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

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

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Special dedication to my beloved mother and father and my brothers and sisters

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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.

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L_{anas}	-	Anastomosis length
W_{anas}	-	Anastomosis width
θ	-	Angle

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CHAPTER 1

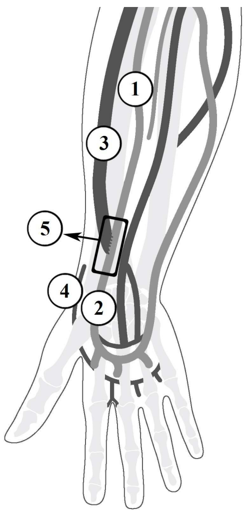
INTRODUCTION

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).



1 - Proximal Artery
2 - Distal Artery
3 - Proximal Vein
4 - Distal Vein
5 - Anastomosis

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

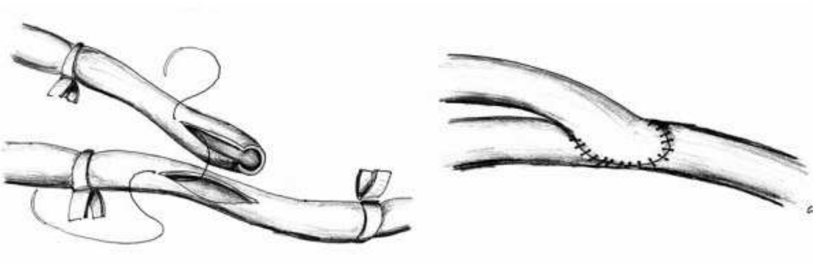


Figure 1.2: Sketch of construction of side-to-end anastomosis.
(Grevious et al., 2003)

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.

REFERENCES

Beathard, G.A. (2007). Physical Examination of The Dialysis Vascular Access. *Seminars in Dialysis*. 11(4): 231-236.

Bessa, K.L. and Ortiz, J.P. (2009). Flow Visualization in Arteriovenous Fistula and Aneurysm Using Computational Fluid Dynamics. *Journal of Visualization*. 12(2): 95-107.

Canneyt, K.V., Pourchez, T., Eloot, S. Guillame, C., Bonnet, A., Segers, P. and Verdonck, P. (2010). Hemodynamic Impact of Anastomosis Size and Angle in Side-to-end Arteriovenous Fistulae: A Computer Analysis. *Journal of Vascular Access*. 11(1): 52-58.

Carew, T.E., Vaishnav, R.N. and Patel, D.J. (1968). Compressibility of The Arterial Wall. *Circulation Research*. 23: 61-68.

Chua, L.P., Ji, W. And Zhou, T. (2005). In Vitro study on The Steady Flow Characteristics of Proximal Anastomosis Models. *International Communication in Heat and Mass Transfer*. 32: 464-472.

Cole, J.S., Watterson, J.K. and O'Reilly, M.J.G. (2002). Is There a Haemodynamic Advantage Associated with Cuffed Arterial Anastomoses. *Journal of Biomechanics*. 35: 1337-1346.

Dashty, M., Akbarkhanzadeh, V., Zeebregts, C.J., Spek, C.A., Sijbrands, E.J., Peppelenbosch, M.P. and Rezaee, F. (2012). *Characterization of Coagulation Factor Synthesis in Nine Human Primary Cell Types*. Scientific Report. nature.com.

Elsharawy, M., Naim, M.M., El-Daharawy, H.A.M., Ahmed, I.H. and Mohammed, S.H.A. (2010). Effect of Anastomotic Length on The development of Intimal Hyperplasia in The Distal Anastomosis of Bypass Graft. *Vascular*. 18(5): 256-263.

Ene-Iordache, B., Cattaneo, L., Dubini, G. and Remuzzi, A. (2012). Effect of Anastomosis Angle on The Localization of Disturbed Flow in 'Side-to-end' Fistulae for Haemodialysis Access. *Nephrol Dial Transplant*. 0: 1-7.

Ene-Iordache, B. and Remuzzi, A. (2011). Disturbed Flow in Radial-cephalic Arteriovenous Fistulae for Haemodialysis: Low and Oscillating Shear Stress Locates the Sites of Stenosis. *Nephrol Dial Transplant*. 0: 1-11.

Fry, D.L. (1968). Acute Vascular Endothelial Changes Associated with Increased Blood Velocity Gradients. *Circulation Research*. 22: 165-197.

Fung, Y.C. (1993). *Biomechanics: Mechanical Properties of Living Tissues*. (2^{nd} ed.) New York: Springer-Verlag.

Gasser, T.C., Ogden, R.W. and Holzapfel, G.A. (2006). Hyperelastic Modeling of Arterial Layers with Distributed Collagen Fibre Orientations. *Journal of the Royal Society Interface*. 3: 15-35.

Grevious, M.A., Loth, F., Jones, S.A., Arslan, N., Curi, M.A., Schwartz, L.B. and Bassiouni H.S. (2003). Technical Considerations in The Construction of Vascular Anastomoses. In: Moore, J.E. and Zouridakis. G. *Biomedical Technology and Devices Handbook*. London: CRC Press. 576-594: 2003.

Hofer, M., Rappitsch, G., Perktold, K., Trubel, W. and Schima, H. (1996). Numerical Study of Wall Mechanics and Fluid Dynamics in End-to-side Anastomoses and Correlation to Intimal Hyperplasia. *Journal of Biomechanics*. 29(10): 1297-1308.

Hughes, P.E. and How, T.V. (1996). Effects of Geometry and Flow Division on Flow Structures in Models of The Distal End-to-side Anastomosis. *Journal of Biomechanics*. 29(7): 855-872.

Hürlimann, D., Ruschitzka, F. and Lüscher, T.F. (2002). The Relationship between The Endothelium and The Vessel Wall. *European Heart Journal Supplements*. 4(A): 1-7.

Konner, K., Nonnast-Daniel, B. and Ritz, E. (2003). The Arteriovenous Fistula. *Journal American Society of Neprology*. 14: 1669-1680.

Koshiba, N., Ando, J., Chen, X., Hisada, T. (2007). Multiphysics Simulation of Blood Flow and LDL Transport in a Porohyperelastic Arterial Wall Mode. *Journal of Biomechanical Engineering*. 129: 374-385.

Krueger, U., Zanow, J. and Scholz H. (2002). Computational Fluid Dynamics and Vascular Access. *International Society of Artificial Organs*. 26(7): 571-575.

Kumar, A., Jha M.S., Singla M., Gupta N., Raina P., Dubey D. and Srivastava A. (2007). Radio-median Cubital / Radiocephalic Arteriovenous Fistula at Elbow to Prevent Vascular Steal Syndrome Associated with Brachiocephalic Fistula: Review of 320 Cases. *Indian Journal of Urology*. 23(3): 261–264.

Lally, C., Dolan, F. and Prendergast, P.J. (2005). Cardiovascular Stent Design and Vessel Stresses: A Finite Element Analysis. *Journal of Biomechanics*. 38: 1574-1581.

Longest, P.W. and Kleinstreuer, C. (2003). Numerical Simulation of Wall Shear Stress Conditions and Platelet Localization in Realistic End-to-Side Arterial Anastomoses. *Journal of Biomechanical Engineering*. 25: 671-681.

Malek, A.M., Alper, S.I. and Izumo, S. (1999). Hemodynamic Shear Stress and Its Role in Atherosclerosis. *Journal of American Medical Association*. 282 (21): 2034-2042.

Milnor, W.R. (1989). *Hemodynamics*. (2nd ed.). Baltimore: Williams & Wilkins.

National Kidney Foundation (2006). KDOQI Clinical Practice Guidelines and Clinical Practice Recommendations for 2006 Updates: Hemodialysis Adequacy, Peritoneal Dialysis Adequacy and Vascular Access. *American Journal of Kidney Diseases*. 48: 1- 322.

Nichols, W.W. and O'Rourke, M.F. (2005). *McDonald's Blood Flow in Arteries: Theoretical, Experimental and Clinical Principles* (5th ed.). London: Taylor & Francis.

Ojha, M., Cobbold, R.S. and Johnston, K.W. (1994). Influence of Angle on Wall Shear Stress Distribution for An End-to-side Anastomosis. *Journal of Vascular Surgery*. 9(6): 1067-1073.

Paszkowiak, J.J. and Dardik, A. (2003). Arterial Wall Shear Stress: Observations from the Bench to the Bedside. *Vascular and Endovascular Surgery*. 37(1): 47-57.

Patel, D.J. and Vaishnav, R.N. (1980). *Basic Hemodynamics and Its Role in Disease Processes*. Maryland: University Park Press.

Pousset, Y., Lermusiaux, P., Berton, G., Gouez, L.J. and Leroy, R. (2006). Flow Dynamics through End-to-side Anastomosis. *Annals of Vascular Surgery*. 20(6): 774-779.

Ridriguez, J.A, Armadans, L., Ferrer, E., Olmos, A., Codina, S., Bartolome, J., Borrellas, J. and Piera, L. (2000). The Function of Permanent Vascular Access. *Neprol Dial Transplant*. 15: 402-408.

Sallam, T.A. Lumsden, A.B., Suggs, W.D. and Ku, D.N. (1996). Low Shear Stress Promotes Intimal Hyperplasia Thickening. *Journal of Vascular Investment*. 2: 12-22.

Sivanesan, S., How, T.V. and Bakran, A. (1998). Characterizing Flow Distributions in AV Fistulae for Hemodialysis Access. *Neprol Dial Transplant*. 13: 3108-3110.

Sivanesan, S., How, T.V. and Bakran, A. (1999a). Sites of Stenosis in AV Fistulae for Haemodialysis Access. *Nephrol Dial Transplant*. 14: 118-120.

Sivanesan, S., How, T.V., Black, R.A. and Bakran, A. (1999b). Flow Patterns in The Radiocephalic Arteriovenous Fistula: An In Vitro Study. *Journal of Biomechanics*. 32: 915-925.

Staalsen, N.H., Ulrich, M., Winther, J., Pederson, M.T., How, T. and Nygaard, H. (1995). The Anastomosis Angle Does Change The Flow Fields at Vascular End-to-side Anastomoses In Vivo. *Journal of Vascular Access*. 21(3): 460-471.

Tricht, I.V., Wachter, D.D., Tordoir, J. and Verdonck, P. (2005). Hemodynamics and Complications Encountered with Arteriovenous Fistulas and Grafts Access for Hemodialysis: A Review. *Annals of Biomedical Engineering*. 33(9): 1142-1157.

Tordoir, J., Canaud, B., Haage, P., Konner, K., Basci, A., Fouque, D., Kooman, J., Martin-Malo, A., Pedrini, L., Pizzarelli, F., Tattersall, J., Vennegoor, M., Wanner, C., Wee, P.T. and Vanholder, R. (2007). EBPG on Vascular Access. *Nephrol Dial Transplant*. 22(2): 88-117.

Zadeh, M.K., Gholipour, F., Naderpour, Z. and Porfakaran, M. (2012). Relationship between Vessel Diameter and Time to Maturation of Arteriovenous Fistula for Hemodialysis Access. *International Journal of Nephrology*. 1-3.

Zhang, J.M., Chua, L.P., Ghista, D.N., Zhou, T.M. and Tan Y.S. (2008). Validation of Numerical Simulation with PIV Measurements for Two Anastomosis Models. *Medical Engineering & Physics*. 30: 226-247.