Computational Analysis on Upper Extremity Vein Graft: Simulation on Kinked Vein Graft

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Abstract

An artery reconstruction in upper extremities is rare performed compared to the artery reconstruction in lower extremities. Primary vascular repair was performed in many cases. As to alleviate vascular occlusion, an interposition vein graft or venous bypass grafting were applied. However, one or more the internal diameters of applied vein graft are blocked or severely narrowed due to the kinking failure on saphenous vein graft. The objective of this study is to investigate the blood flow influence on vein graft with kinking failure. The 3-D computational fluid dynamic method was employed to determine velocity, pressure gradient, resistance of blood flow and wall shear stress on the kinked vein graft. We expect that velocity, pressure gradient, resistance of blood flow and wall shear stress on kinked vein graft to behave non-hydraulically compared to an ideal straight graft. Furthermore, a longitudinal impedance modulus (ZL) is expected to be insufficient due to kinking failure on vein graft.

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Keywords: computational fluid dynamic; numerical method; thrombosis; vein graft; kinking failure

Nomenclature

| Symbol | Description |
|--------|-------------|
| t      | time (s)    |
| u      | velocity component in x direction (m/s) |
| v      | velocity component in y direction (m/s) |
| w      | velocity component in z direction (m/s) |

Greek symbols

| Symbol | Description |
|--------|-------------|
| ρ      | density (kg/m³) |
| μ      | viscosity (kg/(m·s)) |

Subscripts

| Subscript | Description |
|-----------|-------------|
| x,y,z     | axial direction |

1. Introduction

First successful application of blood vessel repair performed by Carrel and Guthire in 1906[1]. Patient who suffered atherosclerosis in upper extremities, the artery reconstructive in upper extremities are choices as reported by Shalabi et al. [2]. The venous bypass grafting or interposition vein graft are applied to patient who suffered with atherosclerosis [3]. The
artery reconstruction in upper extremities is rarely performed compared to the artery reconstruction in lower extremities [4]. In the operative technique, the thrombosed ulnar artery segment is excised, and the saphenous vein graft is harvest and subsequently reversed [3]. The veins are available both on the volar aspect of the forearm and on the dorsum of the foot [5]. The saphenous vein have been proposed as an ideal vein for grafting [6-8] because it reduces operation time, having advantage in lesser number of proximal anastomoses that improved the hemodynamic result [6-8]. The interpositional vein graft should have approximately the same diameter and the same length as the vessel to be repaired [5]. The proximal radius of ulnar arteries have been measured as between 0.203e-2 and 0.215e-2, and the distal radius of ulnar arteries are between 0.215e-2m and 0.184e-2m [9]. The measured length of ulnar arteries are 0.067m and 0.171m [9]. Unfortunately, despite the initial success performed by surgeon, the lifespan of graft is still unpredictable, and there are still many vein graft failure cases that have been reported [3, 5]. Furthermore, it is depending on surgeon skill and technique to ensure clean and matching vein graft stitching [5, 10]. Based on paper review, a mismatched diameter of end-to-end vein graft and a kinked of vein cause the vein graft failure [5, 10]. The kinked of vein are strong related to the over-length of vein [5]. In this study, the three dimensional Computational Fluid Dynamic (CFD) was applied to determine the velocity, pressure gradient, resistance of blood flow and wall shear stress on the kinked vein graft segment in order to study survival rate and to ensure the prolonging of the vein graft lifespan [6, 8, 10, 11]. We proposed the inherent curvature vein graft model with the variable amplitude since the kinked vein graft failures occurred in different amplitude. For flow and wall shear stress observation on the kinked vein graft model, we proposed the straight vein graft model as an ideal vein graft for comparison with the kinked vein graft model since any fluid flows in straight tube provided very accurate fluidic properties.

2. Related research

The three dimension computational fluid dynamic (CFD) approach were applied to calculate velocity, pressure gradient, resistance of blood flow and wall shear stress consist of the searching of flow patterns in a given sinusoidal geometry and applying the boundary conditions for flow variables. The computational fluid dynamic techniques were used previously to investigate the hemodynamic factors such as deformation erythrocytes (i.e., red blood cells, RBCs) [12-14], blood viscosity [15,17], wall shear stress [17,18], and blood velocity [15,16,19,20] in the complex three-dimensional blood microvessels. Those studies demonstrated that the computational fluid dynamic approach can provide not only the motion information of blood flow flowing in the microvessels.

3. Methodology

3.1 Geometry description

The dimension of the conduits, namely the saphenous vein graft was obtained from [5, 21-22]. The three-dimensional geometry of the saphenous vein graph model (Fig. 1) was constructed using the commercial fluid dynamic software GAMBIT. The graft length and diameter is provided in Table 1:

| Graft segment | Amplitude, cm | Proximal and Distal Diameter, cm | Length, cm |
|---------------|---------------|---------------------------------|------------|
| Case 1        | 0             | 0.5                             | 10         |
| Case 2        | 0.05          | 0.5                             | 10.01      |
| Case 3        | 0.15          | 0.5                             | 10.10      |
| Case 4        | 0.25          | 0.5                             | 10.26      |

Fig 1. Geometry of the kinked vein graft model (a) case 1; (b) case 2; (c) case 3; (d) case 4.
3.2 Model properties and flow conditions

The blood was assumed to be an incompressible fluid, Newtonian fluid with a dynamic viscosity (μ) of 0.0035 kg/m-s and the density (ρ) of blood was taken to be 1050 kg/m3 [19, 21]. The kinked vein graft wall was taken to be rigid [19, 21, 23], the non-slip conditions [19, 21, 23] were applied at the kinked vein graft walls, the flow was laminar [22, 23] and a time steady stated velocity profile was used at inlet.

3.3 Governing equations

The blood flow in the kinked vein graft model was modeled by employing the incompressible Navier–Stokes equations as follows:

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

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

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

where \( t \) is time, \( \rho \) is the density, \( p \) is the pressure, \( \mu \) is the blood viscosity. The blood velocity components in \( x \), \( y \) and \( z \) directions are denoted as \( u \), \( v \) and \( w \). The components of gravity effect in these directions are denoted by \( g_x \), \( g_y \), and \( g_z \), respectively. Each node of three dimensional meshing implemented the above differential equations. In this study, the gravity effect was also ignored [19].

3.4 Boundary conditions

The inlet boundary conditions to the model were 8.5 cm/s [6, 10, 24] as a velocity and velocity-inlet as a zone and the zone for the outlet boundary conditions to the model was pressure-outlet. For the wall boundary conditions was set as wall zone, while the specify continuum type for the whole of kinked vein graft models [6, 10].

3.5 Computational Fluid Dynamic Software

The computational fluid dynamics simulations software FLUENT V13 was applied [6, 10, 23]. In the numerical solution as given by Fluent, the governing equation (1), (2) and (3) (linear momentum and conservation of mass) were solved rapidly. Although the equations are steady and simple, several iteration of the solution loops were needed before a solution result was fully converged. By applying this approach, the resultant algebraic equations for the dependent variables (the flow velocities) in each control volume were solved by a Least Squares Cell Based for linear equation solver and discretizations method. The calculation was carried out by setting the convergence criteria as \( 10^{-5} \). The governing equations were calculated rapidly until calculations of all flow variables were converged on a HP workstation Z600 desktop (Intel Xeon, 4 GB RAM). The number of iterations was set as 300.

4. Result and discussion

4.1 Velocity observation

We observed the blood flow characteristic in the kinked vein graft models after iteration of calculation was converged. For the blood flow velocity observation, we chose the computed velocity contours at every cross section of amplitude segment in vein graft (as the result monitors). From the flow simulation, velocity contours are shown in different regions, as shown in Fig. 2.
Fig. 2 Cross section of velocity contours at the kinked vein graft model (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) legend of velocity contours, m/s

Every vein graft model has been extruded about 2 cm before the inlet of vein graft model for an entrance length as uniform velocity needs some length to archive fully developed blood flow velocity. From our observation, case 1 showed us that 8.5 cm/s as the maximum velocity and achieve the maximum velocity compared to the other cases of vein graft model were not archived the maximum velocity.

4.2 Wall shear stress observation

We also observed the wall shear stress in the kinked vein graft models. For the wall shear stress observation, we chose the wall shear stress contours at the whole wall on vein graft (as the result monitors). From the flow simulation, wall shear stress contours are shown in different regions, as shown in Fig. 3. From our observation, case 1 showed us that 0.26 Pa as the wall shear stress for the whole vein graft model. For the other cases model, the results of wall shear stress are over than 0.26 Pa especially at the kinked segment. The highest wall shear stress was shown on the kinked segment of case 4 as the amplitude kinked for case 4 was higher compare to the other cases.
Fig. 3 Cross section of wall shear stress contours at the kinked vein graft model (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) Wall shear stress, Pa

5. Summary

The computed results have revealed that the kinked vein graft model behave non-hydraulically like an ideal straight graft model. We decided to do a steady state simulation in order for experiment validation as to achieve grid independent in geometry meshing. In the future, we will propose to investigate blood flow on an ideal vein graft model with pulsating flow function as to remodeling closely like the real condition of saphenous vein graft. After that, comparison in longitudinal impedance between simulation result and clinical result will be studied, perhaps due to local environment of saphenous vein graft. The long-term survivals of vein grafts are strongly depend on the size and quality of the venous conduit respectively. As stated before, wall shear stress on vein graft has a predictive value for vein graft survival. However, other variable problem variable, such as pressure gradient, flow rates and resistances, carry less predictive value for vein graft long-term survival.

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