follows:

$$\phi_w\left((\rho u - \rho)\Delta t \Delta y\right) + \phi_e\left((\rho - \rho u)\Delta t \Delta y\right) +$$
$$\phi_s\left((\rho v - \rho)\Delta t \Delta x\right) + \phi_n\left((\rho - \rho v)\Delta t \Delta x\right) =$$
$$-P\Delta t \Delta y - P\Delta t \Delta x + \mu \frac{\Delta t \Delta y}{\Delta x} + \mu \frac{\Delta t \Delta x}{\Delta y} \qquad (12)$$

The results obtained are discretized using the QUICK discretization technique.

$$\phi_e(i, j) = -\frac{1}{8}\phi(i-1, j) + \frac{3}{4}\phi(i, j) + \frac{3}{8}\phi(i+1, j)$$

$$\phi_w(i, j) = -\frac{1}{8}\phi(i-2, j) + \frac{3}{4}\phi(i-1, j) + \frac{3}{8}\phi(i, j)$$

$$\phi_n(i, j) = -\frac{1}{8}\phi(i, j-1) + \frac{3}{4}\phi(i, j) + \frac{3}{8}\phi(i, j+1)$$

$$\phi_s(i, j) = -\frac{1}{8}\phi(i, j-2) + \frac{3}{4}\phi(i, j-1) + \frac{3}{8}\phi(i, j)$$

(13)(Arif Fatahillah, 2014)

The final result is obtained by substituting Equation (12) and Equation (13).

$$A \cdot \phi(i-2,j) + B \cdot \phi(i-1,j) + C \cdot \phi(i,j) + D \cdot \phi(i+1,j)$$
$$+ E \cdot \phi(i,j-2) + F \cdot \phi(i,j-1) + G \cdot \phi(i,j+1) = H$$

where

$$A = -\frac{1}{8}(\rho u - \rho)\Delta t \Delta y$$

$$B = \frac{7}{8}(\rho u - \rho)\Delta t \Delta y$$

$$C = \frac{3}{8}(\rho - \rho u)\Delta t \Delta y + \frac{3}{8}(\rho - \rho v)\Delta t \Delta x$$

$$D = \frac{3}{8}(\rho - \rho u)\Delta t \Delta y$$

$$E = -\frac{1}{8}(\rho v - \rho)\Delta t \Delta x$$

$$F = \frac{7}{8}(\rho v - \rho)\Delta t \Delta x$$

$$G = \frac{3}{8}(\rho - \rho v)\Delta t \Delta x$$

$$H = -P\Delta t \Delta y - P\Delta t \Delta x + \mu \frac{\Delta t \Delta y}{\Delta x} + \mu \frac{\Delta t \Delta x}{\Delta y} \quad (14)$$

Variable data was obtained from relevant research and literature studies. These data are used to build algorithms in MATLAB. In MATLAB, the Gauss-Seidel method is used to solve a system of linear equations. The results are shown in the form of a graph in Figure 4.
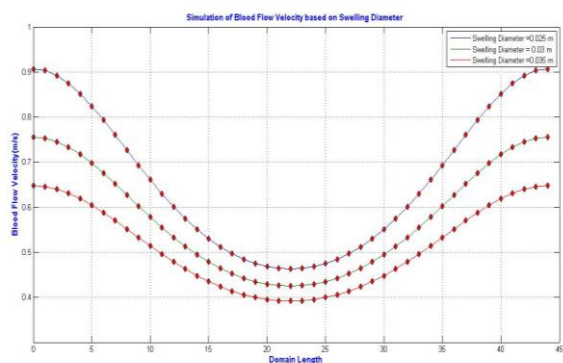

Figure 4. Velocity at Swelling Diameter AAA Model

Figure 4 shows a line graph of blood flow velocity on the diameter of the swelling in the abdominal aortic vessels.

When the swelling diameter is 0.025 meters, it shows that the value of the blood flow velocity is always higher than the swelling diameter of 0.03 meters and 0.035 meters. The velocity of the blood flow of the three graphs decreases as they enter the aneurysm sac. After passing through the aneurysm sac, the velocity of blood flow increases in the distal neck. The conclusion from the changes in each domain in the graph above states that the larger the diameter of the swelling in the aortic blood vessels, the smaller the resulting blood flow velocity, and vice versa. The statement relates to the concept of flow discharge "the smaller the cross-sectional area, the greater the flow velocity".
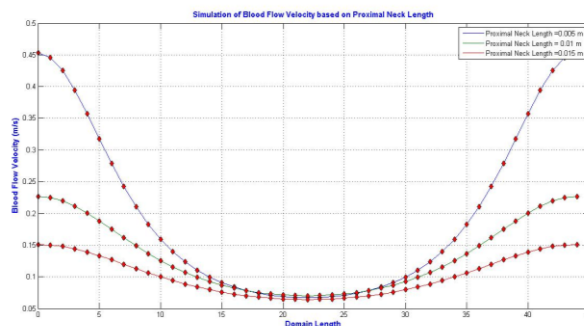

Figure 5. Velocity at Proximal Neck AAA Model

Figure 5 shows the effect of proximal neck length on blood flow velocity. When the proximal neck length is 0.015 meters, it shows that in each domain: it is always lower than the proximal neck length of 0.01 meters and 0.005 meters. The three graphs show that the velocity decreases when entering the aneurysm sac. After passing through the aneurysm sac, the blood flow velocity increases in the distal neck.After passing through the aneurysm sac, the velocity of blood flow increases in the distal neck. The conclusion from the changes in each domain in the graph above states that the longer the proximal neck, the greater the resulting blood flow velocity.
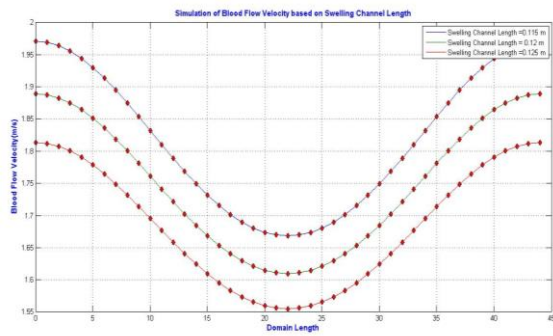
Figure 6. Velocity at Swelling Channel Length AAA Model

Figure 6 shows the effect of swelling channel length on blood flow velocity. When the swelling channel length on the abdominal aortic is 0.115 meters, it shows that the value of the blood flow velocity is always lower than the swelling length when swelling channel lengths are 0.12 meters and 0.125 meters. The blood flow velocity of the three graphs decreases when they go to the aneurysm sac, namely at domain points 22 to 23. After passing through the aneurysm sac, the blood flow rate increases the conclusion from the changes in each domain in the graph above states that the greater the swelling channel length, the smaller the resulting blood flow velocity.

The simulation of blood flow patterns with the effect of swelling diameter on the aortic vessels caused by Abdominal Aortic Aneurysm is illustrated in Figure 7.
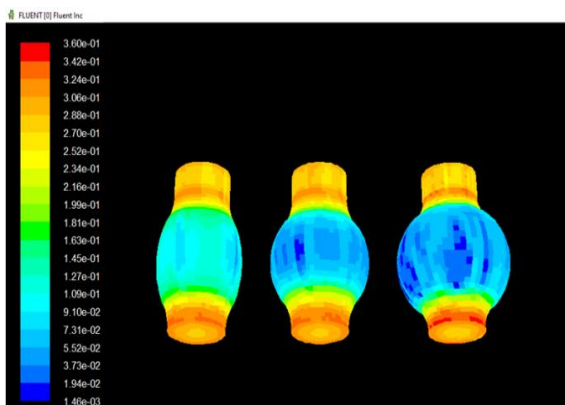

Figure 7. FLUENT Simulation for Swelling Diameter 0.025 m, 0.03 m, and 0.035 m

Simulation of the three geometries of the AAA model above shows that swelling diameter has a significant effect on the velocity in the aneurysm sac region and distal aortic aneurysm. When the diameter of the aneurysm sac increases, the velocity in the center of the aorta gradually decreases. While that of the distal aortic aneurysm gradually increases.

Figure 8 presents the flow patterns in the Abdominal Aortic Aneurysm with the effect of proximal neck length.
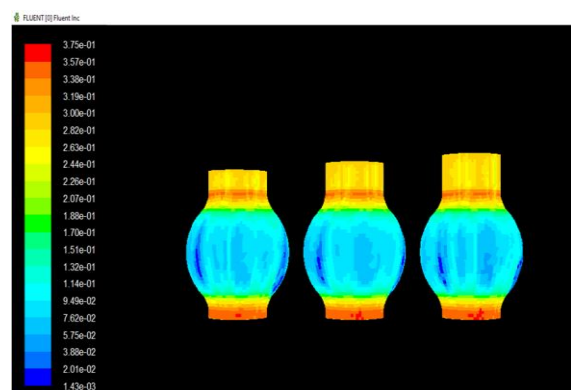

Figure 8. FLUENT Simulation for Proximal Length 0.005 m, 0.01 m, and 0.015 m

Simulations of the three geometries of the Abdominal Aortic Aneurysm above show that proximal length has a not significant effect. It shows the result of color in that simulation of geometries are almost the same. However, The three geometries have different velocities as shown in the figure. Based on the simulation figure, when the proximal neck is short, the velocity in the aneurysm sac is low.

The simulation of blood flow patterns with the effect of swelling channel length on the aortic vessels due to Abdominal Aortic Aneurysm is illustrated in Figure 9.
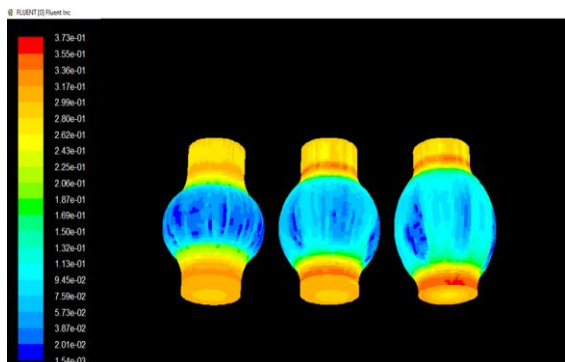
Figure 9. FLUENT Simulation for Swelling Channel Length 0.115 m, 0.12 m, and 1.25 m

The simulation of the three geometries of the Abdominal Aortic Aneurysm above shows that swelling channel length has a significant influence on the swelling channel length on the velocity of blood flow in the area. As the swelling channel length increases, this causes the velocity in the center of the aorta gradually increases as well as in the distal abdominal aorta.

The effectiveness of the finite volume method in solving numerical problems regarding the velocity of blood flow in the aortic vessels due to Abdominal Aortic Aneurysm was analyzed based on relative error. The calculation error rate is set with a tolerance limit of 0.001. Based on the MATLAB simulation results, the velocity of blood flow in the aortic vessels due to Abdominal Aortic Aneurysm which is influenced by swelling diameter, proximal neck length, and swelling length, obtained the relative errors of 0.000189, 0.000237, and 0.000719, respectively.

Based on the Table 1, 2, and 3, it shows that the smaller the error, the more effective the results obtained and the time required will be. These results indicate that the value of blood flow velocity in the aortic vessels due to Abdominal Aortic Aneurysm resulting from numerical computations is convergent and close to the actual value. Therefore, the finite volume method is an effective method for analyzing the velocity of blood flow in blood vessels due to Abdominal Aortic Aneurysm.

Table 1. Number of Iterations and Time for Swelling Diameter

Error	Swelling Diameter	Iteration	Time (Seconds)
	0.025 m	33	0.471363
10^{-3}	0.03 m	22	0.378279
	0.035 m	17	0.289871
	0.025 m	58	0,686819
10^{-4}	0.03 m	38	0.500516
	0.035 m	37	0.314130
	0.025 m	85	0.800222
10^{-5}	0.03 m	54	0.568497
	0.035 m	53	0.398606

Table 2. Number of Iterations and Time for Proximal Neck Length

Error	Proximal Neck Length	Iteration	Time (Seconds)
	0.005 m	42	0.432007
10^{-3}	0.01 m	44	0.468911
	0.015 m	43	0.447494
	0.005 m	63	0.826315
10^{-4}	0.01 m	75	0.898058
	0.015 m	70	0.859363
	0.005 m	84	0.963491
10^{-5}	0.01 m	100	0.948609
	0.015 m	100	1.423912

Table 3. Number of Iterations and Time for Swelling Length

Error	Swelling Length	Iteration	Time (Seconds)
	0.115 m	28	0.427379
10^{-3}	0.12 m	28	0.504729
	0.125 m	38	0.520081
	0.115 m	38	0.436744
10^{-4}	0.12 m	69	0.665435
	0.125 m	75	0.751282
	0.115 m	48	0.589587
10^{-5}	0.12 m	106	1.011339
	0.125 m	111	1.044301

CONCLUSIONS AND SUGGESTIONS

The blood flow mathematical model in the aortic vessels is obtained from the mass equation and the momentum equation.The mass equation has a zero resultant force. From the results of the

research, it was obtained a blood flow mathematical model in the aortic blood vessels due to the Abdominal Aortic Aneurysm.

$$
\phi_w\big((\rho u - \rho)\Delta t\Delta y\big) + \phi_e\big((\rho - \rho u)\Delta t\Delta y\big) +
$$
$$
\phi_s\big((\rho v - \rho)\Delta t\Delta x\big) + \phi_n\big((\rho - \rho v)\Delta t\Delta x\big) =
$$
$$
- P\Delta t\Delta y - P\Delta t\Delta x + \mu\frac{\Delta t\Delta y}{\Delta x} + \mu\frac{\Delta t\Delta x}{\Delta y}
$$

The mathematical model was obtained based on the factors that affect the velocity in the Abdominal Aortic Aneurysm. The numerical results of the mathematical equation model are formed by MATLAB.

The research variables of this research were the swelling diameter, the proximal neck length, and the swelling channel neck. The research variables will be analyzed for their effect on the blood flow velocity in the AAA model. Based on this research, all things considered, the larger the swelling diameter in the aortic blood vessels, the smaller the blood flow velocity produced. The greater the proximal neck length, the faster the resulting blood flow will be. The greater the swelling channel length, the smaller the resulting blood flow will be.

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