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CFD Analysis on Mismatched End-to-end Internal Diameter of RSVG Models

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ABSTRACT

A digital arterial disease in upper extremity is uncommon happened compare to arterial disease in lower extremity. A surgical vein graft interposition is performed as revascularization procedure. However, mismatching between end-to-end internal diameter of reverse saphenous vein graft (RSVG) and existing digital artery cause blockage in RSVG vessel. In previous study, size discrepancy (small to large) in vessel causes the abnormal blood flow and will initiate the thrombosis formations as stated by Rory F. *et al*. Furthermore, their previous study is also supported by clinical theory as written in Wilmer W. *et al*. and Krishnan B. Chandran *et al*. s' text books. The main goal of this study is to analyze the relationship the patterns of blood flow through mismatching between end-to-end internal diameter of RSVG models and existing digital artery (large to small) with effect to the initiation of thrombus formation in RSVG models. A Three-dimensional Computational Fluid Dynamic (3-D CFD) method is employed to investigate blood flow velocity, blood pressure gradient and wall shear stress (WSS) on ideal straight (well matched between internal diameter of RSVG and recipient arteries) and internal diameter mismatched of end-to-end RSVG models. In this experiment, we expect that steady state laminar blood flow demonstrates abnormal flow pattern in mismatched internal diameter RSVG models compared to an ideal straight model. As conclusion, any abnormal blood flow pattern will initiate the formation of thrombus and reduce the vein graft survival.

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INTRODUCTION

Digital arterial disease in upper extremity is uncommon happened compare to arterial disease in lower extremity (Jocelyn A. Segall and Gregory L. Moneta, 2007). It happens due to narrowing in the internal diameter of blood vessel and will lead the increasing in blood vessel wall stiffness. To overcome the block especially in digital artery, a surgical vein graft interposition is performed as revascularization procedure (Jocelyn A. Segall and Gregory L. Moneta, 2007; Raafat Shalabi, Yoysith Al Amri and Elham Khoujah, 2006; Van Carrel A & Guthrie CC, 1906 and Zol B. Kryger, Vinay Rawlani, Gregory A. Dumanian, 2007).For vein grafting procedure, the RSVG has been suggested. Usually, the harvested saphenous vein graft (SVG) is reversely end-to-end attached after the effected artery section is removed (David S.,Ruch, L. Andrew, Koman& Thomas L., Smith, 2001 and George D. Chloros, Robert M. Lucas, Zhongyu Li, Martha B. Holden, AAS, L. Andrew Koman, 2008). H. Piza (1979) and David L. *et al*. (2001) stated that saphenous veins are available at the dorsum of the foot and ankle or the forearm (David S.,Ruch, L. Andrew, Koman& Thomas L., Smith, 2001 and H. Piza-Katzer, 1979).

The RSVG should have approximately the same length and internal diameter with the existing artery as mentioned by H. Piza (1979) in his previous research. The RSVG has several special characteristics compare to other veins. First, it is technically easy to be used because relatively large diameter and wall characteristics. Second, it can be used for perform multiple grafts because it is plentiful. Third, it can reach any artery because it is long and finally, it is easily harvested (Sabik, JF, 2011).

The durability and longevity of vein grafts are still unpredictable. As reported by George D. Chloros (2008), there are so many failure cases and most defected finger were pale and cool (George D. Chloros, Robert M. Lucas, Zhongyu Li, Martha B. Holden, AAS, L. Andrew Koman, 2008; Jocelyn A. Segall and Gregory L. Moneta, 2007 and Zol B. Kryger, Vinay Rawlani, Gregory A. Dumanian, 2007).

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Based on literature review, failure in vein grafting happen due to mismatching between vein graft internal diameter and existing digital artery. In fact, the diameter plays a very important role in prolonging vein graft survival as stated in Christopher L. Skelly *et al*. (2001)s' previous research (Christopher L. Skelly, Shari L. Meyerson, Micheal A. Curi, Francis Loth, and Lewis B. Schwartz,2001).

The 3D CFD method was applied in this study in order to analyze blood flow behaviour in ideal straight and failure case models. The blood flow velocity, pressure gradient and vein graft WSS were observed as to achieve our experiment goals. There were two mismatched end-to-end internal diameter of RSVG models were proposed in our simulation works. The ideal straight RSVG was also introduced as our benchmark model since it provides very accurate result in any monitor result. Finally, all showed results were studied and analyzed again in order to relate with the initiation of thrombus formation.

Related Research:

Rory F. Rickard, Chris Meyer & Don A. Hudson (2009) stated internal diameter difference between the end-to-end vein graft and existing artery could cause attachment failure in surgery (Rory F., Rickard, Chris, Meyer& Don A., Hudson, 2009). The WSS and blood flow patterns in four artery models, where the size of existing artery is smaller than vein graft was numerically analyzed. The simulation works were done by CFD code Fluent ANSYS Inc. application. They found ring vortices happened in the invigilation model. For the fish-mouth model also demonstrated more ring vortices effects compare to the invigilation model. The vein graft demonstrated the complex vertices, spiral, and counter-rotating were dispelled in the oblique region. Least flow separation was found in the first wedge model, with the high flow became centralized but low flow rate value. The distribution impacts of WSS were similar for all models. In the end of their work, they concluded that shortening the length of wedge or increasing the vein diameter to 3.0 mm led to separation in blood flow pattern.

Tzu-Ching Shih, *et al*. (2011) also applied the CFD method in his research for calculating the velocity of Red Blood Cells (RBCs) in six cases microvessels of finger nail-fold (Tzu-Ching Shih, Geoffrey Zhang, Chih-Chieh Wu, Hung-Da Hsiao, Tsung-Hsin Wu, Kang-Ping Lin, Tzung-Chi Huang, 2011). The 3-D model was reconstructed by capturing the 2-D microvessel images and the capillary was assumed as a circular cross section. A non-slip boundary condition was set as their research assumption. An Optical Flow Estimation (OFE) method was applied in order to calculate a flow velocity of Red Blood Cells (RBCs) into each microvessel. The results of simulated CFD and calculation of OFE were observed and compared to each others. They found that the CFD method can provide accurate result of RBCs velocity and can be considered as one of acceptable method.

Research Methodology:

Image Capturing

The dimensions of blood vessel were captured by using 18L6 HD Transducer and Siemens S2000 Ultrasound device as shown in Fig. 1 (a) and (b). Scanning procedure was conducted by Dr Ahmad Helmy Abdul Karim from Radiology Department, Hospital of Universiti Sains Malaysia.

Fig. 1: Captured Image of internal diameter (wall to wall) of recipient artery and SV for (a) Case A and (b) Case B

The Dynamics of Bloodflow:

The simulation works were done by applying the two different internal diameters of recipient arteries that attached with two different internal diameters of harvested vein graft models. The ratio of mismatched attachments are 1:1.1 (as Case A) and 1:1.3 (as Case B), where is large size of internal diameter of recipients were attached to small size of internal diameter RSVGs. The length of RSVG models were set as constant. The 3-D Navier-Stokes equation is applied in the every 3-D vein graft models. The energy and heat equation were ignored in vein graft models since our study only concerns on blood flow patterns.

The blood flow models have been set as the 3-D flow through a rigid wall (vein graft) and the governing equations, the incompressible,(ρ=constant), Navier-Stokes equations (1) to (3) are expressed as:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)+\frac{\partial p}{\partial x}=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x \quad (1)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)+\frac{\partial p}{\partial y}=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y \quad (2)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)+\frac{\partial p}{\partial z}=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z \quad (3)$$

Where ρ= density of blood, μ= viscosity of blood, t=time. The u, v and w, denote for velocity components of blood in x, y and z axis (direction) respectively.

The Navier-Stokes equations were carried out by every node of 3-D mesh of vein graft models. The effect of gravitational forces were also ignored in this simulation works since the length of the models are too short.

The Properties of Vein Graft Models:

The properties of blood flow was assumed as incompressible fluid, non-slip flow, Newtonian fluid with viscosity, μ, is 0.0035 kg/m-s and 1050 kg/m3 for the flow density (ρ).The vessel wall was also assumed as rigid body. Form the calculation, the blood flow was found as a laminar blood flow. The simulation works were done in steady state laminar blood flow since as stated before, t=0s.

The Boundary Conditions in Vein Graft Modeling:

The proximal of vein graft models were set as 12.5cm/s for the velocity and velocity-inlet as a zone. The zone at the distal of vein graft models were set as pressure-outlet (Fig. 2). For the wall of the vein graft models were set as wall zone.

Descriptions of Vein Graft Models:

The construction of RSVG models were designed by applying the drawing software known as GAMBIT as shown in Figure 2 (mismatched RSVG). The dimension details of RSVG model (well matched and mismatched) are shown in Table 1:\

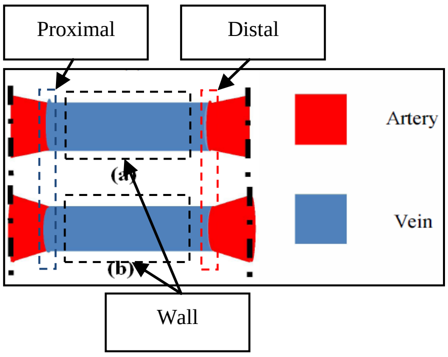


Fig. 2: Schematic Figure Of RSVG Model (a) Case A; (b) Case B

Table 1: The Table Of Dimension Of RSVG Model

RSVG Model	Internal Diameter of Recipient Artery (cm)	Internal Diameter of RSVG (cm)	Length of RSVG (cm)
Case A	0.11	0.10	10
Ideal Straight of Case A	0.11	0.11	10
Case B	0.09	0.07	10
Idea Straight of Case B	0.09	0.09	10

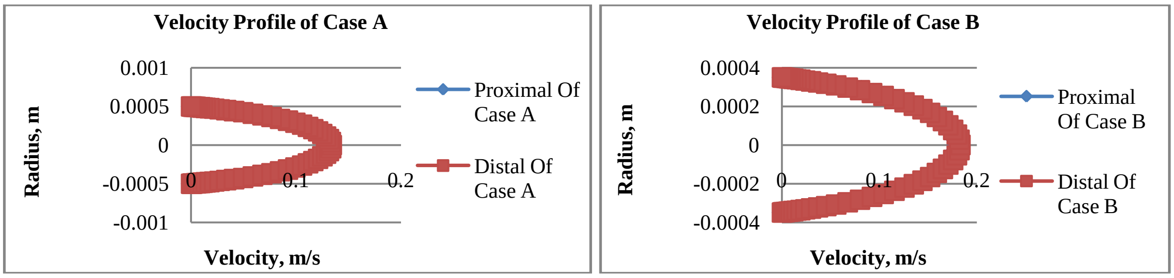
Application of CFD Numerical Software:

In this study, the CFD code name Fluent ANSYS Inc. was also applied. The governing equations (1) to (3) including conservation and linear momentum were solved rapidly since Fluent ANSYS Inc. provides the numerical solution algorithm. Several iterations and looping in solutions happened before achieving the convergence even thought the equations are linear, steady and not complex. A Least Square Cell Based for linear equation solver and discretization method solved the resultant algebraic equations for dependent variables in each control volume (CV) by applying this approach. The convergence in calculating of all blood flow through RSVG models were achieved after repetition of the governing equations calculations on a HP Workstation product named Z600.

RESULT AND DISCUSSION

Blood Flow Velocity Profile:

Observation on blood flow behaviors in RSVG Models were done after calculations were converged. The proximal and distal of RSVG Models for were chosen for observation in blood flow velocity profile. Comparisons have been made between blood flow velocity profile in well matched and mismatched RSVG Models (Fig. 3).



(a) (b)

Fig. 3: Figure of Velocity Profile (a) Case A; (b) Case RSVG Model

Table 2: The Table Of Increment Percentage In Centre Velocity (a) Case A (b) Case B

RSVG Model	Centre Velocity, v_o (m/s)		Increment %
	Proximal	Distal	6.480% (Proximal)
Ideal Straight of Case A	0.1250	0.1250	
Case A	0.1331	0.1342	7.360% (Distal)

(a)

RSVG Model	Centre Velocity, v_o (m/s)		Increment %
	Proximal	Distal	43.84% (Proximal)
Ideal Straight of Case B	0.1250	0.1250	
Case B	0.1798	0.1832	46.56% (Distal)

(b)

The velocity profile at proximal and distal in mismatched RSVG models (Case A & Case B) demonstrated higher velocity of blood flow compare to well matched RSVG model (Table 2). It happens due to decreasing in flow area in RSVG that leads increasing in velocity of blood flow.

Gradient of Blood Pressure:

Observation on gradient of blood pressure also has consideration in this study since it relates to RSVG lifespan. The proximal and distal of RSVG models were also chosen for this observation same as blood flow velocity profile. The results of gradient of blood pressure in Case A and Case B were shown in Fig. 4.

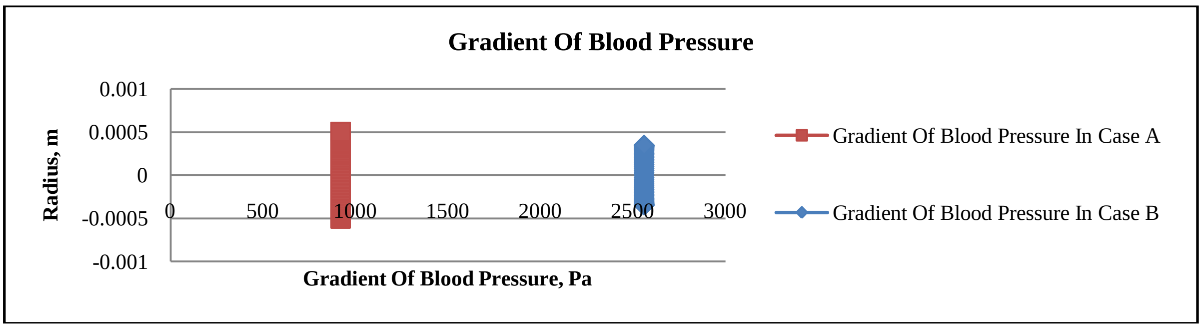


Fig. 4: Figure of Gradient Of Blood Pressure In Case A and Case B

Table 3: The Table of Gradient of Blood Pressure in (a) Case A (b) Case B

RSVG Model	Pressure Gradient, ΔP (Pa)	Increment %
Ideal Straight of Case A	578.5	37%
Case A	919.3	

(a)

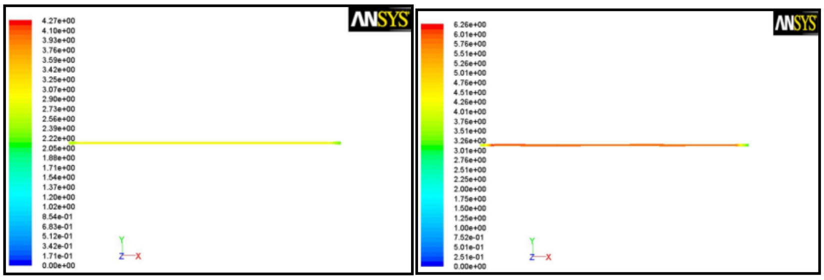
RSVG Model	Pressure Gradient, ΔP (Pa)	Increment %
Ideal Straight of Case B	846.2	202.5%
Case B	2560	

(b)

The Case B demonstrated high pressure gradient compare to Case A (Table 3). It also happened due to different area in RSVG and recipient artery (Wilmer W Nichols, Micheal F O'rourke, Craig Hartley, 1998. McDonald'sFlow in Arteries: Theoretical, experimental and clinical principles 4thEdition,1998).Modification in RSVG pressure gradient also can be related to RSVG lifespan (Christopher L. Skelly, Shari L. Meyerson, Micheal A. Curi, FrancisLoth, and Lewis B. Schwartz, 2001).

WSS Observation:

Our observations were proceeding on WSS impact on RSVG models. Fig. 5 shows that the Case B also demostrated the highest value compare to Case A (Table 4).



(a) (b)

Fig. 5: Figure Of WSS Observation In (a) Case A and (b) Case B

Table 4: The Table Of WSS Observation In Case A and Case B

RSVG Model	WSS (Pa)
Case A	4.27
Case B	6.26

Some researcher suggests that high impact of WSS may start the initiation of formation of thrombosis because of releasing the Endothelium-Derived Relaxing Factor (EDRF). It could reduce the RSVG lifespan by releasing from the WSS. However, the relationship between this mechanism has not been confirmed yet (Wilmer W Nichols, Micheal F O'rourke, Craig Hartley, 1998).

Summary:

As expected, the steady state laminar blood flow demonstrates abnormal flow pattern in mismatched internal RSVG models compared to an ideal straight RSVG models (well matched). The simulated models of mismatched internal RSVG have high possibility in formation of thrombus since reduction in vein graft area sizes have produced high value in velocity of blood flow, pressure gradient and WSS compare to simulated models of ideal straight RSVG. In the future the well matched size of RSVG is suggested for recipient artery to avoid any failure in revascularization procedure.

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