Wall Shear Stress Distribution in Arteriovenous Graft Anastomosis Using Computational Fluid Dynamics

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***Abstract*—This research study about anastomosis configuration of end-to-side brachioaxillary arteriovenous graft (AV graft) by comparing flow pattern of different angles, i.e., 20°, 30°, 45°, and 90° at the anastomosis sites. The study assumption is that the angle of anastomosis relate to intimal hyperplasia at inner vessel wall. The AV graft models were constructed by Computational Fluid Dynamics (CFD) analysis. Since the shear stress are an initiator and modulator of Intimal Hyperplasia (IH). Flow pattern and corresponding wall shear stress are analyzed. The result shows that the anastomosis with small angle is more proper to use than large angle in order to reduce intimal hyperplasia at inner vessel wall which decrease the incidence of stenosis. Also the rate of AV graft reoperation will be decrease.**

***Index Terms*—stenosis, CFD, intimal hyperplasia, brachioaxillary graft, wall shear stress, anastomosis angle**

I. Introduction

End Stage Renal Disease (ESRD) is the malfunction of kidneys, which unable to remove waste or excess fluid from blood effectively [1]. The most common treatment (approximately 1.3 million patients worldwide) of this disease is hemodialysis. The patient was treated by using dialysis machine to draw blood flow from the body and return blood back to the body via Arteriovenous (AV) accesses. Hemodialysis is one choice for treatment. Hemodialysis patients require AV accesses, which are either arteriovenous fistula or arteriovenous graft in order to make it easier to insert the catheter for blood drawing. The AV access is the connection between artery and vein on arm. The connection site is called an anastomosis. Two types of AV accesses are an autogenous and prosthetic. This study focused on brachioaxillary arteriovenous graft on the upper arm, which is one type of prosthetic AV access. The problem is found post AV graft surgery is Intimal Hyperplasia (IH). That is the injured reaction of connective tissue in the vessel wall [2]-[4]. The prosthetic AV graft appears the IH at the outflow vein after the vascular injury [5]. The 60% of AV fistulas fail to mature primarily near the anastomosis area. The AV grafts are not probable to different. This study hypothesis is the different flow pattern and wall shear stress of each angle are the main cause of IH occurring which affect to patency of AV graft.

[6] As other study about the hemodynamics pattern of the end-to-side vascular graft in canines, the results show flow separation was occurred at the toe side. In the other words, the anastomosis effects to normal flow pattern [7]. The other anastomosis angle study is an end-to-side anastomosis in vivo. The result reported the small angle appeared least flow disturbance and the reverse velocity at the preferential site, that effect to IH occurring.

A study on hemodynamic is the blood flow pattern analysis. The simulation model is an alternative for this study that can predict the flow patterns inside the vessel. In addition, the outcome of the simulation model shows the regions of flow pattern and wall shear stress. It benefits to AV access creation in the future.

II. Methods

A. Geometric Models

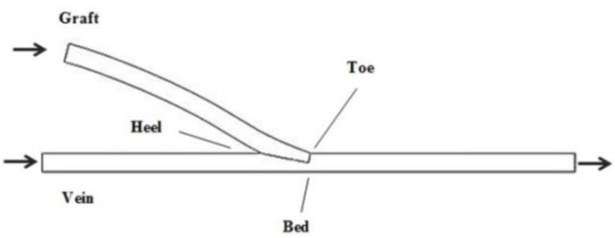

Figure 1. Model of brachioaxillary graft anastomois.

The geometries of our model compose of AV graft and vein. The AV graft uses common prosthetic vascular graft size with diameter of 6mm. The diameter of connected refers to vein nominal value of human size, which is 6mm. At the anastomosis site, the end of brachial artery connects with graft and graft connects with side of axillary vein as shown in Fig. 1. All models

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length is 20cm and distance between inlet site and an anastomosis site is 10cm. The distance of anastomosis site to outlet is 10cm. Angles at the anastomosis sites are 20°, 30°, 45°, 60° and 90° respectively. The different flow pattern and wall shear stress of each angle will be analyzed.

B. Boundary Condition

The models were assumed as rigid wall and the fluid properties were chosen to approximate human blood. The blood is incompressible and non-Newtonian fluid with constant density (ρ) is 1,060kg/m^3 and dynamic viscosity (μ) is 3.0382×10^{-3}kg/m.sec. The Reynolds number at inlet 1 and inlet 2 of all cases were 432 and 617 respectively. The flow rate at inlet and outlet were obtained from medical data. The volume flow rates are 350ml/min at inlet 1 and 50ml/min at inlet 2. Outlet pressure was set zero. Numerical models were creating based on five different connection angles.

C. Computational Fluid Dynamics

The models were created and analyzed by using commercial SolidWorks 2014 [8]. The CFD codes are computed using the numerical algorithm to solution. In this study, grid resolutions were ranged approximately 740,000 cells to 990,000 cells. The computation cells within each model are shown in Table I. Navier-Stokes equations (1a)-(1c) for three dimensional flows were solved by finite volume method.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\vec{X}-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\nabla^2 u \quad (1a)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\vec{Y}-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\nabla^2 v \quad (1b)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\vec{Z}-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\nabla^2 w \quad (1c)$$

The ratio $\frac{\mu}{\rho}$ is the kinetic viscosity of the fluid, and ∇^2 is the Laplacian operator.

The stress tensor equation is:

$$\tau_{ij}=\mu(\dot{\gamma}).\left(\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial x_j}\right) \quad (2)$$

where shear rate is:

$$(\dot{\gamma})=\sqrt{d_{ij}^2-\ d_{ii}.d_{jj}}\,,\ d_{ij}=\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial x_i} \quad (3)$$

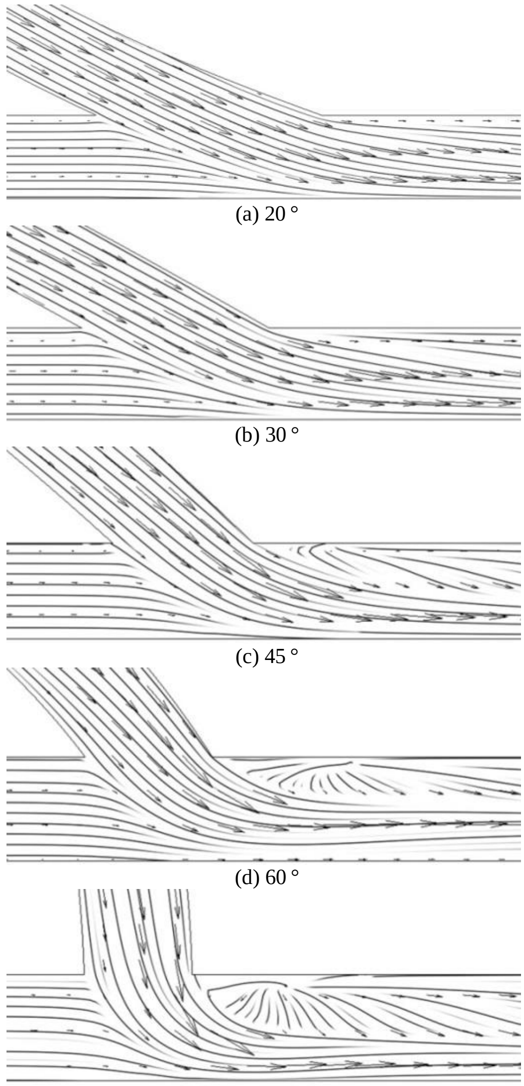
TABLE I. GEOMETRIC CONFIGURATION OF THE NUMERICAL MODELS

Angle	20°	30°	45°	60°	90°
Computational Cells	953337	980349	941434	747967	842303

III. RESULTS

A. Flow Pattern

The connection of artery and vein disturbs the normal blood flow in vessel because both of them have a different flow. High flow from artery encounter with low flow in vein, the flow pattern will be changed. That is, at the connection area fluid has a pressure drop and energy loss. The velocity will be decreased due to raising the cross-sectional area in this site. As follow in Fig. 2, the axial circulation flows appear in with large angle models there are 45°, 60° and 90°, respectively. The location is beside the toe of anastomosis area. The connection with small connection angles models, 20° and 30°, respectively, absence the spiral circulation flow. That shows in Fig. 2. The circulation flow effects of wall shear stress. It makes connective tissue injury then activates IH occurring, describes in conclusion part.



(a) 20°

(b) 30°

(c) 45°

(d) 60°

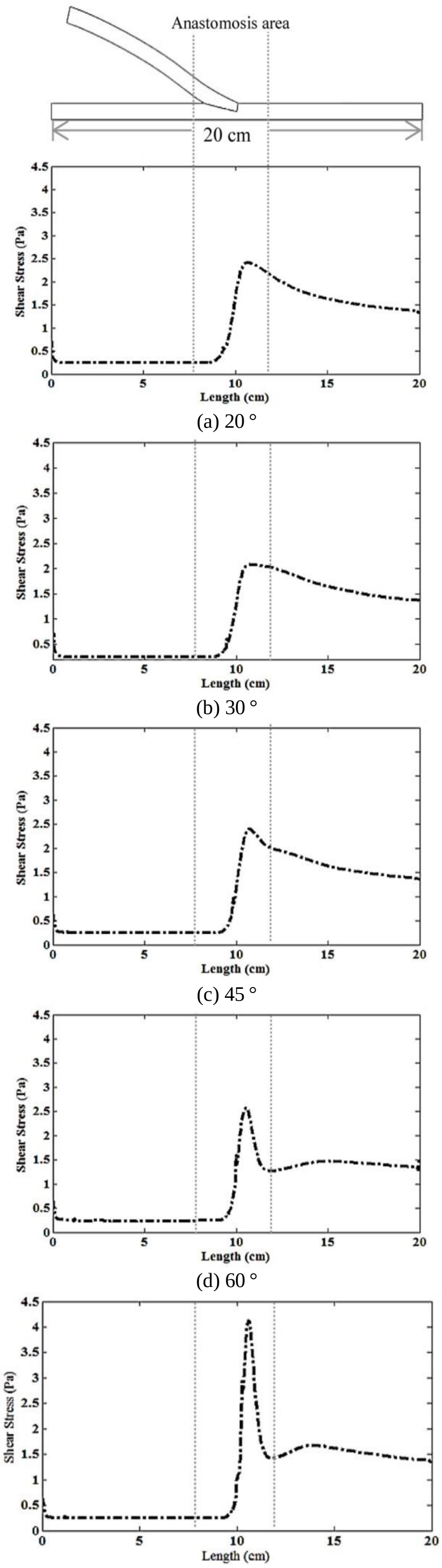
(e) 90°

Figure 2. The velocity streamlines of models of each anastomosis angle.

B. Wall Shear Stress

The shear stress distributions are graphically shown in Fig. 3 and shear stress contours are shown in Fig. 4. The results present high wall shear stress at the anastomosis area in all models. In this area, the wall shear stresses begin to increase at 10cm and decrease at 12cm approximately from inlet. The highest shear stress is found at 90° of angle with 4.13Pa, as shown in Fig. 3(e) and the lowest is found at 30° of angle with 2.09Pa, as shown in Fig. 3(b). Note that, the wall shear stress is steeper with an increasing of the angle from 45°, 60° and

90 ° as shown in Fig. 3(c), Fig. 3(d) and Fig. 3(e). On the other hand, the wall shear stresses are quite similar when increase the angle from 20 ° and 45 ° as shown in Fig. 3(a) and Fig. 3(c). The maximum shear stress at the vessel wall is shown in Table II.



(a) 20 °

(b) 30 °

(c) 45 °

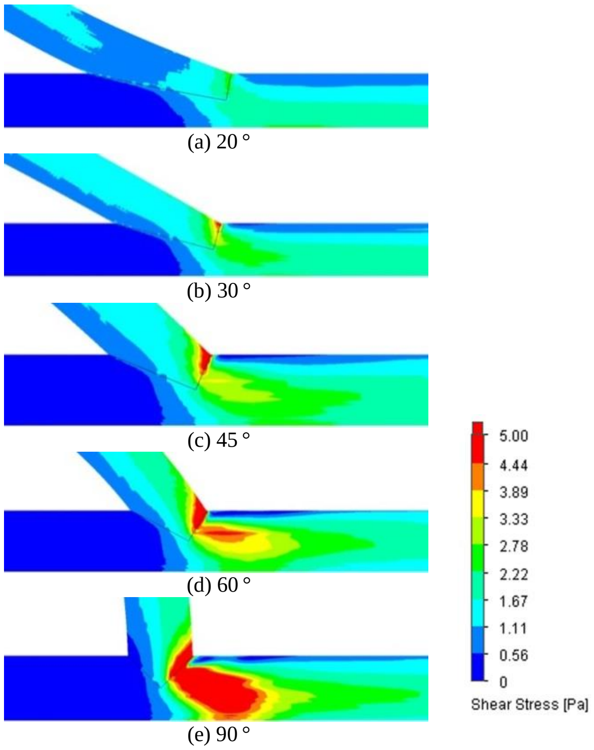
(d) 60 °

(d) 90 °

Figure 3. Wall shear stress distribution of each anastomosis angle.

TABLE II. MAXIMUM SHEAR STRESS AT THE VESSEL WALL

Angle	20 °	30 °	45 °	60 °	90 °
Length (cm)	10.71	10.79	10.72	10.53	10.61
Wall shear stress (Pa)	2.41	2.09	2.40	2.57	4.13



(a) 20 °

(b) 30 °

(c) 45 °

(d) 60 °

(e) 90 °

Figure 4. Wall shear stress contours distribution of each anastomosis angle.

Shear distribution contours are indicated by the color scale with scale as include in the Fig. 4. The 45 °, 60 ° and 90 ° models represent maximum wall shear stress are shown in Fig. 4(c), Fig. 4(d) and Fig. 4(e), respectively. Red color corresponds to higher shear stress level. The maximum shear stress occurs at the toe site of anastomosis area in 30 °, 45 °, 60 ° and 90 ° models. The 20 ° model shows the lowest shear stress than other models that shown in Fig. 4(a). Therefore, the magnitude of the shear stress values depends on anastomosis angle. Since flow pattern considerations compare with wall shear stress. The models, which appeared the axial circulation flow, show the high wall shear stress.

IV. DISCUSSION

The connections between artery and vein effect to flow pattern transformation. [9] Because both vessels are different, that is the pressure in vein much lower than in artery at the same general location [10]. The veins have thin walls and easy to collapsed in a normal function. The velocity blood flow in vein is lower than in the artery because blood flow in this site return to the heart. The effect of connection geometry, the fluid has the energy loss and pressure drop. [11] The energy loss is affected from increasing of cross-sectional area at the anastomosis site. That is, the flow rate will decrease large cross-sectional area. The circulation flow would cause the momentum loss and lead to the pressure drop. Flow structure that appeared the stagnation region was effect from pressure drop. Fig. 2 show the velocity streamlines of each angle model. The 20 ° and 30 ° of the angle show smooth flow pattern along the lines. Since the small angle, the momentum of fluid flow from inlet to the connection area is less than large angle. That is a bit energy loss, flow pattern will not change. The secondary flow patterns appear in large angle of the models. The spiral secondary flow at toe area is shown in 45 °. The re-circulations of flow are appeared in 60 °, 90 ° and wide area in 90 °. The primary stagnation region is found in 45 ° then 60 ° and 90 ° respectively [12], [13]. In the theories, the IH is induced by flow disturbance. Therefore, to find the suitable angle of the anastomosis help to reduce flow disturbance occurring. As the result, the small angles show least flow disturbance appear in Fig. 2(a) and Fig. 2(b). So that it should be considered with wall shear stress. Because the walls shear stress is an effect from flow pattern changing.

Fig. 4 shows wall shear stress contour distribution of each model. Higher shear stress show red color. The red area is vast in 90 ° of the angle that shows in Fig. 4(e). The small angles show low shear stress. The large angles widely appear red area that is high wall shear stress. Table II shows the maximum shear stress. The length in Table II is measured from inlet to outlet. The high wall shear stress locations are quite similar to all of models that are anastomosis area [14]. The study of flow and wall shear stress in end-to-side and side-to-side anastomosis of bypass grafts reported the wall shear stress increase when the blood velocity gradient is increase.

V. Conclusion

[15] Hemodynamic theories refer to the wall shear stress in a vascular are related to IH [16], [17]. The mediators will release in the arteries under the steady flow and laminar blood flow conditions when stimulates on an average approximately 1.5Pa of shear stress. From the references, the wall shear stress is considered to the main influence that occur IH. Numerical results in all models show shear stress value more than 1.5Pa. That means every angles of the anastomosis are possible to IH occurring. However, the results found that the reducing of angle can be decreased the wall shear stress, which decrease the IH occurring. Result considerations conclude that the small angles of anastomosis are suitable for AV access construction more than the large angle. Finally, this study is not only predicted the wall shear stress in a vascular but also helpful for AV access construction. [18], [19], [20] Therefore the anastomosis angle is suitable that help to decrease pathologic process after surgery. This study regards as hemodynamic pattern design, which desire to benefit to the future.

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References

[1] Z. Kharboutly, V. Deplano, E. Bertrand, and C. Legallais, “Numerical and experimental study of blood flow through a patient-specific arteriovenous fistula used for hemodialysis,” *Medical Engineering & Physics*, vol. 32, pp. 111-118, 2010.

[2] G. A. Beathard, *et al.*, “Aggressive treatment of early fistula failure,” *Kidney Int.*, vol. 64, no. 4, pp. 1487-1494, 2003.

[3] T. C. Hodges, *et al.*, “Longitudinal comparison of dialysis access methods: risk factors for failure,” *J. Vasc. Surg.*, vol. 26, no. 6, pp. 1009-1019, 1997.

[4] T. Lee, *et al.*, “Advances and new frontiers in the pathophysiology of venous neointimal hyperplasia and dialysis access stenosis,” *Adv. Chronic Kidney Dis.*, vol. 16, no. 5, pp. 329-338, 2009.

[5] L. M. Dember, *et al.*, “Effect of clopidogrel on early failure of arteriovenous fistulas for hemodialysis: A randomized controlled trial,” *JAMA*, vol. 299, no. 18, pp. 2164-2171, 2008.

[6] S. S. White, *et al.*, “Hemodynamic patterns in two models of end-to-side vascular graft anastomosis: Effects of pulsatility, flow division, Reynolds number, and hood length,” *ASME*, vol. 115, pp. 104-111, February 1993.

[7] N. Staalsen, *et al.*, “The anastomosis angle does change the flow fields at vascular end-to-side anastomoses in vivo,” *Journal of Vascular Surgery*, vol. 21, no. 3, pp. 460-471, 1994.

[8] H. K. Versteeg and W. Malalasekera, “An introduction to computational fluid dynamics the finite volume method,” *Introduction*, vol. 1, pp. 2-3, 1995.

[9] Y. C. Fung, “The veins,” in *Biomechanics: Circulation*, second ed., Springer, 1996.

[10] Y. C. Fung, “Mechanical properties and active remodeling of blood vessels,” in *Biomechanics: Mechanical Properties of Living Tissues*, second ed., Springer-Verlag, 1993, pp. 321-391.

[11] R. Shandas, Y. Khunatorn, C. Degroff, W. Orlando, S. Mahalingam, and L. M. Valdes-Cruz, “An assessment of the major flow features that affect energy loss and potential for thrombus formation within the modified total cavo-pulmonary connection: Computational and in vitro studies,” *Journal of the American College of Cardiology*, vol. 39, p. 401A, 2002.

[12] H. S. Bassiouny, *et al.*, “Anastomotic intimal hyperplasia: Mechanical injury or flow induced,” *J. Vas. Surg.*, vol. 15, pp. 708-716, 1992.

[13] V. S. Sottiurai, *et al.*, “Distal anastomotic intimal hyperplasia: Histopathologic character and biogenesis,” *Ann. Vasc. Surg.*, vol. 3, pp. 26-33, 1989.

[14] T. Frauenfelder, *et al.*, “Flow and wall shear stress in end-to-side and side-to-side anastomosis of venous coronary artery by bass graft,” *Biomedical Engineering Online*, vol. 6, pp. 235-266, 2007.

[15] J. J. Chui, *et al.*, “Effect of disturbed flow on vascular endothelium: Pathophysiological basis and clinical perspectives,” *Physio Rev.*, vol. 91, no. 1, pp. 327-387, 2011.

[16] R. B. Rutherford, *et al.*, *Vascular Surgery*, eight ed., Intimal Hyperplasia, vol. 6, no. 80, 2014.

[17] R. F. Rushmer, “Cardiovascular dynamics: Peripheral vascular control,” *Effect of Posture*, vol. 4, 6, pp. 132-175, 217-245, 1976.

[18] Y. Khunatorn, R. Shandas, C. Degroff, and S. Mahalingam, “Comparison of in vitro velocity field measurements in a scaled total cavopulmonary connection with computational predictions,” *Annals of Biomedical Engineering*, vol. 31, no. 7, pp. 810-822, July 2003.

[19] Y. Khunatorn, S. Mahalingam, C. G. Degroff, and R. Shandas, “A fluid dynamic study of the total cavopulmonry connection of the Fontan operation,” in *Proc. 11th ICMMB International Conference on Mechanics in Medicine and Biology* Maui, Hawaii, April 2-5, 2000, pp. 289-291.

[20] Y. Khunatorn, S. Mahalingam, R. Shandas, and C. Degroff, “Influence of connection geometry and SVC-IVC flow rate ratio on flow structures within the total cavopulmonary connection: A numerical study,” *ASME Journal of Biomechanical Engineering*, vol. 124, pp. 364-377, 2002.

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