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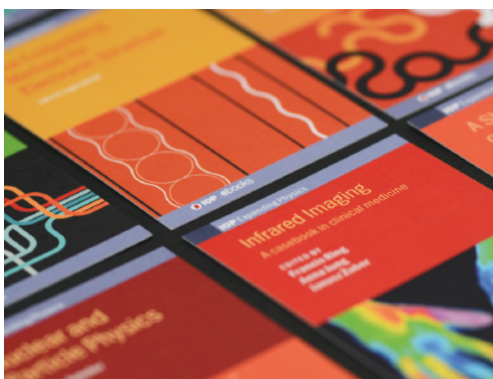
Assessment of an Arterial Stiffness to Demonstrate AVF Performance: Modelling Approach

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Assessment of an Arterial Stiffness to Demonstrate AVF Performance*:* Modelling Approach

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Abstract. Arteriovenous fistula (AVF) defined as shunting in the arterial system and the venous conduit is a preferred vascular access used in haemodialysis. The AVF provide a sufficient increase in blood flow rates for effective dialysis. However maintaining AVF patency become the greatest challenge for dialysis patient. Complications arise from this includes stenosis, aneurism and thrombosis. In previous studies, several methods are used to evaluate the performance of AVF. This study will focus on the assessment of arterial stiffness to demonstrate the performance of a side-to-side AVF. The condition of arterial stiffness which alter haemodynamic of AVF, in fact, will affect its performance and functionality. To gain insight and understanding for the haemodynamic condition, a healthy AVF (without arterial stiffening) has been modelled in the computational fluid dynamic (CFD) framework. The aim of this project is therefore to develop a modelling approach, suitable for the analyses of blood flow field to predict the performance and patency of AVF. A 3D CFD method is proposed to analysis flow field or haemodynamic in terms of blood flow velocity, blood pressure and wall shear stress (WSS) along the AVF. A laminar flow was introduced for the simulation of healthy AVF. Correlations in these haemodynamic parameters to assess the vascular failure supports hypothesis suggesting flow field as predicator for AVF performance. Haemodynamic effects lead to AVF failure were determined. Significant flow disturbances with abnormally high or low WSS obtained from the simulation is used as a primary indicator.

1. Introduction

End stage renal disease (ESRD) is also known as one of the common disease related to public health. It is the last stage of chronic kidney disease (CKD) where kidneys only functioning lower than 10 percent of normal function. Patients suffer from ESRD are unable to utilise the function of kidney to eliminate waste product. Haemodialysis is the primary treatment modality for ESRD. A vascular access is created to ensure efficient and successful haemodialysis. Three types of vascular access commonly use for haemodialysis; arteriovenous fistula (AVF), graft, and catheter. In Malaysia, it is reported that AVF is the most preferred access among haemodialysis patients at 85%, followed by catheter at 13.6% and only 1.4% choose graft [1]. However, in the past 10 years (2007 – 2016) the number of patients undergoing haemodialysis using fistula has consistently and gradually reduced, likely due to the absence of functioning fistula upon initiation of haemodialysis, and the increasing number of elderly and diabetic patients with no vascular access.

AVF is regard as the most preferred type of vascular access due to its superior patency rates and it is surgically created by shunting of the artery and vein. The performance of AVF is essential to determine the effectiveness of haemodialysis. Blood flow rate in range of 350 – 400 ml/min is essential to ensure

efficient haemodialysis and minimise access recirculation [2]. The performance of AVF is highly affected by the haemodynamic conditions.

The arterial stiffness is assessed to evaluate the haemodynamic conditions and performance in AVF. Arterial stiffness which define the compliance of artery to expand can be related to the internal diameter of artery. Change in the internal diameter of artery, which regulated by the stiffness of artery will alter the hemodynamic conditions such as blood flow velocity, pressure of blood flow, and wall shear stress (WSS) exerted on the blood vessel [3].

Wall shear stress (WSS) which is a measure of force of friction from blood acting along the inner wall of blood vessel is proposed as the primary predictor to the AVF performance. The WSS which is extremely high or low will alter the haemodynamic and prone to complications which affect the performance of AVF. The blood flow can be disrupted and become turbulent in the extremely high level of WSS (> 35 Pa). However, abnormal low level of WSS is predicted as a high risk region to induce complications [2].

Computational fluid dynamic (CFD) framework is established to identify and analyse the hemodynamic conditions in the complex AVF geometry [4]. The aim of this study is to develop a 3D CFD simulation for the analysis of blood flow condition which reflect the performance of AVF The flow field conditions in term of velocity, pressure and WSS are determined in order to identify the correlation between the haemodynamic and prevalence of patency in AVF.

2. Methods

2.1. Physic Defined
A laminar physics was used to simulate the blood flow along the healthy AVF. Laminar flow was defined when Reynolds number was approximated to lower than 2300. The normal blood flow condition is laminar flow, which characterises the movement of blood fluid in parallel along the distance of blood vessel. The simulations of AVF performance in this project will set the fluid as blood properties with dynamic viscosity of 0.0035 Pa.s and density of 1050 kg/m^3 [5].

2.2. Geometry Design
The CFD simulation was based on a computer aided design (CAD) model created by AutoCAD 2007. The model of AVF mimic the real fistula was designed. The geometry of healthy AVF was constructed with diameters in 6 mm for vein and 4 mm for artery. Past research shows that the minimum diameter of vein and artery for AVF to achieve maturation was 2 mm [6]. The length of anastomosis was approximated as 12 mm with a total length of 90 mm vein and artery .The anastomosis was created as side-to side geometry. The 3D model of healthy AVF was designed as shown in Fig.1.
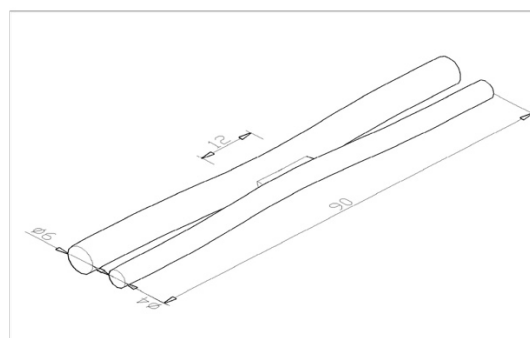

Figure 1.   3D model of healthy AVF

2.3. Fluid Dynamics
The blood flow within the AVF model is governed by an incompressible Navier-Stokes equations as:

$$\rho \frac{\delta u}{\delta t} + \rho (u \cdot \nabla) u = \nabla \cdot [-pI + \mu (\nabla u + (\nabla u)^T)] + F \tag{1}$$

and the continuity equation :

$$\frac{\delta \rho}{\delta t} + \nabla \cdot (\rho u) = 0 \tag{2}$$

where u represent the velocity, ρ is the density, p as the pressure, μ is the dynamic viscosity, I as identity matrix, and F is volume force field. Equation (1) formulated as conservation of momentum and the continuity equation formulated as conservation of mass. The both corresponding equations governed the simulation to solve the velocity of blood flow and pressure along the AV.

2.4. Boundary Conditions

The proximal artery (PA) and distal artery (DA) were set as inlets of flow while proximal vein (PV) and distal vein (DV) as outlets of flow. A time related flow parameters for the inlets were specified by equation (3) and (4).

$$V_{PA}(t) = 0.1 + (\sin(\pi t)\, 0.8) \tag{3}$$

$$V_{DA}(t) = 0.1 + (\sin(\pi t)\, 0.5) \tag{4}$$

The PV and DV were both defined as outlets with velocity of 0.0314 m/s [7] set at the DV to indicate flow of deoxygenated blood back to the heart, while venous pressure of 2.6 kPa was set at the PV [8].

3. Results and Discussion

The haemodynamic within a healthy AVF model was examined, in order to demonstrate the performance of AVF and predict it patency rate. The results of haemodynamic in terms of velocity of blood flow, pressure of blood flow and WSS of blood exerted on the wall of AVF were analysed and validated with theoretical studies.

3.1. Velocity Magnitude of Blood Flow

The results of velocity profile of blood flow from the time dependent simulation are depicted in Fig. 2. The velocity of blood flow along the AVF at time, t equals to 0 s, 0.5 s and 1 s were discussed.

The results show that velocity magnitude of blood flow along the artery is higher than velocity magnitude at the venous side along the time of simulation. This phenomenon of flow velocity can be explained theoretically by the principle of conservation of mass:

$$Q = A_1 V_1 = A_2 V_2 \tag{5}$$

where Q is flow rate, A indicates cross section area of blood vessel, V is the velocity of blood flow, V_1 represent the artery and V_2 represent the vein. The equation show that for a constant flow rate, the area of blood vessel is inversely proportional to the velocity.

In Fig. 2(a), it can be observed that the maximum velocity magnitude of blood flow appeared at the bifurcation of artery, which located along the two proximal and distal sites of the anastomosis. This can be explained as maximum velocity at the centreline of parabolic profile had moved towards the bending sites of proximal and distal anastomosis when the both input velocity is low. Therefore an extremely high velocity was found at both sides of bifurcation of artery to the anastomosis which leads to disturbances of flow.

High velocity of blood flow was located at the anastomosis where large pressure gradient between artery and vein induced a blood flow with greater velocity magnitude. This indicate the anastomosis as site which caused disturbances of smooth blood flow to chaotic Turbulent flow.

Fig. 2(b) and (c) show that velocity of blood near the DV side was lower compared to the velocity of blood flow through the PV side. This is due to the converged blood flow at the anastomosis will

diverged and flow faster towards the side of PV. The initial flow of deoxygenated blood from DV to PV leads to a greater resistance for blood to flow from the artery to the side of DV [9].
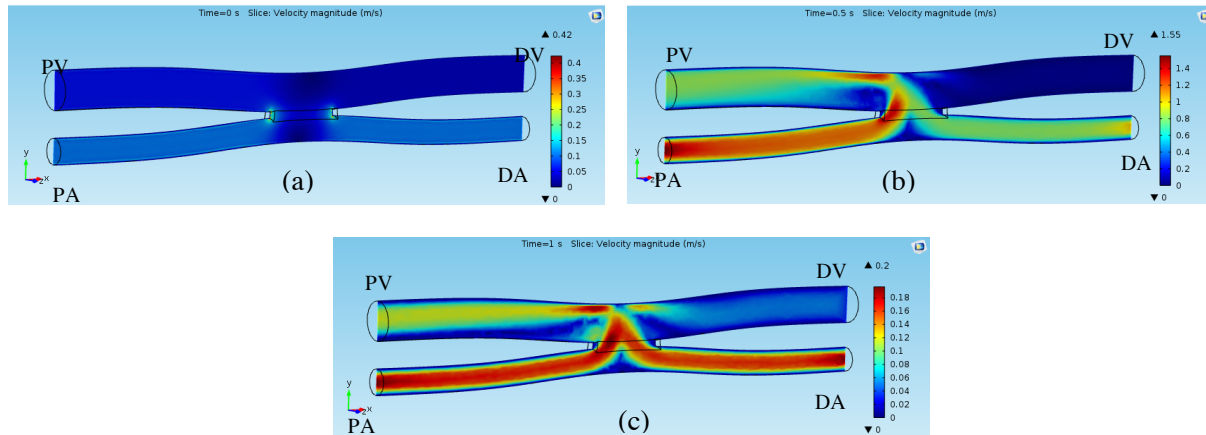

Figure 2. Velocity magnitude (m/s) at (a) t = 0 s, (b) t = 0.5 s and (c) t = 1 s

3.2. Pressure of Blood

The pressure level along the side-to-side AVF was is an important haemodynamic parameter to assess the performance of the AVF. Fig. 3 shows the contour pressure of blood flow in AVF when time, t=0 s, 0.5 s and 1 s. The results of simulation demonstrate that the pressure of blood flow exerted along the artery show greater value compare to pressure along the vein. This result can be explained by the inverse relationship between the cross sectional of blood vessel and the blood pressure as:

$$p = \frac{F}{A} \tag{6}$$

where p is the pressure, F is the force, A is the cross sectional area of vessel.
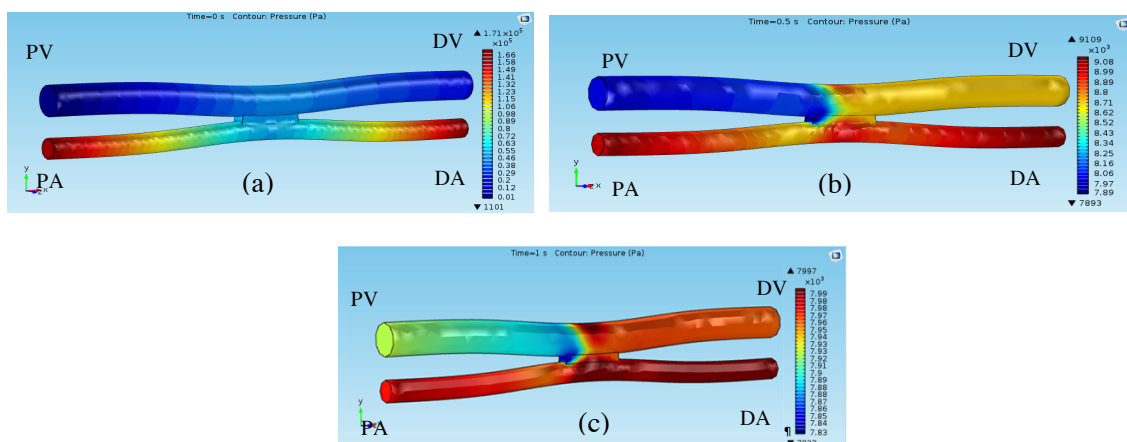
Figure 3. Pressure contour of blood flow at (a) t= 0s, (b) t = 0.5s and (c) t = 1s

The simulation showed that, after the construction of AVF, the blood pressure at vein elevated to value above 20 mmHg (2.6 kPa) which is the physiological level of human systemic venous pressure [10]. The increase of venous pressure by shunting of artery and vein is to ensure adequate blood flow during dialysis [11]. The pressure of blood flow is higher at the DV than the PV due to the explanation that there are a portion of blood return to the heart directed from the DV to PV.

3.3. Wall Shear Stress (WSS) exerted on AVF

The wall shear stress (WSS) play an important role in haemodynamic studies of AVF. It can be used as predictor of AVF performance in haemodialysis. The changes in WSS affect the remodelling of AVF, may influence it patency rate. The results of WSS obtained in the post-processing of simulation was discussed at three different stages; at time, t = 0 s, t = 0.5 s and t = 1 s.
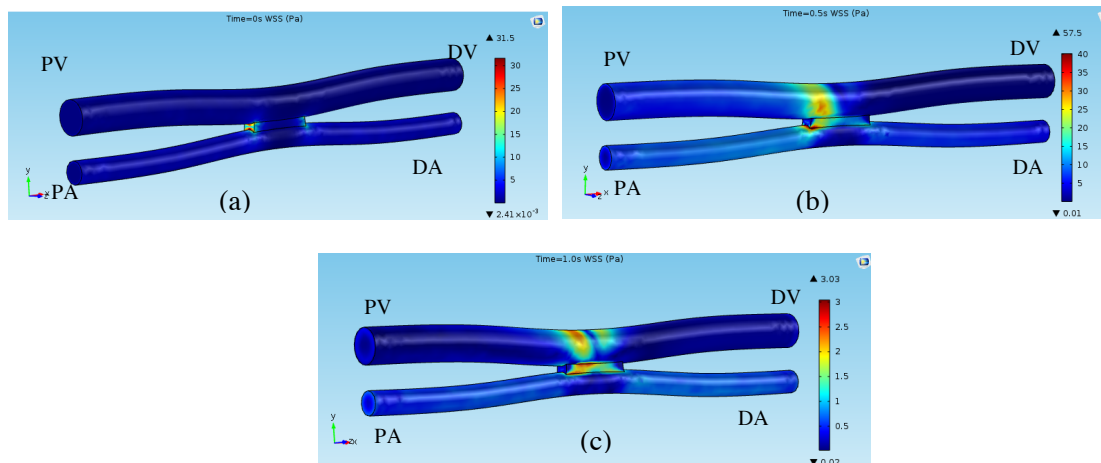
Figure 4. Distribution of WSS at (a) t = 0 s, (b) t = 0.5 s and (c) t = 1 s

The distribution of WSS along the AVF was depicted in Fig. 4. The AVF which functions to induce a greater amount of blood flow to the venous system has brought the WSS distribution to a higher level [12]. This is due to the relationship between the WSS and blood flow rate which defined in equation below:

$$\tau = \frac{32 \cdot \mu \cdot Q}{\pi \cdot d^3} \tag{7}$$

where τ as wall shear stress (WSS), μ is dynamic viscosity, u is the velocity of fluid, Q is flow rate and d is vessel diameter.

The results of simulation show that WSS is high at the bifurcation of artery into the anastomosis. Indicate that the site where blood flow is highly induced into Turbulent flow and causing degradation and damage to elastic mechanism of vessel wall.

The contour plot shows that location of low WSS between 0 to 2 Pa is the segment of DV and the region of artery just below the anastomosis. This is the location of blood vessel which highly promote the platelet lesion and induce common vascular disease such as stenosis, thrombosis and atherosclerosis to affect the performance of AVF for haemodialysis.

4. Conclusion

In recent years, maintaining AVF patency continues to be the greatest challenge for dialysis patients. Arterial stiffness which defined the compliance of blood vessel will influence the vascular function which reflect the patency of AVF. The project is aim to develop a modelling approach to predict the patency rate and performance of AVF. A finite element method with a computational fluid dynamic (CFD) framework was conducted to visualise, study and analyse the flow field and haemodynamic condition of AVF. The haemodynamic condition in terms of velocity of blood flow, blood pressure, and

WSS exerted on the wall along the AVF were focused in order to evaluate the performance of AVF for haemodialysis.

The simulation of healthy AVF was proposed as the initial stage to demonstrate and predict the condition in AVF. This method featuring an insightful analysis of relationship between flows filed conditions and vascular complication in AVF. The assessment of arterial stiffness by employing a CFD analysis to evaluate the haemodynamic conditions had provided a basic demonstration of AVF performance.

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