CHAPTER 4

THREE-DIMENSIONAL (3D) RECONSTRUCTION AND FLUID FLOW SIMULATION THROUGH THE RADIOCEPHALIC ARTERIOVENOUS FISTULA WITH LOCALIZE STENOSIS

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4.1 INTRODUCTION

End stage renal failure occurs when the kidneys cannot function as a result of permanent damage to the kidneys. Currently, Malaysia has been identified as having the highest percentage in the world, where the main cause of end stage renal disease was diabetes. The significant increase of diabetes and hypertension as the main contributor of kidney disease is alarming. In order to treat renal failure, the hemodialysis treatment is the most common treatment for patients to remove waste products such as urea and excessive salt.

Actually, the quality of the vascular access depends on the efficiency of the hemodialysis treatment. The most common and appropriate surgical treatment for vascular access is by creating arteriovenous fistula (AVF). Arteriovenous fistula (AVF) is one of the surgical treatments for those who have late stage renal failure. This treatment is usually created at forearm or wrist to make dialysis easier. Dialysis machine draw blood from the body, filter and then return the blood back to body. If a dialysis needle is inserted into vein frequently, the vein will wound and then is destroyed. So if we create the AVF, the vein will widen as it connects to an artery nearby. Thus, it will make easier to insert needle for dialysis.

The vascular access still have failure rate after the creation of the AVF even many advancements technology and clinical nowadays. It is believed that the main problem for the vascular access to be failed is the hemodynamic condition that creates the progression of the thickening of the blood vessel or intimal hyperplasia (IH). One of the hemodynamic conditions is the stenosis sites. The lifetime of the AVF hemodialysis is always variable which range between months or several years until the fistula stops functioning for adequate hemodialysis. The development of intimal hyperplasia will cause narrowed condition or stenosis to happen in blood vessel. There are minimum researchers that investigate about the stenosis at radiocephalic arteriovenous fistula (RCAVF). Hence the present study is conducted on primary access end to side artery radiocephalic arteriovenous fistula to investigate the flow characteristics of blood through the radiocephalic with localized stenosis numerically.

The objectives of this study is to determine the correlation between flow and stenosis level. Although there are few researches have done about the site of the stenosis in AVF but there are limited research yet about the percentage of stenosis toward the flow rate of blood, flow trajectory and pressure drop through the radiocephalic fistula. There are actually no yet research done numerically about the stenosis at radiocephalic arteriovenous fistula.The main point of this study is to reconstructed three dimensional and fluid flow through the radiocephalic arteriovenous fistula at certain type of stenosis and do the simulation. From this research, we will collect some data and the result will be valuable for medical practitioners to understand about certain parameters such as pressure and flow rate in blood vessel.

Diabetes and hypertension are among of the factors the cause the kidney failure. Nowadays, there are increasing numbers of people that have kidney failure. There is no cure for the kidney failure but with treatment there is possible to live long. Berns (2011), stated when someone that has about 90% of kidney failure, he or she need to go for the dialysis. Hemodialysis is a treatment or medical procedure for someone who has end stage of kidney failure. The purpose of hemodialysis is to remove waste, toxin and fluid from the blood when the kidneys have lost function. Hemodialysis is one of the kidney replacement therapy. Other two are renal transplant and peritoneal dialysis. Samuel

(2009) stated that in hemodialysis treatment, there were actually three main ways to gain access to the blood which are an intravenous catheter, an arteriovenous fistula (AVF) or graft. All of these treatments need for surgery. However, the type of access is depend on the condition of their vascular and the expected time course of the patient‘s renal failure. Most of the doctors and researchers agreed that radiocehalic arteriovenous fistula (RCAVF) is the chosen method to achieve vascular access for chronic hemodialysis in patients with end stage kidney failure compared to grafts and catheters (Sivanesan, 1998). The Kidney Dialysis Outcomes Quality Initiative also suggests that too. This is because RCAVF exhibit lower rates of complication, fewer hospitalizations, longer patency, and lower patient morbidity and involve lower costs. It is also not involved of the synthetic material and has lowest rate of infection.

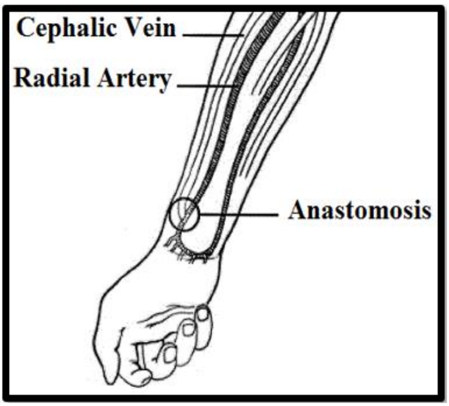


Figure 4.1: End to side radiocepalic arteriovenous fistula (RCAVF)

From the Figure 4.1, the RCAVF is connection between radial artery and cephalic vein. The RCAVF was conducted at forearm or wrist. Josef (2007) stated that the small surgery is done by sewing the end side cephalic vein together with the radial artery.

4.2 METHODOLOGY

4.2.1 Design Process

The Information and data are important in order to carry out the study. The first step is to gain as much information as possible, especially those from the previous study. The information may be available from the research projects, journals, related books, Health Department and internet as well.

To achieve the objective of the study, several steps were used in order to accomplish the good result. Thus, in order to reconstruct the model, the ideal software that are useful is the Computational Fluid Dynamics software called Engineering Fluid Dynamic (EFD). A three-dimensional computer model of the end-to-side radio cephalic arteriovenous fistula (RCAVF) will be created using EFD Lab software package. The model will be based on the geometrical data obtained from the biplanar fistulalogram. The diameter of the vein and artery will be set fix. The inner and outer diameter of vein will be 5.6 mm and 6 mm while the inner and outer diameter of artery is about 3.6 mm and 4 mm. The length of the artery is about 96 mm and the length for the vein is about 50 mm. The connection between artery and vein is made by the anastomosis by assuming an ellipse shape of anastomosis length and anastomosis width.

In order to develop and create the three-dimensional model by using EFD Lab software, there is need to collect data for the design. After consider the suitable and proper design as the previous researches has done (Galego, 2000), the length, width and angle of the anastomosis are fixed to 6 mm,4 mm and 30° respectively. Table 3.1 below shows briefly the parameter of the RCAVF model. Table 4.1 shows the parameter for the RCAVF model. The length, width and angle of the anastomosis are obtained from the previous researcher (Galego, 2000). While for diameter outer of vein and artery is obtained from (Van Canneyt, 2010).For the point of the contact of the blood vessel's surface, we used the fillet. The fillet is often used to help to reduce stress and strengthen the corner. It is common inside the corner. The fillet used for the model is 0.2 mm. The thickness of the blood vessel is 0.2 mm

Table 4.1: Parameter for the RCAVF model

Parameter	Value
Length of the anastomosis	6.0 mm
Width of the anastomosis	4.0 mm
Angle of anastomosis	30°
Diameter of inner vein	5.6 mm
Diameter of outer vein	6.0 mm
Diameter of inner artery	3.6 mm
Diameter of outer artery	4.0 mm

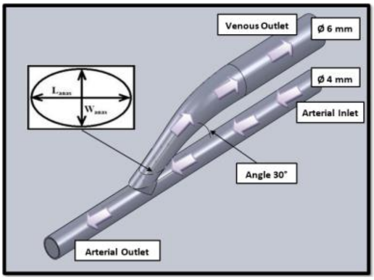


Figure 4.2: 3D image after using the SolidWorks

The Figure 4.2 above, show the model of RCAVF. The blood will flow from arterial inlet along the blood vessel and then will be distributed to the arterial outlet and venous outlet. The outer diameter for artery is 4 mm and outer diameter for vein is 6 mm. The angle of the anastomosis is 30°. The length of all type of the stenosis will be fixed to 6 mm.

For type 1, type 2 and type 3 of stenosis, the percentage of the stenosis will be varied started from 20%, 30%, 40%, 50%, 60%, 70% and 80% for each of the type. Hence, there will be about twenty-one models overall. Every model will be simulated static pressure at inlet artery and the static pressure at outlet venous. The outlet artery flow rate will be 1.2x m^3/s.

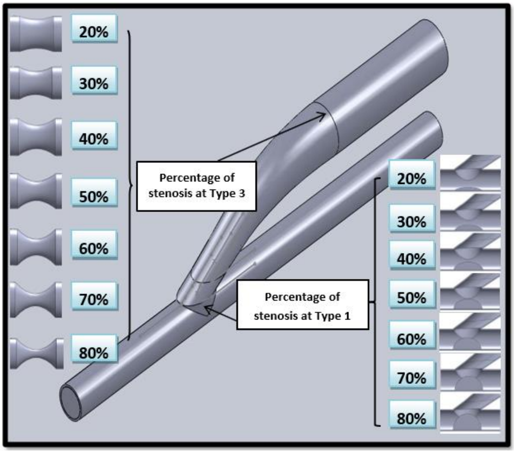


Figure 4.3: Variation of the percentage of the stenosis at type 1 and type 3

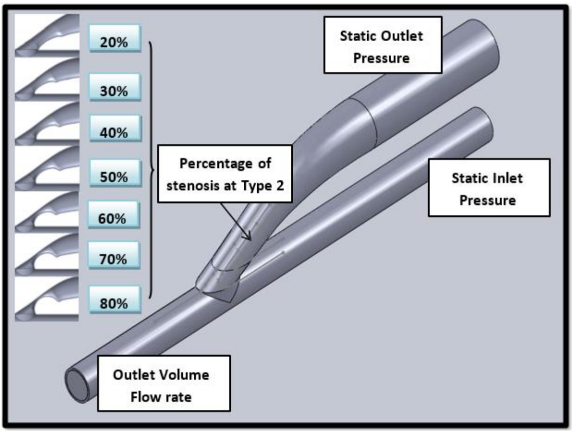


Figure 4.4: Variation of the percentage of the stenosis at type 2

Figure 4.3 and Figure 4.4, show the variation of the percentage of stenosis at type 1, type 2, and type 3 stenosis.

The percentage of the stenosis means the percentage of the reduction of the diameter or the thickening of the blood vessel. As the percentage of the stenosis increase, the blood vessel seems to be narrowed. The model will be simulated under these three types stenosis respectively.

Table 4.2: Fluid properties of the blood

Fluid Properties	Value
Density ,ρ	1050 kg/m³
Viscosity , μ	0.0035 Pas
Specific heat, (Cp)	3770 J/kgK
Thermal Conductivity, k	0.5 W/mK

Table 4.2 shows the fluid properties of the blood vessel. From the researcher Cole (2002) and Bessa and Ortiz (2007), the fluid properties were obtained: dynamic viscosity, $\mu = 0.0035$ Pa.s and density, $\rho = 1050$ kg/m³. All vessel walls are assumed to be rigid and the blood flow was considered laminar, Newtonian, non-pulsatile, incompressible and homogenous. The blood is considered laminar where the fluid will flow in parallel layers with no disruption between the layers. The motion of the blood in laminar flow is very orderly with the particle moving in the straight line parallel to the blood vessel.

The blood is assumed to be incompressible fluid since the density remains constant within the parcel of fluid which moves with the fluid velocity. Furthermore, the blood used in the model is considered homogenous since the density remains constant and uniform throughout. The model cannot be flexible and pliable. Thus, the models need to be rigid so that the flow will moves smoothly. After putting the parameters and setting the boundary condition, all models can be simulated by using the COSMOSFloWork from SolidWork software. The COSMOSFloWorks can simulate the flow trajectory, velocity, pressure, vorticity, temperature and others. Actually, COSMOSFloWorks is the best tools to be used since it offers a variety of the results visualization tools that allow us to gain valuable insight into the performance of the model. From COSMOSFloWorks, it provides the measurement result at any location with the point parameter tool. Moreover, the graph result variation along any SolidWork sketch and result can be listed automatically and export data to Microsoft Excel. In addition, the COSMOSFloWorks can illustrate the flow trajectory inside the model with the animated bands, 3D arrows, pipes or spheres. Furthermore, the COSMOSFloWorks can create the animation of result by using SolidWorks Animator as well as the result plots can be saved in JPEG and BMP format.

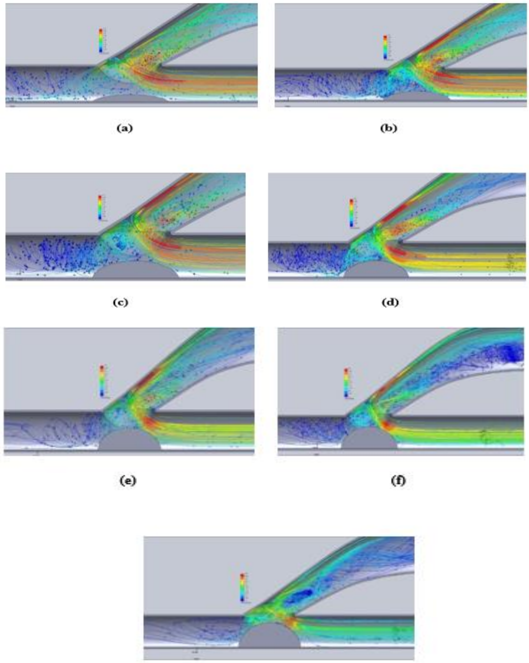
The first thing to do after selecting the COSMOSFloWork, we need to create the lids. Create the lids at the edge of the blood vessel which are at inlet artery, outlet artery and outlet venous. Next, choose the general setting to set up the parameter and properties such as exclude the cavity, take the z-plane reference, and set the internal flow and others. After that, choose the fluid with laminar flow and insert the properties of the fluid. For initial mesh, choose level 7 with manual separation and the minimum gap size is 0.0005m. After completing the general setting, the model is ready to be simulated. The result will give us the information about the flow trajectory, velocity, pressure and others. To get the plotted data of velocity and pressure versus length at the stenosis, we need to create the line of x-y line along the center of the blood vessel through the stenosis site. The reference point needs to be chosen and create the line x-y along the blood vessel to the stenosis. The result will show us, the plotted data of the velocity and pressure versus length in Microsoft Excel format. From the result obtained, we can see clearly the flow of the blood throughout the blood vessel. In addition, we can see the color of the flow which indicate the level of the velocity or pressure whether it is critical or not.

4.3 RESULTS AND DISCUSSION

In this chapter, the main discussion focuses on the correlation between the flow and stenosis level. RCAVF models with localized stenosis are reconstructed by using SolidWorks 2008, and then the models are simulated using CFD software. The stenosis included the stenosis type 1, type 2 and type 3. The percentage of the stenosis will be varied from 20%, 30%, 40%, 50%, 60%, 70% and 80%. The result of the simulation will show the velocity distribution, flow trajectory and the pressure drop of the blood flow.

4.3.1 Flow trajectory

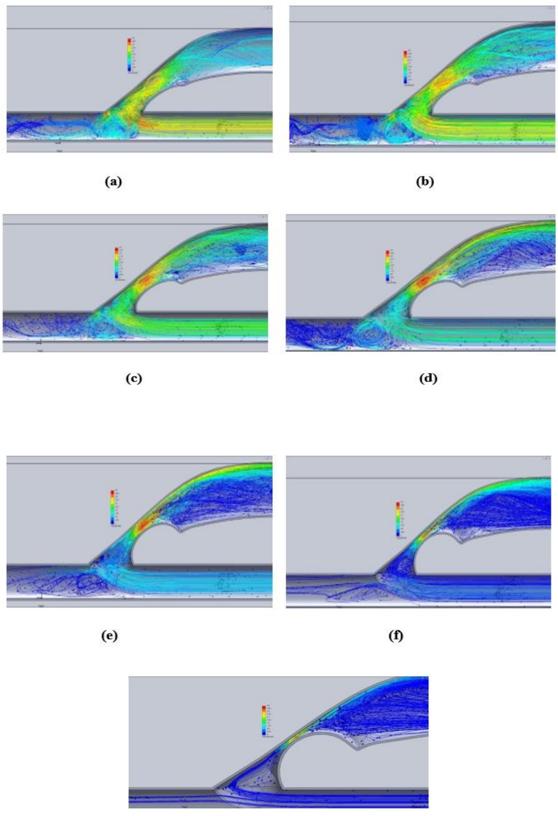
Flow trajectory is very important in flow analysis in order to traces any movement of the blood flow. From this flow trajectory, we can virtually see the flow of the blood with the effect of the stenosis. Moreover, flow trajectory can provide useful information about the zone of the flow patterns whether there is any stagnation, separation, backflow or recirculation. These types of flow pattern will lead to the progression of the intimal hyperplasia that lead to the development of the stenosis.



(g)

Figure 4.5: Flow trajectory for the type 1 stenosis: (a) 20%, (b) 30%, (c) 40%, (d) 50%, (e) 60%, (f) 70% and (g) 80%

According to the Figure 4.5, the blood will flow from arterial inlet and then distributed through the arterial outlet and venous outlet. As stenosis occurs, there is stagnation point at the inner wall of the cephalic vein. We can see from this simulation, there are the stagnation points for all of the stenosis. The stagnation point will give the velocity zero and the static pressure is maximum. From the Figure 4.5, the stagnation point creates the vortex at lower and upper of it. With the presence of the stagnation point and vortex, the formation of the stenosis might occur at the stagnation point since its velocity is zero. For the stenosis from 20 percent to 30 percent, there is no backflow of the blood. Instead for 40 percent until 80 percent stenosis, we can see the backflow of the blood after stenosis. Cholesterol is one of the substances that blood carry as it goes around the body. As the backflow happen, the blood that carry cholesterol will form after the stenosis. As a result, this will lead to the progression of the stenosis



(a) (b) (c) (d) (e) (f) (g)

Figure 4.6: Flow trajectory for the type 2 stenosis: (a) 20%, (b) 30%, (c) 40%, (d) 50%, (e) 60%, (f) 70% and (g) 80%.

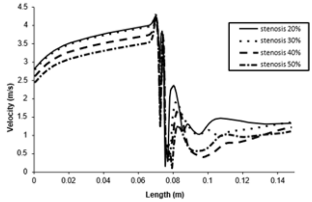
From the Figure 4.6, we can see the flow pattern of the type 2 stenosis from 20 percent to the 80 percent stenosis. Stenosis type 2 occurred at the inner wall of the curved region in the cephalic vein. For the 20 percent to 40 percent of the stenosis, the flow velocity is considered low and moderate. As the percentage of the stenosis increase which is 50 percent and above, the flow velocity become higher. We can see the color of the contour where the stenosis occurs is red. Moreover, there is also the backflow or the recirculation of the flow after the stenosis. As percentage of the stenosis becomes increase, more the formation of the backflow and the recirculation happen. For the stenosis of 50 percent until 80 percent, the backflow can be seen clearly after stenosis site. From the Figure 4.6, we can see the flow pattern of the type 3 stenosis. Type 3 stenosis occurred at the proximal to the curves segment where the vein straightens out. For the stenosis of 20 percent to the 50 percent, the colored of the contour is green and yellow. It describes that, the flow velocity of the blood flow is low or moderate. There is no sign of vortex and backflow yet until it come to the 50 percent of the stenosis. As it come to 50 percent stenosis and above, there is sign of the vortex and backflow occur frequently after the stenosis site. From 60 percent to 80 percent of stenosis, the flow velocity is increase and higher. The contour region at the stenosis is color red which describes that region have the higher velocity.

4.3.2 Velocity Distribution

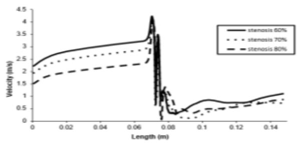
Velocity pattern illustrated the flow rate of the blood along the radiocephalic arteriovenous fistula. As we all know, the velocity is proportional to the flow rate. As the velocity increase the flow rate will also increase and vice versa.

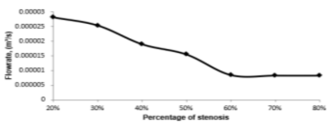
$$Q = AV \tag{1}$$

Where Q is the flow rate, m³/s, A = area m² and V = velocity, m/s. If the percentage of the stenosis increases, the flow velocity will become higher. The narrowed area around the stenosis makes the blood flow to move faster.



(a)



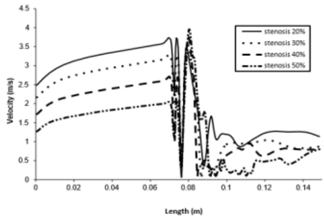


(b) (c)

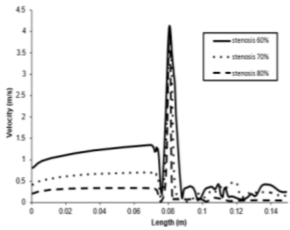
Figure 4.7: (a) Velocity distribution for the 20 percent to 50 percent type 1 stenosis; (b) Velocity distribution for the 60 percent to 80 percent type 1 stenosis and (c) Flowrate for various percentage of type 1 stenosis

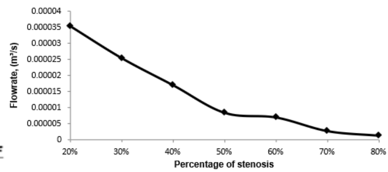
According to the Fig 4.7 (a) and (b), we can see the graph of the velocity versus the length for the various percentage of type 1 stenosis. To get this graph, the x-y plot needs to be done along centerline of the blood vessel. By considering that the stenosis is occurred at 0.075 m to 0.08m, we can see the highest peak curve is the stenosis of the 80 percent which is about 1.4 m/s and followed by the 70 percent (1.1 m/s), 60 percent (1 m/s), and 50 percent (0.69 m/s) until 20 percent (0.58 m/s). The lowest peak curve is 20 percent of stenosis. As the blood flow after the stenosis, the pathway of vessel become widens and the velocity decreases. The recommended and ideal flow rate to do the hemodialysis is 500 ml/min (8.33 x10^-6 m^3/s) or above. By applying the equation Q=AV, we can simply know the flow rate of the blood after stenosis. It is obvious from figure 4.6, we can see that when the stenosis size become larger, the flowrate after stenosis become lower.

From 20 percent to 50 percent stenosis, we can see the flow velocity after stenosis seem to be decreased but after a moment all of them increase little. The flow rate for 20 percent (2.82 x10^-5m^3/s), 30 percent (2.54 x10^-5 m^3/s), 40 percent (1.9 x10^-5 m^3/s) and 50 percent (1.55 x10^-5 m^3/s). The flow rate for the 20 percent to 50 percent stenosis are exceeding the 500 ml/min (8.33 x10^-6 m^3/s) which are ideal for hemodialysis. The flow rate of 20 percent to 50 percent stenosis is considered good to do the hemodialysis. In Figure 4.6, we can see as the stenosis increase, the flowrate is decrease. However, for the 60 percent to 80 percent stenosis, we can see the flow velocity after stenosis seems to be decreased and maintain at the lower velocity. The flow rate for the 60 percent is (8.48 x10^-6 m^3/s), 70 percent (8.32 x10^-6 m^3/s) and 80 percent (8.31 x10^-6 m^3/s). Therefore, 70 percent and 80 percent of the stenosis is considered below the recommended flow rate which are below 500 ml/min (8.33 x10^-6 m^3/s) to do the hemodialysis. Hence the hemodialysis cannot be done if there is 70 percent and 80 percent of the stenosis exist.



(a)



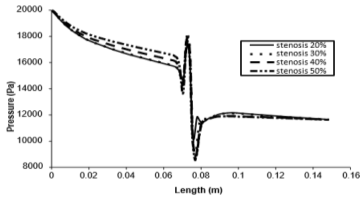


(b) (c)

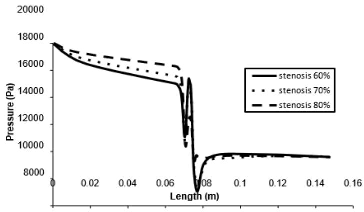
Figu r e 4.8: (a) Velocity distribution for the 20 percent to 50 percent type 2 stenosis; (b) Velocity distribution for the 60 percent to 80 percent type 2 stenosis; (c) Flowrate for various percentage of type 2 stenosis.

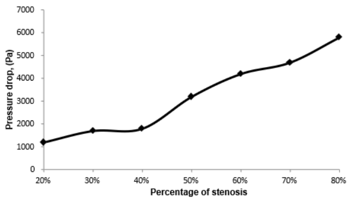
4.3.3 Pressure drop

Pressure drop describes as the decreased of the pressure from one point to another point in the blood vessel. Pressure drop is the result of the stenosis that obstruct on the blood flow. As the stenosis become bigger, the velocity or flow rate of the blood will become higher thus the pressure will become lower. Consistent with the Bernoulli's Theory, the increased of the blood flow is accompanied by the pressure reduction. The pressure is inversely proportional to the velocity.



(a)





(b) (c)

Figure 4.9: (a) Pressure drop for the 20 percent to 50 percent type 1 stenosis; (b) Pressure drop for the 60 percent to 80 percent type 1 stenosis; (c) Pressure drop for the various percentage of stenosis type 1.

4.3 CONCLUSION AND RECOMMENDATIONS

This chapter presented the three-dimensional reconstruction and computational fluid dynamics (CFD) simulation of radiocephalic arteriovenous fistula (RCAVF) models with localized stenosis. Three stenosis configurations were investigated, with stenosis severity ranging from 20% to 80%, to evaluate their effects on blood flow characteristics, including flow trajectory, velocity distribution, flow rate, and pressure drop.

The simulation results demonstrated a strong relationship between stenosis severity and hemodynamic behavior within the RCAVF. As the percentage of stenosis increased, blood velocity at the stenotic region increased significantly due to the reduction in vessel cross-sectional area. Higher degrees of stenosis also produced more complex flow patterns, including flow separation, vortex formation, recirculation zones, and backflow downstream of the stenosis. These disturbed flow conditions are recognized as factors that may contribute to the progression of intimal hyperplasia and further vascular access dysfunction.The analysis further showed that increasing stenosis severity resulted in a reduction in post-stenotic flow rate and an increase in pressure loss across the stenotic segment. For stenosis levels below 60%, the flow rates generally remained above the recommended threshold for effective hemodialysis. However, stenosis levels of 70% and 80% resulted in flow rates below the recommended value of 500 mL/min, indicating a higher risk of access insufficiency and potential failure of hemodialysis treatment. Overall, the findings demonstrate that CFD is a valuable tool for assessing the hemodynamic impact of stenosis in RCAVF. The study provides insight into how stenosis location and severity influence blood flow behavior and may assist clinicians in identifying critical stenosis conditions before vascular access failure occurs. These findings may contribute to improved monitoring, diagnosis, and management of arteriovenous fistula function in patients undergoing hemodialysis.

4.5 ACKNOWLEDGEMENT

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