A Numerical Study of Stent Expansion

Joopmon Bamrungwong  
Department of Industrial Physics and Medical Instrumentation, Faculty of Applied Science  
King Mongkut’s University of Technology North Bangkok  
Bangkok, Thailand  
joopmpondej@gmail.com

Nakarin Sangphor  
Department of Industrial Physics and Medical Instrumentation, Faculty of Applied Science  
King Mongkut’s University of Technology North Bangkok  
Bangkok, Thailand  
nakarin.gram@gmail.com

Weerasak Ussawawongaraya  
Department of Industrial Physics and Medical Instrumentation, Faculty of Applied Science  
King Mongkut’s University of Technology North Bangkok  
Bangkok, Thailand  
weerasak.u@sci.kmutnb.ac.th

Abstract— Coronary Artery Disease (CAD) is mostly caused by the accumulation of fat and tissue in the artery walls and the obstruction of blood flow within the blood vessels. The narrowing of blood vessels results in symptoms of heart muscle weakness because there is not enough blood to feed. There are three methods of treatment for coronary artery disease including drug therapy, balloon dilation, and stenting (Percutaneous Transluminal Coronary Angioplasty (PTCA), and Coronary Artery Bypass Grafting (CABG) surgery). Several previous research studies found that the stent model created is based on the types of stents used in medicine. The aims of this paper are to conduct a simulation study of the interaction between the stent and the plaque attached to the blood vessels. The 3D model is created by SolidWorks and transferred to Ansys to perform structural analysis, and then the model is transferred to CFX to study the flow over the stent in the blood vessel using the Carreau fluid model. As for structure analysis, it was found that the results achieved using linear simulation and nonlinear simulation were not different. In the stent structure simulation, while the stent expanded over plastic deformation, the maximum stress was on the apex in both the linear and nonlinear studies. Obviously, the nonlinear simulation takes a lot of time to obtain the result when compared to the linear model simulation. The simulation result found that blood flow in the expanded stent is characterized as a loop that necks around struts; this might lead to stent vibration and harm to the blood vessels due to the loop of pressure along the stent length.

Keywords— Coronary Stent, Finite Element, Percutaneous Transluminal Coronary Angioplasty (PTCA)

I. INTRODUCTION

Coronary heart disease, also called coronary artery disease, is caused by the accumulation of plaque that sticks to the walls of the coronary arteries. As a result, the size of the inside of the blood vessels is smaller, leading to a reduction in the flow of blood to the heart. The amount of blood flowing through the blood vessels is smaller compared to the flow through normal blood vessels [1]. This causes coronary artery disease and myocardial ischemia in severe cases if there is a large accumulation of sludge and grease. This results in a blockage that eventually leads to heart failure. Coronary artery disease can be treated in three different ways by drug therapy, balloon, Percutaneous Transluminal Coronary Angioplasty (PTCA) [2], and Coronary Artery Bypass Grafting (CABG). This paper will discuss PTCA. With the new technologies, it is very popular to use a coronary stent which is a small mesh tube-shaped medical device deployed to treat narrow PTCA. In this paper, the finite element analysis (FEA) and computational fluid dynamics (CFD) simulation models were used and developed to study the engineering properties that affect specific stent functional attributes. There are not many reports about what impacts the stent by the hemodynamic behavior on the stent material. However, a number of numerical studies have considered both the mechanical and hemodynamic effects of stent implementation [3]. This study uses a 3D model FEA for the analysis of the mechanical and hemodynamic effects on a stent, comparing linear and nonlinear solutions. It is expected to help to design the stent better. The computational fluid dynamics model generated a 3D model of the blood vessels including plaque and stent to calculate the wall shear stresses and strain distribution in a stented vessel carrying blood to the heart. The 3D model is shown in Fig 1.

Fig. 1. The cross-section of a 3D model of a blood vessel with plaque and stent

In 1986, Schneider AG’s self-expanding stent was implanted into the patient’s coronary artery for the first time. At that time, the limitation of delivery equipment and the installation of stents was found in this scenario, until in 1987, Palmaz and Schatz treated a patient with coronary artery disease with the stent, which was very successful. There was no recurrence of stents in the early stages up to 87%, but there were 2.8% of stents in the later stages. At present, the technology of stents has been greatly developed. Therefore, stents in various organs have been developed and improved. For example, the duodenal stent, esophageal stent, etc. Coronary stents resemble small lattice structures with expandable properties. When they are expanded, they form a rhombus shape, forming long and small hollow tubes [4]. The outer wall of the artery is adjacent to the inner wall, supporting and expanding the narrowed blood vessels after the accumulation of large amounts of fatty plaque to treat the coronary artery enabling a return to working better. This allows the blood to flow through the blood vessels more easily. An expandable stent is performed using a Percutaneous Transmural Coronary Artery (PTCA). The method of inserting a stent to expand the coronary artery relies on the
principle of balloon expansion, in which the outer layer of the balloon has a stent. When the correct position is obtained, the doctor will enlarge the balloon. The stent is then placed in the desired position. Once the stent is installed, the doctor will reduce the size of the balloon and remove the delivery set from the patient's body. The coronary stent is inserted, in which process the patient undergoes a very short preparation time when compared to surgical treatment methods. The method of treatment is relatively safe and has a high therapeutic effect. After this treatment, the patient must take an antithrombotic drug and lifelong antiplatelet drugs. The stents can be divided into three types. First, self-expanding stents, such as wall stents. Second, a balloon-expandable stent, such as the Palmaz and Schatz stent. And last, the thermal memory stent, such as Nitinol [5].

II. MATERIALS AND METHODS

The aims of this paper are a simulation investigation of the interaction between the stent and plaque attached to the blood vessels. Blood flow information obtained from Doppler ultrasound was used as the initial condition to apply to the CFX. The 3D model of blood vessels including plaque and stent was created by SolidWorks and transferred to Ansys to perform the structural analysis. Then the model was transferred to CFX to study the blood flow over the stent in the blood vessel. The material properties for the simulation identified in Ansys are shown in Table 1. The connection between materials for blood vessels and plaque was defined as the MPC bond contact. The part of the stent and plaque is defined as frictionless contact. The surface pressure loads are applied to the stent surface representing the balloon expansion pressure leading to a pressure of 15 atm. The models are defined as linear and nonlinear to compare the results, and the interesting points were defined as key points and calculated by the snipped command in Ansys.

\[ \dot{\gamma} = \sqrt{2d_g d_s} \]  

The Carreau model is a type of generalized Newtonian fluid and is one of the most widely used mathematical models for blood. The equation is written as:

\[ \mu = \mu_0 + (\mu_\infty - \mu_0)(1 + K^2\dot{\gamma}^2)^{n-1} \]  

Where

- \( \mu_0 \) is the viscosity at zero shear rate (Pa · s) or low shear rate asymptotic values
- \( \mu_\infty \) is the viscosity at infinite shear rate (Pa · s) or high shear rate asymptotic values
- \( K \) is the relaxation time (s)
- \( n \) is the power index

All parameters are material coefficients of the Carreau fluid model. The models in Equation 3 are non-Newtonian models in CFX and the parameters \( K \) and \( n \) control the transition region [7]. At a low shear rate (\( \dot{\gamma} \ll \frac{1}{K} \)) a Carreau fluid model behaves as a Newtonian fluid with viscosity \( \mu_0 \).

At intermediate shear rates (\( \dot{\gamma} \geq \frac{1}{K} \)) a Carreau fluid behaves as a power-law fluid. At a high shear rate, which depends on the power index \( n \) and the infinite shear rate viscosity \( \mu_\infty \), a Carreau fluid model behaves as a Newtonian fluid again with viscosity.

The mathematical process in CFD (Computational Fluid Dynamics) uses Carreau’s law in the fluid domain [6]. The Carreau model is used to explain the behavior of the fluid that depends on the relationship between the deviatoric stress tensor and the strain rate tensor. In the domain with low shear rates and complex shear thinning blood, the mathematical model can be accurately written as:

\[ \tau_{ij} = 2\mu\dot{\gamma}d_j \]  

Equation 1 is a generalized Newtonian model but unlike the Newtonian model because the influence of the viscosity is not constant but it depends upon a function of the shear rate that can be written as:

TABLE I. Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (Pa)</th>
<th>Poisson’s ratio</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood Vessel</td>
<td>8.0E+06</td>
<td>0.475</td>
<td>1000</td>
</tr>
<tr>
<td>Plaque</td>
<td>2.19E+06</td>
<td>0.49</td>
<td>1000</td>
</tr>
<tr>
<td>Ni_Ti</td>
<td>5.00E+10</td>
<td>0.35</td>
<td>6500</td>
</tr>
</tbody>
</table>

TABLE II. Material properties of Carreau’s Law for CFX [6]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Blood (non-Newtonian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1059.5</td>
</tr>
<tr>
<td>Time Constant (s)</td>
<td>3.313</td>
</tr>
<tr>
<td>Power Law Index</td>
<td>0.3568</td>
</tr>
<tr>
<td>Low Shear Viscosity (kg/m.s)</td>
<td>0.056</td>
</tr>
<tr>
<td>High Shear Viscosity (kg/m.s)</td>
<td>0.00345</td>
</tr>
</tbody>
</table>

In the 1600s, Robert Hooke discovered a simple linear relationship between force (F) and displacement (u), known as Hooke’s Law. A common example is a simple spring, and a linear structure obeys this linear relationship. Linear structures are well-suited to Finite Element Analysis, which is based on linear matrix algebra. A structure is nonlinear if the loading causes significant changes in stiffness. There are three main sources of nonlinearities that are geometric nonlinearities, material nonlinearities, and contact or changing status nonlinearity. As for this paper, both geometric nonlinear and contact were used to analyze the stent and plaque with blood vessel deformation.
The 3D model of the stent is created by SolidWorks as shown in Fig 2 [8,9]. The stent crimped model is assembled with the plaque and blood vessels as shown in Fig 2(a), and it is transferred to Ansys for finite element calculation. As for the stent expansion, the model is also assembled with new plaque and blood vessels as shown in Fig 2(b), and is transferred to CFX for CFD calculation using Carreau’s model. The 3D models of assembly in the initial state for structure analysis and CFD analysis are shown in Fig 3 and Fig 4, respectively. Fig 4 shows the stent expanded and combined with blood material for studying the flow past the struts.

![Fig. 2: The 3D model of the stent: (a) crimped model state (b) expanded model state](image)

![Fig. 3: The cross-section model of assembly in the initial state for structure analysis](image)

![Fig. 4: The assembly model in the initial state for CFD analysis](image)

### III. RESULTS

The assembly model results were calculated via both linear model and nonlinear methods, and the simulation results are shown in Fig 5. The interesting point is that calculations to find out the expansion of the plaque and stent found that the linear and nonlinear simulations were not different at approximately delta 3 microns. The expansion shape was not different while the crown of the stent expansion was only very slightly different. The maximum principal stress was approximately 100 MPa. The stent structure simulation revealed that when the stent expanded over plastic deformation the maximum stress was on the apex in both the linear and nonlinear models.

![Fig. 5: The simulation results from: (a) linear model (b) nonlinear model](image)

In the part of the flow through the blood vessel it was found that the blood flow is characterized as a loop necking around the struts and expanding after flowing past the struts as shown in Fig 6.

![Fig. 6: The blood flow through the stent: (a) vector plot (b) streamline plot](image)

![Fig. 7: shows the specific vector plot of the blood flow over the strut on a specific plane](image)
The flow over the strut consensus with the streamline plot leads to necking like a loop of blood flow. The result from CFX revealed that while the blood flow through the stent expanded like the flow passing an obstacle as shown in Fig 7, the vector plot presents the flow over the strut and Fig 8 shows the flow passing over many struts with velocity and pressure on the strut.

Fig. 8. The pressure along the stent length

IV. CONCLUSION

Computational Fluid Dynamics and Finite Element Analysis simulation models were investigated and developed to evaluate the engineering properties that affect the stent functional attributes. The results from FEA are comparable to those of other researchers in considering the deformation of the stent. The coronary stent is designed to heal and dilate the narrowed blood vessels back to their original size before the narrowing. The coronary stent acts as a lattice to support the tube to prevent further narrowing. The structural analysis found that the researcher can use linear simulation instead of nonlinear techniques that consume significant simulation time. The result is not very different. The flow over the strut might lead to a vortex at the impact side shown in Fig 7 and pressure along the stent can be seen that is related to the blood flow as a loop and necking around the strut as shown in Fig 8. This might lead to stent vibration and cause harm to the blood vessel. The simulation also found that the maximum wall shear stress is on the entrance at the apex of the crown.

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REFERENCES