# NUMERICAL SIMULATION ON THE EFFECT OF ANASTOMOSIS AND STENOSIS UPON RADIOCEPHALIC ARTERIOVENOUS FISTULA

WAN ANUAR BIN WAN HASSAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2014

# ABSTRACT

In the present study, the hemodynamic effect of variations of anastomosis angle and length and stenosis were investigated on several parameters such as pressure drop and wall shear stress. A total of 36 three-dimensional, simplified models of side-to-end radiocephalic arteriovenous fistula (RCAVF) were used to analyse the hemodynamic effect of anastomosis angle and length and other 21 models were used to analyse the hemodynamic effect of stenosis under average systolic and diastolic arterial and venous pressure. The flows in the models were simulated using EFD Lab software solving the Navier-Stokes equation with steady flow conditions. The results showed that high pressure drop over the anastomosis were observed for RCAVF with smaller anastomosis angle and length and for RCAVF with larger percentage of stenosis. Results also showed that the pressure drop over the anastomosis decreased significantly for the case of anastomosis angle less than $30^o$ and anastomosis length less than 6 mm. For cases with anastomosis angle larger than $45^o$, the pressure drop decreased slightly and became relatively constant. For anastomosis length, the pressure drop decreased slightly for anastomosis length of 5 mm to 10 mm and stabilized for anastomosis length of 8 mm to 10 mm. The analysis showed that the size of stenosis larger than 63% for Type 1, 48% for Type 2 and 63% for Type 3 tends to progress. Full progression of these stenoses results in the formation of blood clot or thrombosis, thus affecting the function of RCAVF. Therefore, it is recommended that the anastomosis angle should be considered between $30^o$ to $60^o$ (around $45^o$) and the anastomosis length should be maintained between 7 mm and 8 mm to minimize adverse effects. It is also suggested that Type 1, Type 2 and Type 3 stenosis should be treated early before they narrow to 63%, 48% and 63%, respectively, due to the progression of these stenoses.

# ABSTRAK

Dalam kajian ini, kesan hemodinamik terhadap variasi sudut dan panjang anastomosis dan stenosis telah dikaji terhadap beberapa parameter seperti kejatuhan tekanan dan tegasan ricih pada dinding. Sejumlah 36 model tiga dimensi sisi-ke-hujung *radiocephalic arteriovenous fistula* (RCAVF) yang dipermudah telah digunakan untuk menganalisis kesan hemodinamik sudut dan panjang anastomosis dan 21 model yang lain telah digunakan untuk menganalisis kesan hemodinamik stenosis pada tekanan purata sistolik dan distolik salur arteri dan vena. Aliran di dalam model telah disimulasi menggunakan perisian computer EFD Lab dengan menyelesaikan persamaan *Navier-Stokes* pada keadaan aliran mantap. Hasil kajian menunjukkan kejatuhan tekanan yang tinggi telah dapat diperhatikan untuk RCAVF dengan sudut dan panjang anastomosis yang lebih kecil dan untuk RCAVF dengan peratusan stenosis yang lebih besar. Hasil kajian menunjukkan bahawa kejatuhan tekanan melalui bahagian anastomosis berkurangan secara mendadak untuk kes sudut anastomosis kurang dari $30^o$ dan panjang anastomosis kurang dari 6 mm. Untuk kes dengan sudut anastomosis melebihi $45^o$, kejatuhan tekanan berkurangan secara sedikit dan agak malar. Untuk kes panjang anastomosis, kejatuhan tekanan berkurangan secara sedikit untuk panjang anastomosis 5 mm ke 10 mm dan menjadi stabil untuk panjang anastomosis 8 mm ke 10 mm. Analisis menunjukkan bahawa saiz stenosis yang lebih besar daripada 63% untuk Kelas 1, 48% untuk Kelas 2 dan 63% untuk Kelas 3 berkemungkinan untuk membesar. Pembesaran penuh stenosis ini akan menyebabkan salur darah tersumbat atau thrombosis seterusnya memberi kesan kepada fungsi RCAVF. Adalah dicadangkan agar sudut anastomosis patut dikekalkan antara $30^o$ dan $60^o$ (sekitar $45^o$) dan panjang anastomosis patut dikekalkan antara 7 mm dan 8 mm untuk mengurangkan kesan yang kurang baik. Turut dicadangkan agar Kelas 1, Kelas 2 dan Kelas 3 stenosis patut dirawat lebih awal sebelum salur darah masing-masing mengalami stenosis sehingga 63%, 48% dan 63% disebabkan oleh keupayaan stenosis ini untuk membesar.

## TABLE OF CONTENTS

## LIST OF TABLES

# LIST OF FIGURES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $L_{anas}$ | - | Anastomosis length |
| $W_{anas}$ | - | Anastomosis width |
| $\theta$ | - | Angle |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Surgical creation of vascular access is the first step for a patient to undergo hemodialysis (HD) process. It is proposed by Dialysis Outcomes Quality Initiative (DOQI) guidelines that arteriovenous fistula to be used as primary vascular access for hemodialysis patients (Zadeh et al., 2012). Mature arteriovenous fistula was recorded to have more advantages compared to arteriovenous graft including lower alteration rate, superior overall patency and lower cost (Zadeh et al., 2012). Radiocephalic arteriovenous fistula (RCAVF) is the primary access and was known as the chosen access for hemodialysis (Sivanesan et al., 1998; Kumar et al., 2007; Bessa and Ortiz, 2009) with the best median duration, exceeding seven years compared to other types of vascular access (Ridriguez et al., 2000). RCAVF was commonly constructed in side-artery-to-end-vein anastomosis due to its ease of construction and because of the problems widely reported with side-to-side and end-to-end configurations (Sivanesan et al., 1998; Konner et al., 2003).

In order to study the blood flow through RCAVF, segments of RCAVF must be clearly understood. Figure 1.1 schematically illustrates the segments of RCAVF;

the proximal artery (1), the distal artery (2), the proximal vein (3), the distal vein (4) and the anastomosis (5) (Canneyt et al., 2010). RCAVF is surgically created by connecting an artery and a vein at wrist as illustrated in Figure 1.2. The segment where artery and vein are connected together is known as anastomosis. The function of RCAVF creation is to enlarge the diameter of vein thus making it stronger and applicable for hemodialysis processs. Even though the anastomosis segment is important in arteriovenous fistula creation, there is no adequate scheme proposed by any researchers to suggest the suitable and best configuration of anastomosis length and angle for anastomosis creation. Optimization of the anastomosis segment can improve the patency rate of arteriovenous fistula (Krueger et al., 2002). In addition, some causes of flow disturbances can be avoided during the process of construction if more valuable information on the effects of anastomosis angle and length and flow distributions through arteriovenous fistula were available (Sivanesan et al., 1999a).

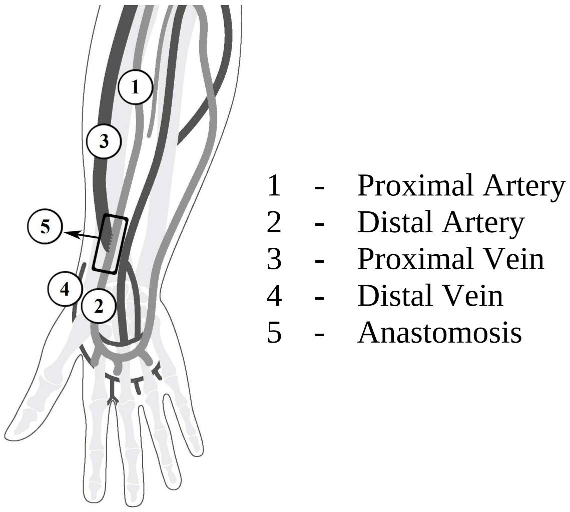

**Figure 1.1:** The anatomy of arteriovenous fistula (AVF). (Canneyt et al., 2010)

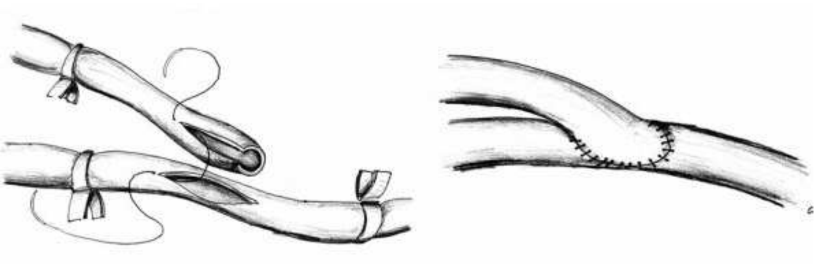

**Figure 1.2:** Sketch of construction of side-to-end anastomosis. (Grevious et al., 2003)

Many researchers have studied the hemodynamic effect of anastomosis angle and length in numerical, in-vitro or/and in-vivo, however, their domain of studies were in distal leg artery bypasses, human aorta bypasses and animal (dog, pig or sheep) aorta bypasses, not in the context of arteriovenous fistula (Pousset et al., 2006; Chua et al., 2005; Staalsen et al., 1995). While, other researchers who have done numerical studies on arteriovenous fistula or arteriovenous graft such as Hofer et al., (1996), Cole et al., (2002), Krueger et al., (2002), Bessa and Ortiz (2009) and Ene-Iordache and Remuzzi (2011), all of them conducted their research using model with a fixed value of anastomosis segment without varying the dimension of the anastomosis angle and length. Therefore, for the first part of this study, blood flow through RCAVF was simulated by varying the anastomosis angle and length. The anastomosis angle was varied over $20^o$, $30^o$, $45^o$, $60^o$, $75^o$ and $90^o$ while the anastomosis length was varied from 5 mm up to 10 mm.

Local hemodynamics has been accepted to have had an influence on the progression of intimal hyperplasia, which was the reason for large proportion of late failures in RCAVF (Sivanesan et al., 1999a; Hofer et al., 1996; Krueger et al., 2002). Late failure is defined as the failure that occurs after three months of used. Intimal hyperplasia progression led to the development of stenosis in RCAVF. Fistula's geometry seemed to be implicated by the development of stenosis, thus influenced the hemodynamics of the process (Sivanesan et al., 1999b). Stenosis in RCAVF will obstruct the blood flow from moving through blood vessel and through hemodialysis machine. The narrowing is often caused by the development of intimal hyperplasia and arteriosclerosis. Venous stenosis is one of the principal causes of AVF thrombosis. Signs of stenosis can be a change in the thrill or vibration in RCAVF, a change in bruit or sound of the flow of blood through RCAVF, high venous pressure and swelling (Beathard, 2007). All these symptoms finally can be attributed to the early and late failures of RCAVF.

Although, there are several methods exist that may be used for evaluation (such as doppler ultrasound and digital subtraction angiography (DSA)) and treatment (such as percutaneous transluminal angioplasty (PTA)) of RCAVF stenosis, it is still not sufficient to support the effort in reducing the numbers of stenosis`s patient. This phenomenon happens because the failure to detect the early signs and symptoms of RCAVF failure. An effective way to solve this problem is by understanding the blood flow motion through RCAVF. Understanding the blood flow motion through RCAVF can help the medical practitioners and give early warning on the potential risk of the RCAVF failure.

The stenosis inside RCAVF has two dominant factors; locations or sites of stenosis and degrees or sizes of stenosis. Each factor gives the significant impact to the blood flow motion. Almost every patient with RCAVF failure had suffered different dominant factors of stenosis. Due to that matter, the requirement of blood flow analysis is very important to understand the early signs in order to predict the development and formation of stenosis inside RCAVF. In current practice, clinical diagnosis for the patient with suspected RCAVF stenosis is diagnosed using scanning techniques like doppler ultrasound and digital subtraction angiography (DSA) to look for the obstructive blood vessel which are relatively inaccurate and followed by further treatment like percutaneous transluminal angioplasty (PTA). A RCAVF stenosis tends to narrow the internal diameter of blood vessel and restrict the blood flow to pass through. There is time for the stenosis to increase progressively and finally becomes worse with RCAVF failure before the patient receives proper treatment.

Very few researchers had studied the correlation of location and size to investigate the flow behaviour in RCAVF stenosis. This situation happens probably due to the lack of specific images of stenosis and the limitation of computer resources to reconstruct the model. Besides, there is no adequate classification scheme proposed by any researchers to suggest the regular sizes and shapes of stenosis inside RCAVF even though Sivanesan et al., (1999a) and Ene-Iordache and Remuzzi (2011) published the suggested locations or sites of RCAVF stenosis.

For the second part of this study, RCAVF stenosis was simulated by varying the locations according to Sivanesan et al., (1999a) and Ene-Iordache and Remuzzi, (2011) and sizes within the RCAVF region. The three locations or sites of stenosis were located on the arterial floor at the anastomosis, on the inner wall of the curved region of the proximal vein and just proximal to the curved region where the vein becomes straight (Sivanesan et al., 1999a and Ene-Iordache and Remuzzi, 2011). In this study, the size of stenosis was varied from 20% up to 80%. The size of stenosis was defined as the constriction ratio of the diameter of normal blood vessel lumen. It was expected that small size of stenosis would have insignificant effect on the blood flow pattern. The National Kidney Foundation Kidney Disease Outcomes Quality Initiative (NKF KDOQI) has provided the clinical guidelines for stenosis treatment. It was documented that stenosis occurred in arteriovenous fistula should be treated if the stenosis constriction is greater than 50% of the lumen diameter and associated with several clinical or physiological abnormalities. Suggested method of treatment is percutaneous transluminal angioplasty or surgical revision. In addition of that, several researchers including Tordoir et al., (2007) also suggested that when the stenosis caused the diameter of blood vessel to narrow by greater than 50%, the treatment for stenosis should be performed. Even though it is suggested that the treatment for stenosis should be performed when the degree or size of stenosis exceed or greater than 50%, there are still some arguments from other researchers that the stenosis should be treated earlier to avoid fistula failures.

In order to explore on how significant the flow will be altered by different configurations of anastomosis and also by the presence of stenosis at different locations and sizes, Computational Fluid Dynamics (CFD) had been chosen to simulate the blood flow inside the RCAVF. Within the last decade, CFD had become a popular choice among the researchers. The capability of the methods is proven to give good approximation results. Therefore, in this study commercial CFD software has been used to analyse blood flow through simplified RCAVF models.

Zones of irregular flow patterns (stagnation, separation and recirculation) were the affected zones where intimal hyperplasia that lead to the development of stenosis was known to occur. Intimal hyperplasia was observed to occur at the heel and the toe of anastomosis segment, on the artery floor opposite the anastomosis, on the inner wall of the curved region of proximal vein and just proximal to the curved region where the vein becomes straight (Sivanesan et al., 1999a and Ene-Iordache and Remuzzi, 2011). Visualization of flow patterns in RCAVF was very important for identifying the regions where intimal hyperplasia and stenosis can develop as suggested by Bessa and Ortiz (2009).

Due to the lack of studies that described hemodynamic of RCAVF by considering the effect of the anastomosis segment and stenosis itself, therefore, the aim of this project is to investigate the hemodynamic effect of anastomosis angle and length and stenosis in the setting of RCAVF.

## 1.2 Problem Statement

Anastomosis is one of the important segments in radiocephalic arteriovenous fistula (RCAVF) construction. Improper construction of RCAVF might lead to inefficient blood flow condition resulting in non-maturation of RCAVF. Sivanesan et al., (1999a) and Canneyt et al., (2010) suggested that deep understanding of anastomosis angle and length and flow distributions through fistula would help proper construction of the fistula. Many researchers had studied the hemodynamic effect of anastomosis angle and length in numerical, in-vitro or/and in-vivo, however, their domain of studies were in distal leg artery bypasses, human aorta bypasses and animal (dog, pig or sheep) aorta bypasses, not in the context of arteriovenous fistula. While, other researchers who have done numerical studies on arteriovenous fistula or arteriovenous graft such as Hofer et al., (1996), Cole et al., (2002), Krueger et al., (2002), Bessa and Ortiz (2009) and Ene-Iordache and Remuzzi (2011), all of them conducted their research using simplified model with a fixed value of anastomosis segment without varying the dimension of the anastomosis angle and length. Very few researchers used numerical analysis to study the effect of hemodynamic of anastomosis segment in the context of RCAVF by varying both the anastomosis angle and length.

Stenosis was known as one of the cause of vascular access failures. Stenosis inside RCAVF tends to narrow the internal diameter of blood vessel and restrict the blood flow to pass through. There is time for the stenosis to increase progressively and finally becomes worse with RCAVF failure before patient receives proper treatment. Very few researchers had studied the correlation of location and size to investigate the flow behaviour in RCAVF stenosis. In addition, there is no adequate classification scheme proposed by any researchers to suggest the regular sizes and shapes of stenosis inside RCAVF, although Sivanesan et al., (1999a) and Ene-Iordache and Remuzzi (2011) had published the suggested locations or sites of RCAVF stenosis. Due to that matter, very few researchers had analysed numerically the correlation of location and size of stenosis to investigate the flow behaviour in RCAVF stenosis.

Therefore, both the effect of anastomosis angle and length and the effect of stenosis need to be studied numerically. The effect of anastomosis angle and length was studied by varying the length and angle of simplified RCAVF anastomosis while the effect of stenosis was analysed by varying the locations and sizes of simplified RCAVF stenosis.

## 1.3 Research Objectives

The main objective of this study is to investigate the effect of anastomosis segment and stenosis on side-to-end radiocephalic arteriovenous fistula (RCAVF). Specific objectives are:

i. To determine the best configurations of anastomosis angle and length for RCAVF creation.
ii. To predict the critical percentage of stenosis where the value of wall shear stress (WSS) exceed the normal physiological value of wall shear stress (WSS).

## 1.4 Research Scope

Four research scopes have been determined to help achieve the research objectives:

i. Only simplified side-to-end models of RCAVF are analysed in the simulation.
ii. All vessel walls are assumed as rigid walls.
iii. Steady blood flows are used in the simulation.
iv. Solution and discussion are based on numerical simulation only.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter reviews the anatomy of side-to-end radiocephalic arteriovenous fistula (RCAVF), previous study on anastomosis segment and stenosis, factors related to RCAVF failures and blood properties. Regarding the previous study on anastomosis segment, this chapter describes the clinical studies on anastomosis construction and previous study (numerical and experimental) on anastomosis angle and length. For the previous study on RCAVF stenosis, this chapter describes the classification of RCAVF stenosis and factors involved in the development of RCAVF stenosis. Appendix A shows several publications related to this research. Present study covered most of the important parameters.

## 2.2 Side-to-end Radiocephalic Arteriovenous Fistula (RCAVF)

The side-artery-to-end-vein (side-to-end) anastomosis at the wrist is the most common technique used and performed for vascular access. Side-to-end anastomosis at wrist is surgically created by connecting the cephalic vein to radial artery to create a vascular access called radiocephalic arteriovenous fistula (RCAVF). RCAVF was commonly constructed in side-artery-to-end-vein anastomosis due to its ease of construction and because of the problems widely reported with side-to-side and end-to-end configurations (Sivanesan et al., 1998; Konner et al., 2003). There are five important segments of RCAVF consisting of the proximal artery, the distal artery, the proximal vein, the distal vein and the anastomosis. The connection between radial artery and cephalic vein was made by an anastomosis assuming an ellipsoidal cross section with a given anastomosis length ($L_{anas}$) and width ($W_{anas}$) as shown in Figure 2.1. The heel and toe will be created by the construction of side-to-end RCAVF anastomosis. The toe is a region at the end of anastomosis segment near to the distal artery or arterial outlet. While the heel is a region at the other end of anastomosis near to the proximal artery or arterial inlet.

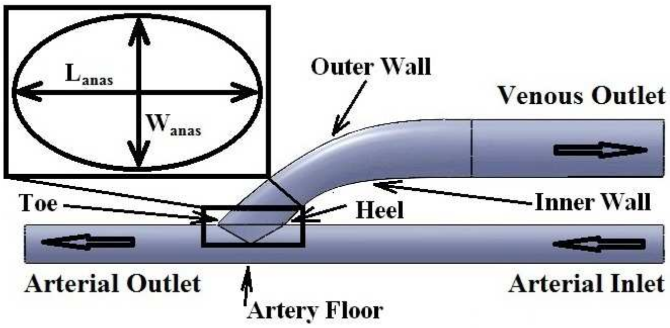

**Figure 2.1:** Illustration of inner wall, outer wall, heel and toe of RCAVF.

## 2.3 Anastomosis Angle and Length

Sivanesan et al., (1999a) stated that some causes of flow disturbances can be avoided during the process of construction of arteriovenous fistula if more valuable information on effects of anastomosis angle and length and flow distributions through arteriovenous fistula were available. While Krueger et al., (2002) stated that optimization of the anastomosis can improve the patency rate of vascular access. In their study, Sivanesan et al., (1999a) measured the anastomosis lengths and angles for 25 side-to-end radiocephalic arteriovenous fistula. Anastomosis lengths in 25 RCAVF varied from 6 to 11 mm while anastomosis angles varied from $36^o$ to $62^o$.

Ojha et al., (1994) utilised the photochromic tracer technique to visualise the flow and analyse the instantaneous wall shear stress through side-to-end anastomosis models with variation of angles of $20^o$, $30^o$, $45^o$ and $60^o$. They observed the increasing in flow separation and shear stress when the anastomosis angle increased. Hughes and How (1996) analysed the flow behaviour of three different angles; $15^o$, $30^o$ and $45^o$ of distal anastomosis models using transparent polyurethane models. They observed separation of flow at the toe of anastomosis in the $30^o$ and $45^o$ models. However no separation of flow was observed for $15^o$ model. Canneyt et al., (2010) performed non pulsatile numerical analysis on side-to-end RCAVF with varied anastomosis angles; $27^o$, $34^o$, $45^o$, $53^o$, $63^o$, $76^o$ and $90^o$. They concluded that the pressure drop increased slightly for angle smaller than $45^o$, stabilised at $45^o$ and decreased significantly for angle higher than $45^o$.

Zhang et al., (2008) experimentally studied two models with anastomosis angle of $45^o$ and $90^o$. They found out that model with $45^o$ anastomosis angle had more potential in reducing intimal thickening and/or atherosclerosis compared to model with $90^o$ anastomosis angle. In 2011, Ene-Iordache and Remuzzi (2011) studied the flow through RCAVF using a model with fixed $49^o$ anastomosis angle. They concluded that preferential localization of stenosis to occur may be predicted by the localization of oscillating and low hemodynamic stress. Then in 2012, Ene-

Iordache et al., (2012) studied the effect of anastomosis angle on the flow through RCAVF by varying the anastomosis angle over $30^o$, $45^o$, $60^o$ and $90^o$. They found out that disturbed flow occurred in all models specifically on the arterial floor at the anastomosis and on the inner wall of the curved region of proximal vein. They considered the smallest angle; $30^o$ to be the preferred angle to minimize the development of intimal hyperplasia.

Very few researchers had studied the effect of anastomosis length on hemodynamic of RCAVF. Elshawary et al., (2010) performed 16 arterial bypass grafts in eight German Shepherd dogs by varying the anastomosis length 3, 3.5 and 4 times the internal diameter of the artery. They observed the intimal hyperplasia was significantly decreased at the heel and toe of the anastomosis with the increasing of anastomosis length. While, Canneyt et al., (2010) studied the impact of anastomosis size by varying the sizes of anastomosis using geometries of anastomosis length ($L_{anas}$ in mm) times anastomosis width ($W_{anas}$ in mm) of 6x3, 6x4, 8x2, 8x3 and 10x3. They analysed that pressure drop decreased with the increasing of anastomosis size. In the present study, the anastomosis length and angle were varied to determine the effect of anastomosis angle and length on hemodynamic of side-to-end RCAVF. Based on previous study, the anastomosis length was varied from 5 mm to 10 mm while the anastomosis angle was varied over $20^o$, $30^o$, $45^o$, $60^o$, $75^o$ and $90^o$.

## 2.4 RCAVF Stenosis

Sivanesan et al., (1999a) studied 25 side-to-end radiocephalic arteriovenous fistulae for duration of two years and found out that stenosis occurred in all 25 fistulae after three months the fistulae were surgically created. They classified the stenosis into three specific locations or sites as shown in Figure 2.2. Stenosis that occurred on the arterial wall at the anastomosis was classified as Type 1 stenosis. Stenosis that occurred at the curved region on the inner wall of proximal vein was classified as Type 2 stenosis as shown in Figure 2.3 while stenosis that occurred on proximal vein just proximal to the curved region where the vein vessel becomes straight was classified as Type 3 stenosis (Sivanesan et al., 1999a; Ene-Iordache and Remuzzi, 2011). The first two types of stenosis (Type 1 and Type 2) were suspected as an adaptation result due to hemodynamic alteration when the anastomosis was surgically created. Type 3 stenosis was reported generally progressive. The progression of Type 3 stenosis interrupts and narrows the venous lumen resulting in limiting blood flow through proximal vein.

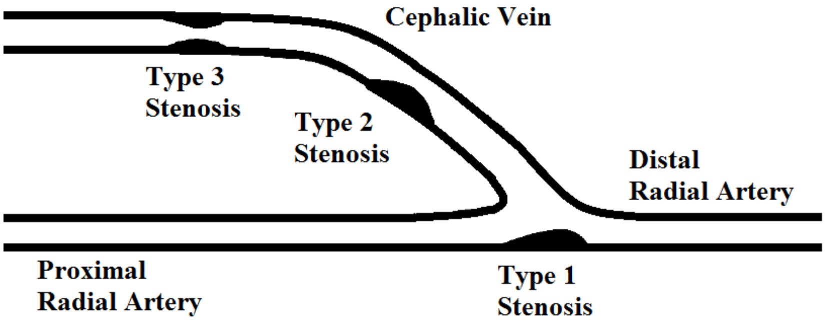

**Figure 2.2:** Sites of stenosis in radiocephalic arteriovenous fistula (RCAVF).

The National Kidney Foundation Kidney Disease Outcomes Quality Initiative (NKF KDOQI) has provided the clinical guidelines for stenosis treatment. It was documented that stenosis occurred in arteriovenous fistula should be treated if the stenosis constriction is greater than 50% of the lumen diameter and associated with several clinical or physiological abnormalities. In addition to that, several researchers including Tordoir et al., (2007) suggested that when the stenosis caused the diameter of blood vessel narrowed by greater than 50%, the treatment for stenosis should be performed. Stenosis with larger percentage of constriction (larger than 50% constriction) will obstruct the blood flow from moving through blood vessel and through hemodialysis machine. Fully progression of the stenosis will result in blockage of blood vessel thus affecting the function of RCAVF.