Computational Fluid Dynamic Study of Blockage in Artery With and Without Bypass

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Abstract: In complex vessel geometry different temporal, spatial variation takes place which occur under pulsatile conditions. The high Wall Shear Stress (WSS) at the wall affected by the disturbed flow may ultimately lead to endothelial cell dysfunction, which leads to atherogenesis and thrombosis. The present study observes WSS and streamlines due to stenosis with and without Bypass Artery. It was found that by adding bypass Artery there is tremendous decrease in wall shear stress in the stenosis. Reverse flow of blood through stenosis was observed in 30 Bypass Models. Hence the blood flow stabilizes and can be reached at optimum level in 50% stenosed artery. Based on this paper findings, it can be deduced that there would be a low risk of further atherosclerosis when the bypass artery is added.

1. Introduction

Heart diseases are a fatal factor when weighed against an average human's life expectancy. Sudden deaths, mostly, happen due to these heart diseases. For the incident of heart failure, sudden heart death is one of the major causes, which could occur for a number of reasons. "Aging" is statistically one of the highest contributors for a sudden heart death, categorized under the reasons of "natural death". In an experiment performed on an age group ranging from 45 to 65, men had a 7 times higher chance of dying due to sudden heart death as compared to women. Engineering sciences has intertwined with the "medicine" branch which has created a catacomb of opportunities in medical problem solving and diagnosis. There are many cardiovascular diseases which affects people and atherosclerosis is the most common form of cardiovascular disease. Atherosclerosis causes several deaths per year. Blood movement decides the progression and initiation of such cardiovascular disease and decide the behavior of the Wall of the vessel. According to major Medical Services, about 80% of the mortality is caused due to cardiovascular system it is mostly caused due to any increment in the blood resistance which causes the loss of blood flow in the concerned vascular bed.

Bypass Method in coronary artery goes by another name coronary artery bypass graft. Fundamentally, an artery is abstracted from a different part of the patient body as a graft. This created graft is known to divert blood from around the narrowed components of the specific artery. The techniques used in the process are considered consequential [1]. The categorization is done twofold: firstly, individual technique and secondly, sequential technique. The individual technique thoroughly depends on the number of arteries that were blocked and henceforth utilizes the same number of graphs. Here, in this technique the surgeon is supposed to connect each and every graft in an end to side manner of the arteries' vessel. On the contrary sequential technique requires only one graft which is connected to a whole narrowed down artery by a side-to-side cessation and/or a culminate to side cessation. This graft and technique is to be operated from experience. The hemodynamic as well as the flow pattern of the graft is linked to its patency rate and therefore, it is consequential. The reason behind it is that after
the bypass surgery, the newly created bypass graft gets directly or indirectly sabotaged at the distal anastomosis [2]. Therefore, the key points that this project is set to illuminate is to utilize CFD or computational fluid dynamics techniques to curate a simulation of the blood flow in a constructed coronary artery and henceforth, analyzing the actual flow in the CABG (Coronary Artery Bypass Graft).

2. Literature Review

Several research papers were studied, it’s been found that crucial blockage in blood vessels and showed that when 70 % blockage within the vessel section, there’ll be respectable decrease in blood flow of vessels [3]. Few studies also centered their models on varying graft angles $45^\circ, 75^\circ, 60^\circ$ with 70% stenosis [4]. Jae-Sung et al. have concluded that the best model of Bypass artery will be when diameter of artery is equivalent to diameter of Bypass [5]. P. Halder et. al carried out comparative analysis of non-Newtonian and Newtonian blood flow in 50 % stenosis by using Carreau-Yasuda Model and focused on velocity fields, Wall Shear Stress and found high WSS near stenosis, comparatively more deflation of velocity profile near stenosis in Non-Newtonian that Newtonian fluid [6]. Some researchers also focused on calculation Wall Shear Stress (WSS) and flow separation zone of 3 dimensional stenosed tube with different severity and found that the oscillation of WSS is depends upon severity of stenosis and axial position of pipe [7]. Some researchers also attempted on studying the CABG by using Computational Fluid Dynamics (CFD), attempted to explain flow behaviour in eccentric and concentric stenosed model for various graft angles [8]. Blood flow was resolved in the coronary arteries with successive blockages in which three consecutive sinusoidal blockages were taken in two different concentrations of 84% and 70% and solid vessels [9]. It was found that an increase in shear pressure and a decrease in normal pressure became severe by increasing the blocking rate. These changes are most severe when the flow of blood is at its highest level. Investigations show that there is no direct vertical flow after the blockage due to Reynolds’ low number [9]. By taking non-Newtonian blood structures, Tu and Deville mimic blood stenosis using Herschel-Bulkley, Bingham and the law of force in a solid circular tube with a partial closure [10]. They have admitted that the disturbance is strong with vorticity and continuous behind the geometric barrier especially for severe stenosis. In an experiment Tang et al measured off-line stress relationships and expressed that the distribution of pressure has a very high pattern and both the intensity and intensity of compression occur within the stenotic phase [11]. T. Shaw et al investigated the flow of Casson fluid through a frozen bifurcated artery and found that in both the female and coronary arteries the differences in axial velocity and the rate of flow of yield pressure were the same [12].

Very few works are reported in literature for a stenosed artery with bypass using sinusoidal inlet profile. In this study we have simulated the blood flow from 50% stenosis to study the effects of Bypass at different Graft Angles and compare the results of 50% stenosis without Bypass.

3. Methodology

Symmetrically stenosed artery was taken for numerical simulation. In (r, z) coordinate system the profile of stenosis can be represented mathematically as given in [13]:

$$r = r_0 \left(1 - \frac{\delta}{z_0} \left(1 + \cos \frac{2\pi z}{z_0}\right)\right)$$

$$-z_0 \leq z \leq z_0$$

$r = \text{artery radius with the function of } z \text{ in the stenosis region, } L = \text{length of the artery and } r_0 = \text{radius of the artery. In this case, } \delta = 0.5 \text{ represents the 50% severity of stenosis } \& z_0 = 1.0 \text{ as given in [13].}$
Fig. 2(a) and 2(b) represents Schematic diagram and mesh structure of 50% stenosis and Grid distribution. The 2D CAD model was setup in Solidworks and exported in igs format to ANSYS for meshing.

The Outlet’s Static Pressure was kept at 13332 Pa. The governing equations of continuity and momentum for the model can be represented as:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{2}
\]

\[
\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = -\nabla p + \nabla \tau \tag{3}
\]

Where stress tensor, \( \tau \), and strain rate are related by:

\[
\tau = \mu (\nabla \mathbf{U} + (\nabla \mathbf{U})^T) - \frac{2}{3} \delta \nabla \mathbf{U} \tag{4}
\]

Above equation were solved for a Non-Newtonian fluid, for unsteady laminar flow yields the primitive variables: pressure, \( \rho \): density, \( \mathbf{U} \): velocity. \( t \) denotes time here.

For the artery wall, the condition of no slip boundary was applied and at the inlet boundary, time dependent velocity was imposed. The outlet, whereas, had an assigned condition of an opening type of boundary with pressure outlet. For Inlet, a sinusoidal velocity profile is being used. The velocity variation is given in Fig. 1. The simple pulsatile can be given as:

\[
\mathbf{U}(t) = 1 + \sin \left(\frac{2\pi t}{T}\right) \tag{5}
\]

\( \mathbf{U} \): velocity, \( T \): Time Period. \( t \) denotes time here.

![Fig. 1. Sinusoidal unsteady inlet velocity used in Model computation.](image)

![Fig 2.](image)

**Fig 2.** (a) Schematic diagram artery with 50% stenosis, here \( r \): radial direction, \( D \): Diameter, \( L \): length of artery; and (b) Grid distribution

Bypass was added in this same artery model [modal without bypass as shown in Fig 2(a) and its grid in 2(b)] at different Graft Angle (A) and graft diameter \( d \) as shown in Fig. 3(a). Grid distribution
for bypass is shown in Fig 3 (b). All boundary conditions were same as model without bypass model. Table 1 gives the details of different modal of artery with bypass.

![Fig. 3](a) Schematic diagram of Artery with By-pass (b) Grid distribution

| No. of Models | Graft Angle (A) | D (mm) | d (mm) |
|---------------|----------------|--------|--------|
| 1             | 30             | 2      | 2      |
| 2             | 45             | 2      | 2      |
| 3             | 60             | 2      | 2      |
| 4             | 75             | 2      | 2      |

Table 1: Model Dimension of the bypass Graft

The ANSYS Mesh used to build the mesh for the proper analysis. No. of nodes and elements are increased gradually from 71325 to 446481 and 91217 to 446481 respectively for independence of Grid (Fig. 4). For the alteration of the mesh nodes from 157450 to 446481, the result displayed a not so exceptional difference in the velocity profiles. A grid with anywhere about 200000 elements is ought to be the optimal grid for such usage (Fig. 4).

![Fig 4](image)

Fig 4. Velocity variation in radial direction at location z = 0

Dynamic viscosity for the Non-Newtonian fluids was implemented using the Carreau-Yasuda model as

$$
\mu = \mu_\infty + \frac{(\mu_a - \mu_\infty)}{(1 + (\lambda \gamma)^n)^{\frac{1}{n}}} 
$$

(6)

Table 2: Values used in Carreau-Yasuda Model for mimicking blood

| Variables                  | Value       |
|----------------------------|-------------|
| low shear viscosity, $\mu_0$ | 0.056 Pa.s  |
| high shear viscosity, $\mu_\infty$ | 0.00345 Pa.s |
| Time Constant, $\lambda$    | 3.3313 s    |
| Power Law Index, $n$        | 0.3568      |
| Yasuda Exponent, $a$        | 2           |
| Flow Shear Rate, $\gamma$  | $\geq 0$    |
Different variables and constant values of Carreau-Yasuda model is given in Table 2. This fluid viscosity caused by a low shear thinning mimics well blood flow model [14-15].

4. Results and Discussion
The validation is of Numerical model without Bypass has been done by comparing the velocity profile of once reported in literature by P. Halder et al [6]. The present model velocity profile is in good agreement with literature.

The fully developed steady state of flow through proper simulations and the results were compared with non-Newtonian fluid with previous founding in literature Fig. 5 shows velocity profile at Re = 200 and Fig. 6 streamline distribution of the artery after one cycle of pulsatile flow at Re=350. The Non-Newtonian blood flow gives a deflated velocity profile with negative velocity near the wall.

![Fig. 5. For validation, velocity profile at Z = 0.001. at Re = 200](image)

![Fig 6. velocity streamlines of complete cycle in 50 percent stenosed artery with and without bypass at Re=350](image)
Fig. 6 shows some of the instances of blood flow for complete one cycle in an artery with and without bypass. At $t = 0.05$ s 7 vortexes are observed near the walls, by observing fig 6 from $t= 0.5$ to $t=7$ sec there is an increase in whirling motion of blood and all vortex have merged to form bigger vortex. At $t=7$ sec it is observed that vortex was formed even before stenosis and blood flow is highly unstable. Finally, at $t=0.75$ s there is a uniform blood flow with no whirling motion but then again at $t=8$ it is observed that vortexes are generated near walls and it keeps on increasing till $t=1$ sec and this cycle keeps on happening. After flow of one cycle, 9 vortexes generated near the walls, whirling motion of blood is witnessed which is not a stable flow in an artery.

![Image](a)

![Image](b)

![Image](c)

![Image](d)

**Fig. 7.** (a)30° Graft Angle of by-pass artery 50% stenosis (b)45° Graft Angle of by-pass artery 50% stenosis (c)60° Graft Angle of by-pass artery 50% stenosis (d)75° Graft Angle of by-pass artery 50% stenosis, at Re= 350, at t=0.75 sec

Fig. 7 shows streamline distribution of all models of bypass artery at $t = 0.75$ sec. At this time step it has been observed that at 30° Graft Angle there is a clockwise flow of blood through stenosed artery and by-pass, but at Graft Angle 45°, 60°, 75° blood flows in anti-clockwise direction in the same time step (t=0.75).

| Graft Angle | WSS at Stenosis |
|-------------|-----------------|
| Upper Wall  | Lower Wall      |
| 1: without By-pass | 237.4959825 | 229.4830533 |
| 2: 30°     | 82.31438772    | 76.60927164 |
| 3: 45°     | 90.73629973    | 85.08632808 |
| 4: 60°     | 99.42359236    | 94.00288312 |
| 5: 75°     | 102.523754     | 97.2067871  |

| Table 4: Maximum WSS of bypass Artery |
|--------------------------------------|
| WSS | Upper wall |
|-----|------------|
| 1: 30° | 145.6877 |
| 2: 45° | 225.7709 |
| 3: 60° | 141.5199 |
| 4: 75° | 108.5532 |
As it can be observed at table 3 that by applying bypass WSS is reduced at stenosis (0,0) tremendously. But it has also been found that as Graft angle increases WSS also increases by some value. As shown in table 4, Model 3 (Graft angle = 45°) has maximum Wall Shear Stress at Upper wall as compared to other bypass.

5. Conclusion and future work
The present work of numerical modelling of sinusoidal blood flows through constricted stenosed artery with and without Bypass to understand hemodynamics. The models were studied for non - Newtonian fluid flows with Carreau-Yasuda Model. Conclusions that are drawn based on our research:

- Clockwise blood flow in Artery with bypass (30° Graft Angle) was observed, hence there is a reverse flow of blood in stenosed Artery at t=0.75 sec
- Formation of vortexes before stenosis was observed at t= 0.65 sec in Artery model 1 which is without Bypass.
- WSS can be reduced tremendously by adding bypass.
- Maximum Wall Shear Stress was observed at upper wall with Bypass Artery of Graft Angle 45°. So, it is not feasible to use Bypass with Graft Angle 45°.
- In future it is proposed to perform simulation with different degree of stenosis and to see their effect with bypass graft.

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