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Improving the Blood Flow in the Coronary Artery Using the Conical Stent

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Abstract: *The aim of this research is to study the effect and efficiency of using conical stent in the coronary artery and comparing the results with the cylindrical stent. The following factors: Oscillatory Shear Index (OSI), Time-Averaged Wall Shear Stress (TAWSS) and Wall Shear Stress Gradient (WSSG) have been considered. The traditional cylindrical stent currently used has a consistent diameter, which does not match the physiological change of the coronary artery. On the contrary, the conical stent used in this study is consistent with the physiological change of vascular diameter. However, the effect of the conical stent implantation on the coronary hemodynamics remains unclear. The coronary artery with 80% stenosis and two stent models were drawn using SolidWorks software. All models were exported to and solved using computational fluid dynamics (CFD) software.*
The results of hemodynamic indicators including oscillatory shear index OSI, Time-Averaged wall shear stress TAWSS and wall shear stress gradient WSSG were improved by either the cylindrical or the conical stent implantation. However, it was noted that after installing the conical stent the oscillatory shear index value was very low (lower than 0.008) while it was 0.5 in some areas in the cylindrical stent case. The TAWSS values in the conical stent was within the natural range 0.7-6 Pascal (Pa) while it was high in some areas in the cylindrical stent case about 60 Pa. The wall shear stress in the conical stent case becomes more uniform along the stent, without any major change in direction or value in comparing with the cylindrical stent case.

Keywords: *Blood fluid, coronary artery, OSI, TAWSS, WSSG, cylindrical stent, conical stent*

INTRODUCTION

In today's world the people are habitual of living high lifestyle where mental challenges are increasing day by day, but physical work is decreasing [1]. Coronary artery disease known as atherosclerosis occurs when excess cholesterol attaches itself to the walls of blood vessels. Embedded cholesterol also attracts cellular waste products, calcium and fibrin. This leads to a thickening of the vessel wall by complex interaction with constituents of the artery. The resulting pasty build up known as plaque can narrow or even block an artery and here appears the importance of stent in reopening the artery [1, 2]**.**

A stent is a device that is used to support arterial walls to alleviate the blockage of arteries due to plaque and maintain the artery opening to facilitate the blood flow, the stent has a major problem after the installation which is the restoration of artery stenosis during a period of surgical procedure [3, 4]. Computational fluid dynamics is a powerful and effective method for understanding the correlation between stent and blood flow in an artery [5, 6]. The traditional cylindrical stent currently used in the percutaneous coronary intervention (PCI) has a consistent diameter, which does not match the physiological change of the coronary artery [7].

In this paper, the conical stent has been studied with variable diameter along the stent. A comparison between the results of cylindrical and conical stents was done for a transient flow case which simulates a heart pulse.

THE IMPORTANCE OF THIS RESEARCH

Understanding the effect of the stent on blood flow is one of the biggest challenges as this understanding helps in reducing the rate of restenosis after surgical intervention. The importance of this research lies in studying the effectiveness of using the conical stent in the coronary artery in pursuit of a more stable model of stent that is less likely to collapse after a period of surgical intervention.

RESEARCH OBJECTIVES

This research aims to compare between the traditional stent with the conical stent for transient flow, and to reduce the restoration rate after stent installation. Also, a new and more stable model of coronary stent has been adopted.

RESEARCH METHOD

4.1. Establishment of the required models:

All the models were established by SolidWorks (solid modeling software). All dimensions to be used according to reference [7], which simulates a portion of the coronary artery. The artery consists of three sections: the entry area and the exit area and the one between them in which the narrowing occurs. The entry and exit areas are cylindrical and the connecting area between them is a cone trunk: cylinder diameter of the entry area is 4.5 mm, the diameter of the exit section cylinder is 2.5 mm, the length of the entry and exit areas are 10 mm, the length of the joining area between the entry and exit section is 25 mm.

In order to conduct the numerical study, three artery models were considered:

1. Artery with stenosis by 80% Figure.
2. Artery with a transitional cylindrical stent (stent diameter 4 mm, stent length 15 mm) **Error! Reference source not found.**
3. Artery with conical stent (inlet diameter 4 mm, outlet diameter 2.5 mm, stent length 15 mm) Figure. In both cases 2, 3 the artery was fully enlarged, and the role of stenosis neutralized.

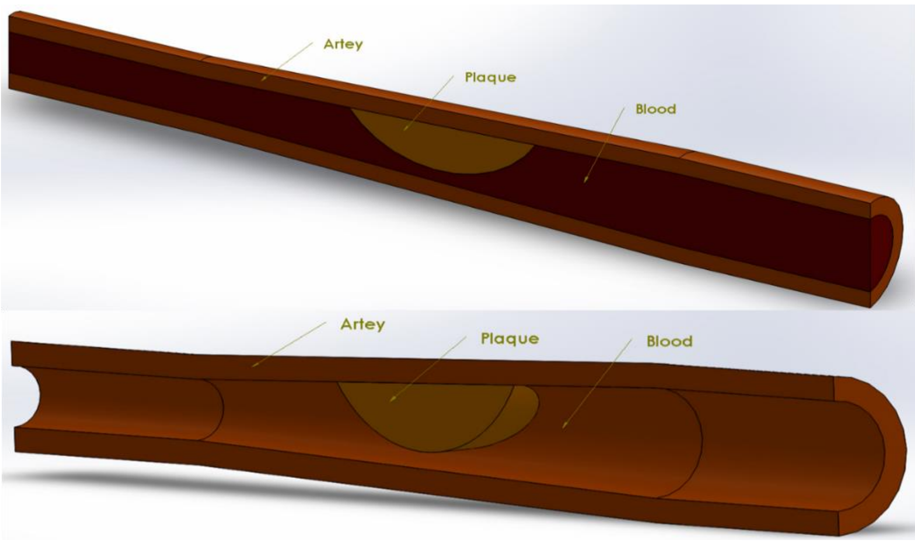

Figure.1: Geometry model for coronary artery with 80% stenosis.

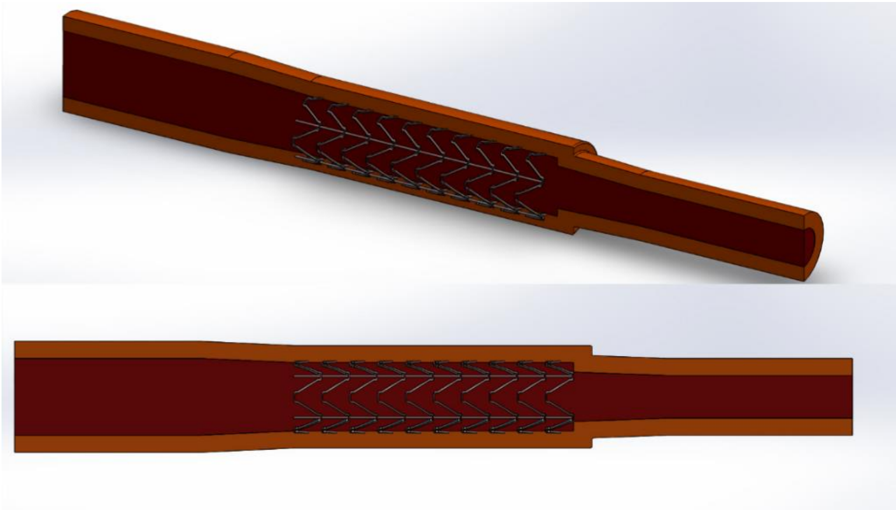

Figure.1: geometry model for coronary artery with cylindrical stent.

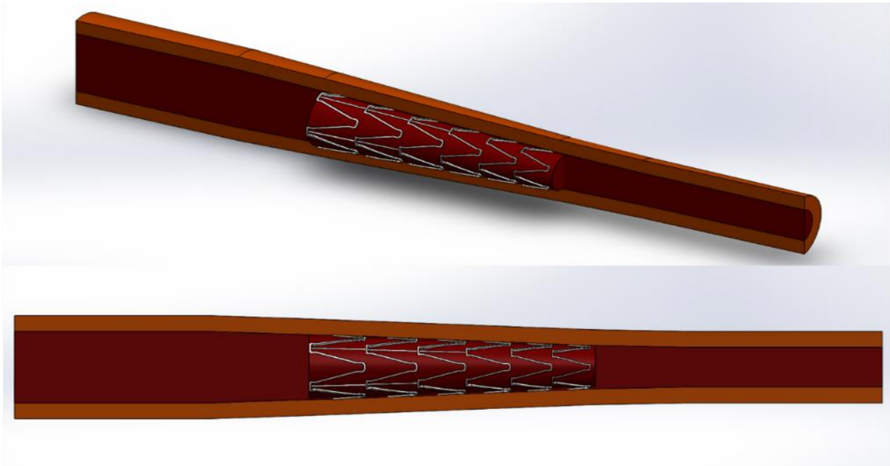

Figure.3: geometry model for coronary artery with conical stent.

4.2. Meshing:

The three vascular lumen models were imported into CFD software to divide the grid. Mixed hexahedral and tetrahedral grids were used in other parts. In order to ensure the calculation precision, the size of the grid was within 0.15 mm. The grid was partitioned as follows: model 1 (1,127,575 units); model 2 (817,555 units); model 3 (256,338 units).

3.4. Boundary Conditions:

The blood was treated as a incompressible Newtonian fluid, as it was possible to treat blood in the arteries and relatively wide blood vessels as a Newtonian fluid while it could not be treated as well in the small capillaries [7].

Solution assumptions:

- Transient flow
- Laminar flow
- Incompressible fluid

- Isotropic flow
- Newtonian flow
- Continuous flow
- No-slip condition at the wall

Blood properties: density 1060 kg/m^3, kinematic viscosity 0.004 $kg/m.s$

Boundary conditions for transient flow: The blood flow velocity profile was defined during a single heartbeat of 0.8 s as a boundary condition at the inlet according to Figure, outflow at the exit.

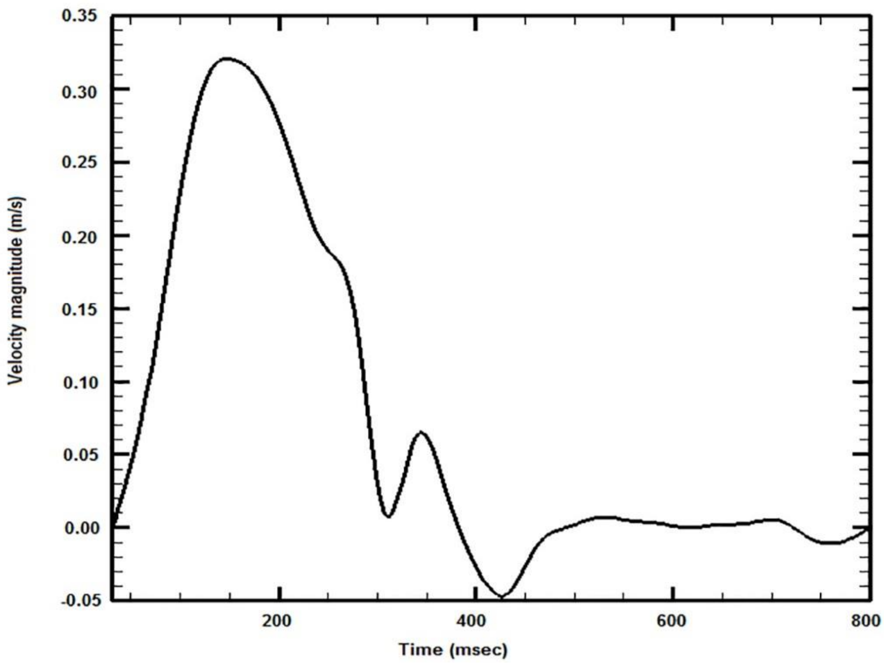

Figure.4: Transient velocity profile employed to simulate pulsatile flow conditions in a human coronary artery.

4.4. Numerical study:

The flow in the arteries is considered as three-dimensional, so the problems were solved as three-dimensional using CFD software and by applying the boundary conditions.

Semi Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm was used in the solver and Second order Up-wind Finite Volume Method to calculate the space discrete scheme.

The following solution settings were used: Time step 0.01s, Number of time steps 80.

The exit velocity, pressure and residuals were monitored during the calculation. The calculation was considered convergent when the flow at exit turned stable and the residual fell to 10^{-4}.

Governing equations:

Momentum equation

$$\rho\left(\frac{\partial V}{\partial t}+V.\nabla V\right)=-\nabla p+\mu\nabla^2 V+f \qquad (1)$$

mass conservation equation

$$\frac{\partial \rho}{\partial \tau}+\nabla.(\rho v)=0 \qquad (2)$$

RESULTS AND DISCUSSION

In order to simulate the effects of both cylindrical and conical stent on blood flow during a heartbeat, the solution was done to obtain the velocity and wall shear stress values in each time step. Then the equations of oscillatory shear index OSI and Time-Averaged wall shear stress TAWSS and Wall Shear Stress Gradient WSSG were defined.

the three indicators are considered as very important in reflecting the dynamic change of the hemodynamics, so these values were compared for both cylindrical and conical stent models.

5.1. Oscillatory Shear Index OSI:

Oscillatory Shear Index (OSI) is used to identify regions on the vessel wall subjected to highly oscillating WSS directions during the cardiac cycle. The OSI can be defined as the fraction of angle and magnitude change between the instantaneous WSS and the Time-Averaged WSS. It ranges from 0 to 0.5, where 0 represents a total unidirectional WSS and the theoretical maximum value (0.5) describes a purely unsteady. Low OSI values occur where flow disruption is minimal. while high OSI values (with a maximum of 0.5) highlight sites where the instantaneous WSS deviates from the main flow direction in a large fraction of the cardiac cycle, inducing perturbed endothelial alignment [8, 9]. OSI is given by the following formula:

$$OSI = 0.5 \times \left(1 - \frac{\left|\int_0^T WSS\, dt\right|}{\int_0^T |WSS| dt}\right) \qquad (3)$$

Before the stent implantation, OSI values was significantly unsteady and higher than normal blood vessels and reached the maximum value 0.5 in several positions in the artery wall which increase the ability of the occurrence of damage in the inner surface of artery wall, because the stenosis prevents the flow from passing naturally, which causes the flow to resist and thus increase the wall shear stress forces Figure-a. While after installing the cylindrical and conical stents, the OSI values became very low and approached zero, especially along the stented area Figure-b-c.

However, in the cylindrical stent case the OSI values was very high and reached 0.5 in the small area in the region between the end of stent and the artery Figure-a, this is due to the sudden change in artery section, although this region is small but it promotes the occurrence of restenosis in the future. while this region was not present in the conical stent case, the maximum value of OSI was 0.008, which it within the accepted range of OSI values Figure-b.

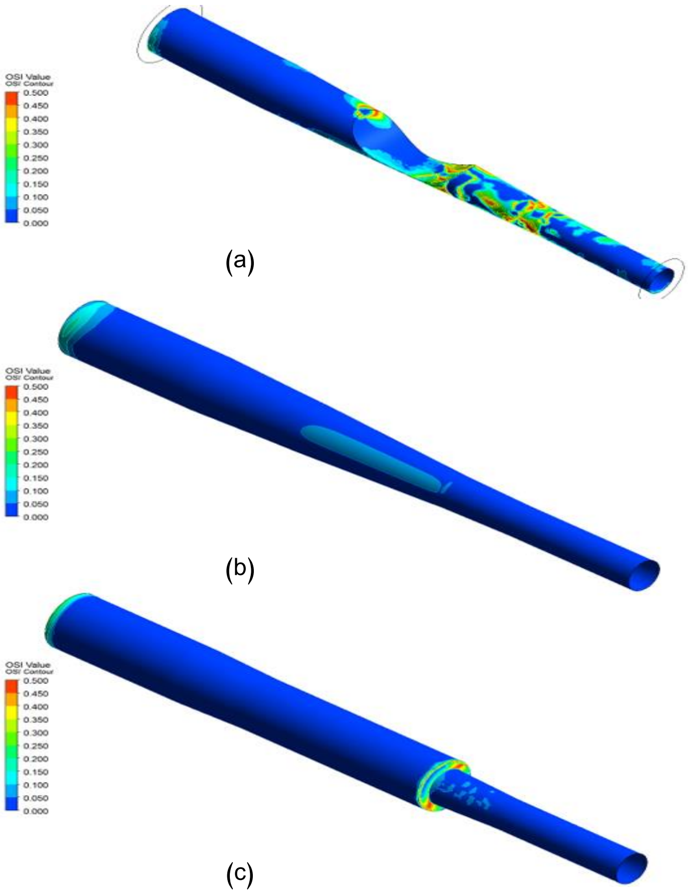

Figure.5: OSI (a) artery with stenosis. (b) artery with cylindrical stent. (c) artery with conical stent.

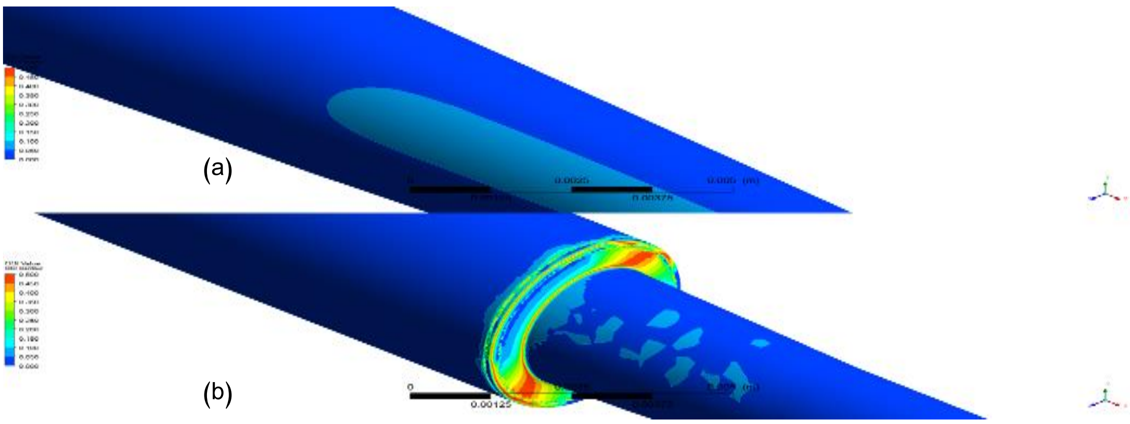

Figure.6: OSI values in the stenosis area (a) artery with cylindrical stent. (b) artery with conical stent.

5.2. Time-Averaged wall Shear stress TAWSS:

Time-Averaged wall shear stress represents the integration of shear stress with time during a blood circulation and is given by the following formula:

$$TAWSS = \frac{1}{T}\int_0^T |WSS|\, dt \qquad (4)$$

Low TAWSS values (lower than 0.4 Pa) are also known to promote an atherogenic endothelial phenotype, while high TAWSS (higher than 40 Pa) values can cause direct endothelial injury and increase the risk of getting thrombosis. Whereas the mean values (greater than 1.5 Pa up to about 10 Pa) represent the normal state that protects the artery endothelium [8, 9].

Before stent installation, TAWSS was very high especially in the stenosis area and ranged between 20 Pa and 93 Pa in the center of stenosis. in addition, there was an area after the stenosis with a very low TAWSS values lower than 0.4 Pa. All these values induce the occurrence of damage in artery endothelium and increase the ration of stenosis Figure.2-a.

After stents installation, TAWSS values ranged between 0.7 Pa and 6 Pa along the artery Figure.2-b-c. however, in cylindrical stent case there is a sudden change in TAWSS values in the area between the end of the stent and the artery which decreases to 0.2 Pa and then rises to 60 Pa. This induces the restenosis after the stent is installed **Error! Reference source not found.**-a, while TAWSS values ranged within the normal values with no and sudden changes in the conical stent case **Error! Reference source not found.**-b. This means that the conical stent has improved the hemodynamics of blood along artery better than the cylindrical stent.

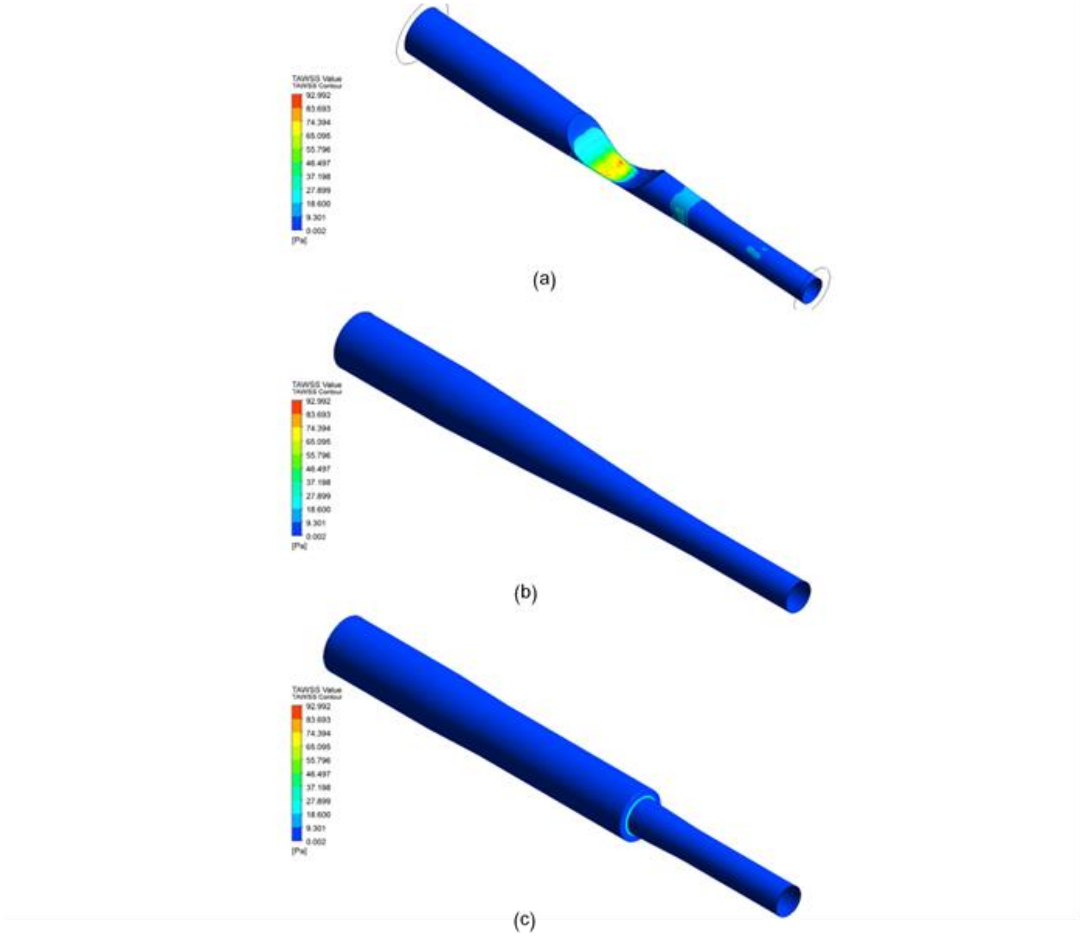

Figure.2 :TAWSS (a) artery with stenosis. (b) artery with cylindrical stent. (c) artery with conical stent

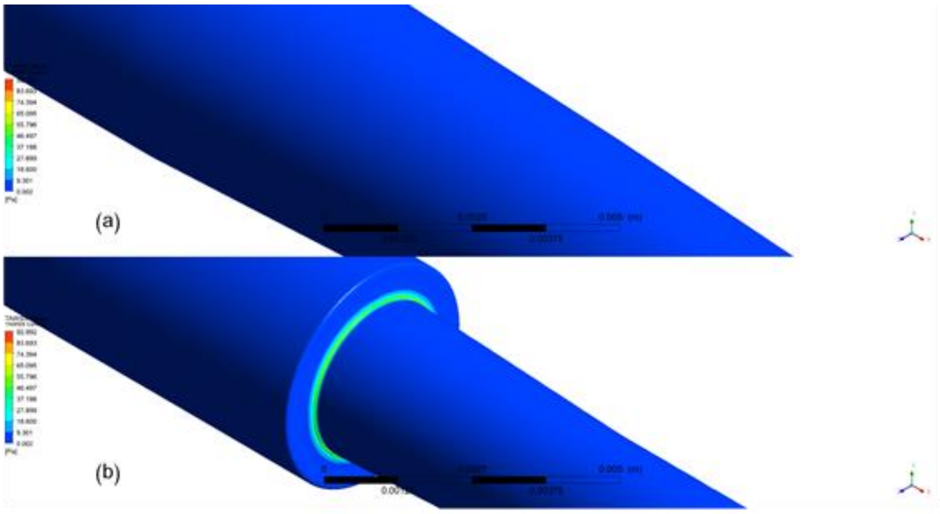

Figure.8: TAWSS values in the stenosis area (a) artery with cylindrical stent. (b) artery with conical stent

5.3. Spatial wall shear stress gradient WSSG:

Spatial wall shear stress gradient is an indicator of the tension of the endothelial cells of the artery, which describes the rate of change of the WSS vector with time [10, 11] and is given by the following formula:

$$WSSG = \sqrt{\frac{\partial t_{wm}2}{\partial m} + \frac{\partial t_{wn}2}{\partial n}} \quad (5)$$

A large WSSG acting on the artery wall could increase the permeability of endothelial cells by forcing them out of alignment with each other due to the different magnitudes of WSS.

Before stents installation, WSSG values was significantly different in the adjacent cells in stenosis center.in addition, these values were very high which graded between 15 Pa and 79 Pa in the stenosis center and suddenly decrease in the area after stenosis to reach a very low value lower than 0.5 Pa. All these values induce the occurrence of damage in endothelial cells due to the significant different in WSSG values between the adjacent cells and increase the ration of stenosis Figure-a.

After stents installation, WSSG values in the adjacent cells became closer and almost equal with no significant changes Figure-b-c. but in cylindrical stent case there was a sudden change in WSSG values in the area between the end of the stent and the artery, which suddenly graded from 0.1 Pa to 37 Pa, this increase the cells stress and induces the restenosis after installation Figure-a. while WSSG values graded in the normal ranges with no sudden changes in values Figure-b.

this means that the conical stent has improved the stability of the cells more than the cylindrical stent, which leads to increase the reliability of the conical stent after installation.

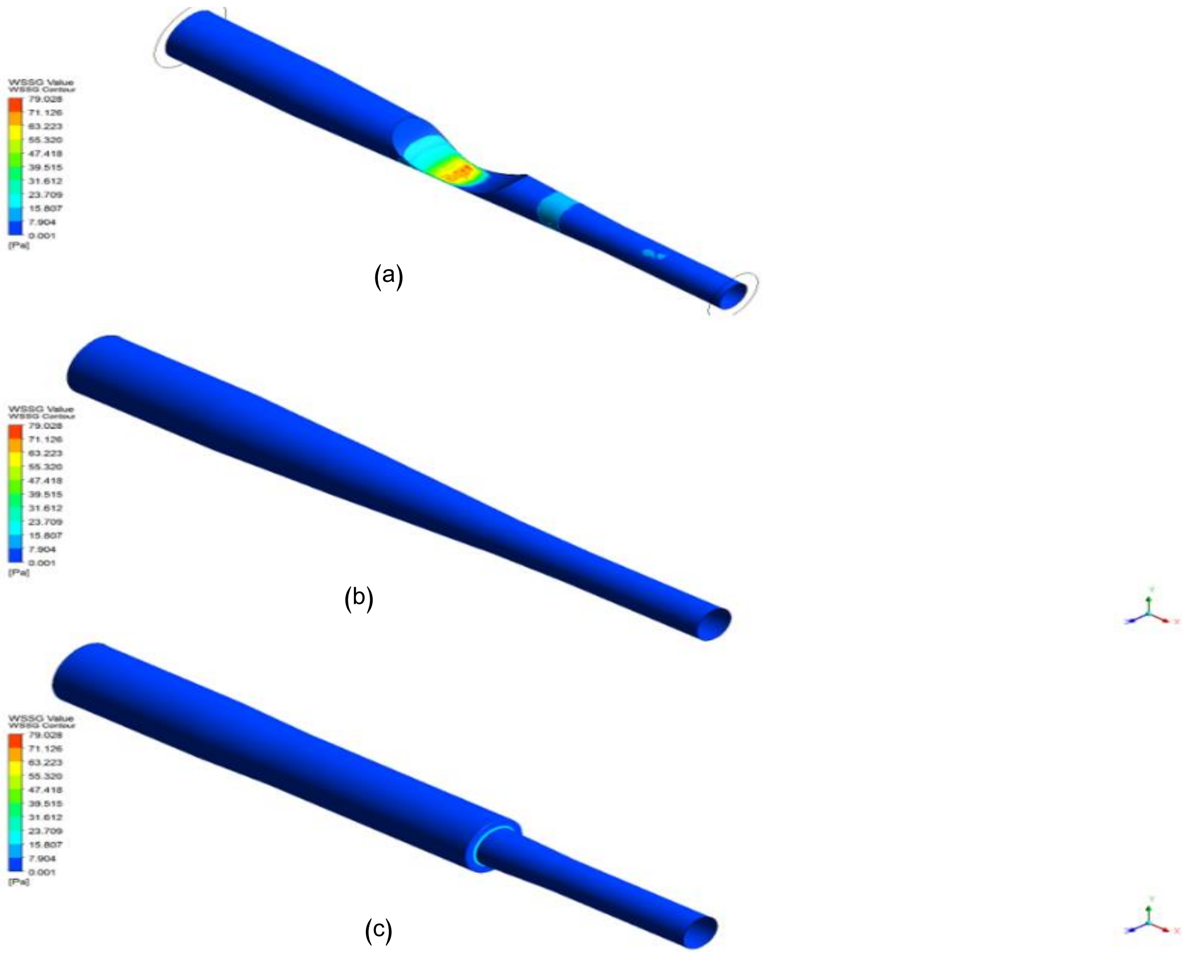

Figure.9: WSSG (a) artery with stenosis. (b) artery with cylindrical stent. (c) artery with conical stent.

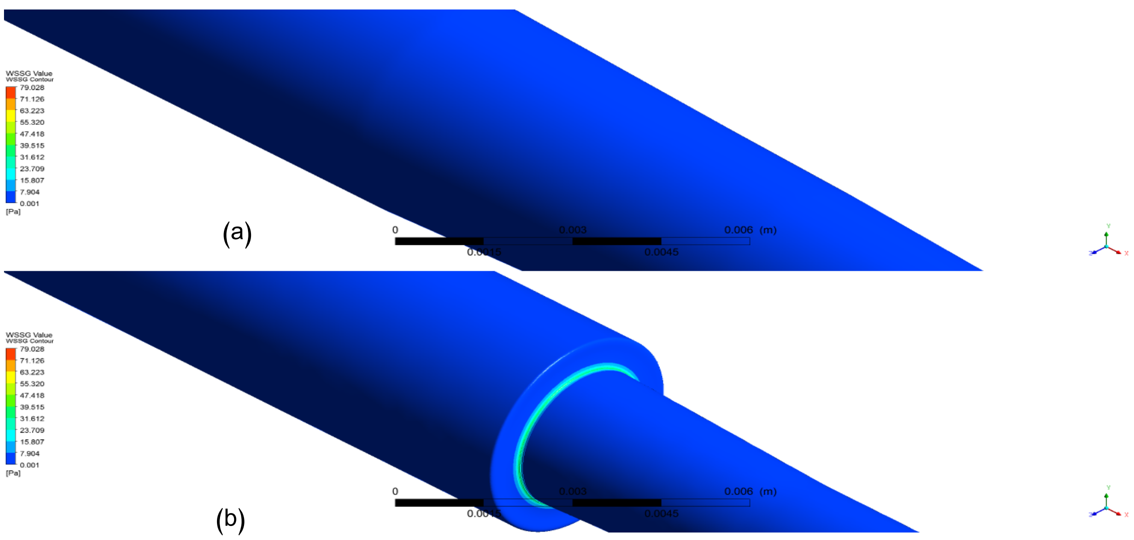

Figure.10: WSSG values in the stenosis area (a) artery with cylindrical stent. (b) artery with conical stent.

CONCLUSION

1. Both cylindrical and conical stents can eliminate the stenosis in the coronary artery and recover blood flow, but in comparing between them the conical stent showed more advantages.
2. The installation of the conical stent was more suitable for the artery physiology, as it expanded the artery without causing excessive expansion of blood vessels.
3. OSI values was low along the artery in the conical stent case while there were high values in some areas in the cylindrical stent case (0.5 at the end of stenosis).
4. TAWSS values were closer to the natural conditions in the conical stent case without the presence of high values areas or sudden changes.
5. WSSG values for the adjacent cells were more homogenous and stability in the conical stent case in comparing with the cylindrical stent case.

All these indicators show that the artery response to the conical stent installation better than the cylindrical stent installation.

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