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Three-dimensional Simulation of Blood Flow in Stented Vessels and the Comparison of Wall Shear Stress in Various Stent Plans Using CFD

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ABSTRACT: After stent implant in vessel,fatty plaques are broken, the vessel wall is transformed and due to the presence of stent,new conditions will arise which can cause anunusual biological reaction**.**In the present study,using computational fluid dynamic , the spatial and temporaldistribution of wall shear stress were modeledas three-dimensionalon the vessel wall and stent under pulsatile conditions for three different models**.**By comparing the level of vessel wall and stent, the maximum wall shear stress was concentrated on the stent level. On the vessel wall, the spatial distribution of wall shear stress at the stent part showed that the more itis moved from the center of the vessel wall to the stent peacock,the more the rate of wall shear stress has a decreasing trend**.** Also, in comparing stents with each other, the most desirable stenthaving the lowest percentage of vessel area with wall shear stress < 0.5 Pais identified. Since the lessthe percentage of the area is,the less the possibility of probabilityof increasing the *intimal*layer that has become a limitation for stent vessels will become.

***Keywords*:** Computational fluid dynamics; Numerical simulation; Restenosis;Stent;Wall shear stress

INTRODUCTION

According to the World Health Organization report in 2004, cardiovascular diseases have causedthedeath of about 17 million human worldwide that is the main cause of mortality in the industrialized and developing countries.Atherosclerosis or creating fat in the intra coverof the vessel wallsis the most common form of cardiovascular disease. When atherosclerosis develops in the blood vessels, vessels called Coronary arteries that supplyoxygen and nitrogen to the heart muscles,suffer from severe stenosis and finallylead to a heart attack.The carotid arteries bringing blood to the head and neck may also be faced with this disease that causes in stroke ifthere is severe stenosis, given that the diameter ofthe coronary artery is smaller than the diameter of the carotid artery; however the incidence possibility of the disease is higher in the coronary artery.

In the advanced stages of the disease, specific clinical measures such as bypass graft,Angioplastyor Balloonand Stent Implantare used to treat vascular occlusion.

Stenting is aninterventional cardiovasculartechnique that has led to considerable progress in the atherosclerosis therapy. Stents are mesh tube wires that are located in wall vessel using catheter and cause to improve and restore blood flow by patenting arteries in the stenosisarea.

stentswere first usedinarteries of animalsby (Dotter ,1969). After assessing the successful results of implantingEmtalstainless andnitinol stents in animals (Sigwart et al., 1987).the firstself-expanding stent made of stainless steel was successfullyplaced on thecoronaryarteryof human (Kastrati et al., 2001).

Stentsare simply implanted, increase the reliability coefficient of angioplastyand increase the clinical success of surgeryby reducing the rate of restenosis.However, restenosisin stent is a major limitation in the rate of stent implant.

Medical theories

Figure 1 shows a view of the stent in the vessel. Afterplacing stent, the stentedpart ofvesselcan be restenosis by four key processes that are Thrombus formation, Arterial inflammation,NeointimalHyperplasia and Remodeling.

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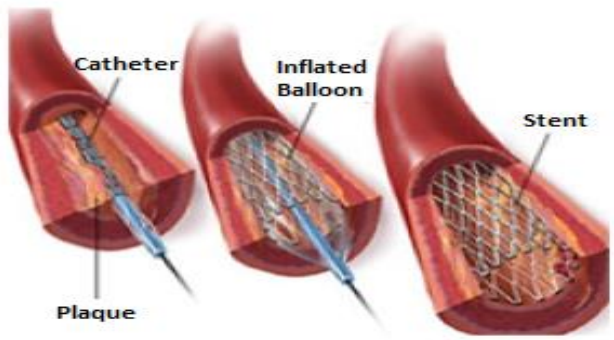


Figure 1. A view of the stent implanted in vessel

In summary, the Thrombus formation that immediately initiates after stent implant is the closed mass of blood. Arterial inflammation which starts during 24 hours after the surgery is due to the inflammatory response that the immune system of body shows to the presence of the stent. NeointimalHyperplasia (NIH) begins during several weeks after stent implant. In the process, the tissue growth quickly occurs in vessel and around the implanted stent. Thus, the smooth muscle cells which normally reside in the inner layer of vessel displace toward inside near the stent where they are amplified and formed toward the mass of new tissue narrowing the vessel. Remodeling initiates from about four weeks after stenting in the waythat collagen depositionsbeinga type of proteinin the tissue lead to the vascular contraction in the outer layers of vessel.

After stenting, the restenosismechanism composed of four processes wasstated in the chronological order.The main driver is generally the presence of the stent thatcauses to create the abnormal hemodynamicsin the wall vessels.

In general, if out of NIH process, thegrowth ofnew tissue being the main cause of vessel restenosisis kept at least,the stenting techniquewill likely be successful.However, if the tissue growth is excessive and vessel cannot adapt itself to the new tissue without losingthe efficacy, new surgery will be necessary.

In the stented vessels, the growth rate of NIHis reversely dependent on the shear stress; therefore, it has afundamental rolein creatingrestenosis instents (LaDisa et al., 2005). According to the suggestions inthe previous studies (Ku et al.,1997), [5].thelimitamount of 0.5Pa was determined for the critical wall shear stress as these areas are prone to restenosis.So, as the percentage of WSS< 0.5pa of vessel be lower, the probability of restenosis rate is decreased. In this case, stents are more appropriate that the area percentage is lower for them. In the present study, the percentage of low WSS was compared with each other in variousplans of stent and the maximum rate of WSS was determined in the area of stent and vessel and also the places havingthe highest rate of WSSon stents and stent-vessel wall were identified.

MATERIALS AND METHODS

To study patterns of blood flow in thestentedvessel,we have simulated three-dimensional models under pulsatile flow conditions using computational fluid dynamics (CFD). Our measuringcriteria focused specifically to determine WSS, so thatas an important factor for growingEndothelialCell,it has been shown near the strut area of vessel wall.

In three plans specified in figure 2, our models are now used in the commercial market. In these plans, a part of a unit stent is only modeled that is one part of wall only modeled to resolve WSS (He et al., 2005).As we see in Figure 2, a unit stent is composed of two struts and a connector between them. Thegeometry of these stents wascreated three-dimensionally and done in the software SOLIDWORK 2011, the radial of the modeled vessel was 5mm and the thickness of all stents was equal. Its amount was determined equal to0.7mm.To prevent the internal effects of flow limit in the desired area, the length of input and output proximal and distal were considered equal to2-3.5mm. Also, the wall models were considered ascurve which this issue leads to more accurate results than the flat wall.

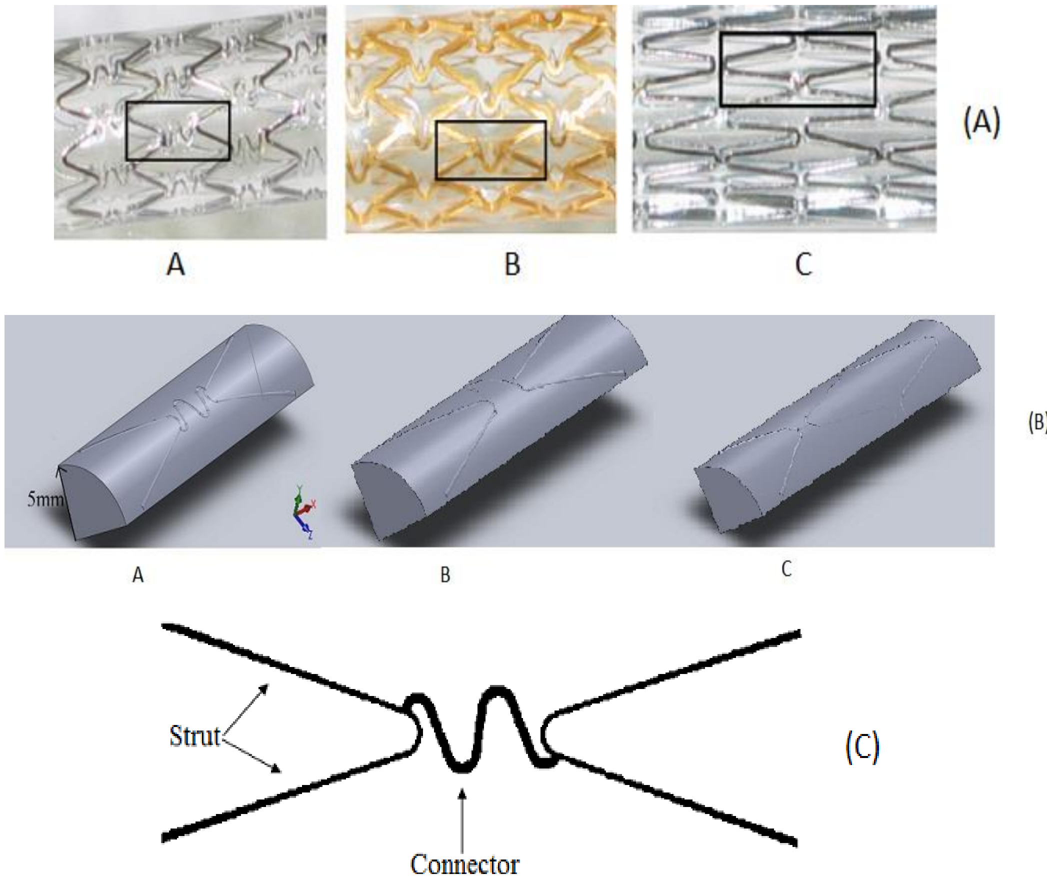


Figure 2. (A) three different models of stent with the commercial name of each; the rectangular box represents the modeled area in CFD. (B) The three-dimensional geometry of various models of stent. (C) The view of a unitof stent

To create the blood flow which is avery unstable pulsatile flow, the solutionconsisting of 39.8%volume Glycerin, 59.7% volume distilled Waterand 0.5% volumeGadoliniumhave been used. In the stented areaand before and after it, the arterial wall was assumed rigid. Research has shown that according to the increase inthe stiffness of the arterial wall due to Plaque formation, the error caused by the assumption is negligible (Dehlaghi et al.,2007), [7]. The elasticity property of vessels has been ignored. Also, the symmetry boundary conditions were used for the side walls. The above solution has the viscosity of 0.004 kg/m.s and density of1065 kg/m^{3}Simulating a beat with a range of Reynolds number between 210 to 465 and a beat with the Womersle number about 8 was predicted for the model input.

Simulation

Simulation was donebased on three-dimensional model and with triangular elements in the number of 321921, 319452 and 336109 elementsfor the stent of typeA, B, and C, respectively, meshing has been conducted by the preprocessor GAMIT software. The mesh independence of the greatconvergence (<10%) of speed was determined across the length of the stented model. For each period cycle, the size of time step was considered equal to 0.008 or in the rate of 75 steps.

In the greater vessels, the error suffered from the Newtonianassume of being blood is negligible because the vessel diameter is larger in comparison with the diameter ofindividual cells of blood.

In the present study, since the vessel diameter was considered equal to 1cm, the blood is an assumedNewtonian fluid. The Navier-Stokes equation governed on the flow was solved by CFD and using the finite volume method.

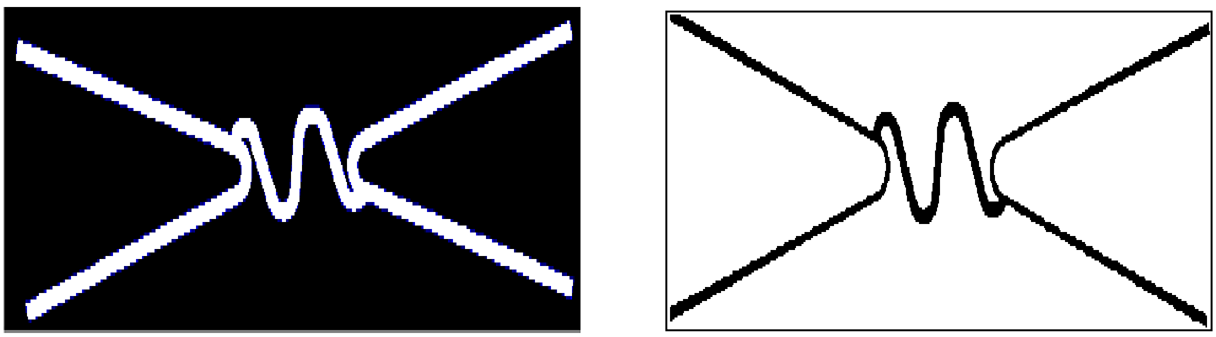
$u=0\nabla$ Continuity equation $u/\partial t + u . \nabla u) = -\nabla p + \mu\nabla^2 u\rho(\partial$ Navier-Stokes

u,μ,p and ρ are Velocity vector, Blood viscosity, Stress and Blood density.

RESULTS AND DISCUSSION

RESULTS

Results of wall shear stress were reported in two areas: one area of the strut surface called stent area and other vessel wall surface called vessel area which is shown in Figure 3.The temporal changes were reported in five specific times during a period of cardiac cycle (figure 4).



A B

Figure 3 . (A) Stentarea, the tube-shaped partdistinguished from the part of vessel wall. (B) Vessel area, the white part separated from the stent area

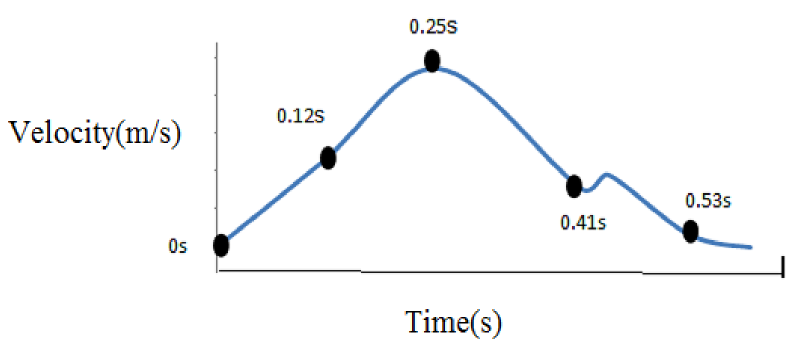


Figure 4. the determined times during a cardiac cycle

At 0.12 second, the velocity of blood flow has an increasing trend and at 0.25 second, reaches the maximum amount that is called thediastolic peak. Then, at 0.41second,thevelocity of blood flow takes a decreasing trend and at 0.52 seconds, reaches the lowest its amount. According tothe previous suggestions (Henry et al.,2000), [8].the limit amount of 0.5Pawas determinedfor the critical wall shear stress so that these areas are prone to *restenosis*. Thus, to compare the performance of these three stents, the stented area percentage of wall vessel exposed to the WSS less than 0.5Pa was investigated.

Figure 5 shows the graphical diagram of vessel area percentage with the magnitudeof WSS <0.5Pa for each stent model at 5 selected times.High and low values changes during a complete *cardiac cycle*. As it was notedearlier, as the area percentage is lower, that is the stent has less capabilityfor *restenosis*.At the maximum time of the blood flow (0.25s) called the diastolic peak, the area percent of WSS <0.5Pa was between 15-20% for all models.

When the blood flow takes a decreasing trendor reaches its minimum amount, this amount significantly increases. Comparing threemodels of stent with each other indicates that stent A has the lowest area percentage with low WSS duringa cycle.

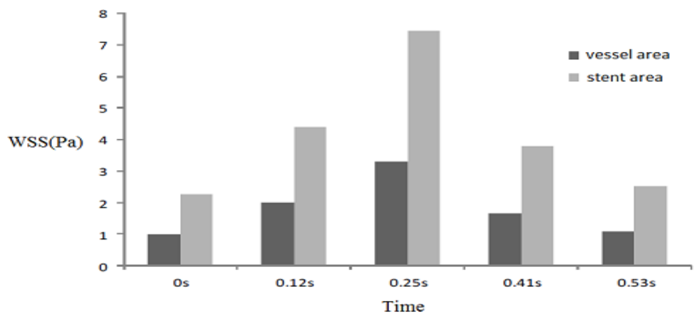


Figure 5. The graphical diagram of the percentage of the vessel area with WSS<0.5 for all three stent models

Figure 6 shows the comparison between the maximum amount of WSS on the stent and vessel area in the selected times during one cycle.This diagram is related to the stent A and two other models have also such a trend. So that in all times, the maximum WSS amount was achieved on the stent area in comparison with the vessel area. The maximum WSS amount was reported in the time of diastolic blood flow (0.25s).

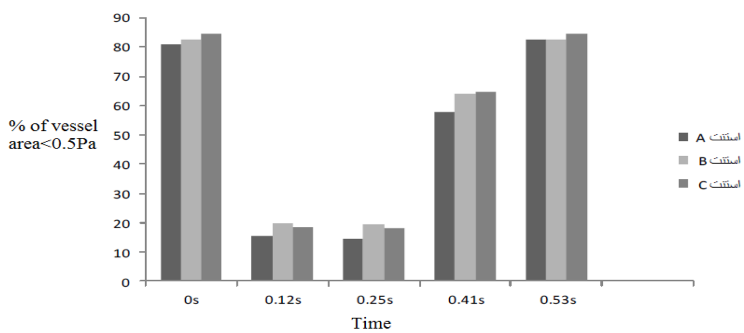


Figure 6. The comparison of the maximum amount of WSSon the stent and vessel area for stent A

Figure 7 shows a comparison between the maximum WSS in the stent area. As it is obvious in the figure,stent B has the highest amount among all times of cycle and then, stent A has the highest one. Figure 8 shows a comparison between the maximum WSS in the vessel area.This diagram reports the slight difference among all models. Out of them, stent A has slightly higher than the amount of other two models.

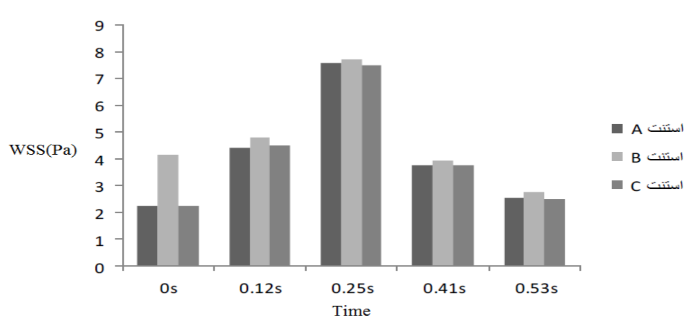


Figure 7. Comparing the maximum wall shear stress in the stent area for three stent models.

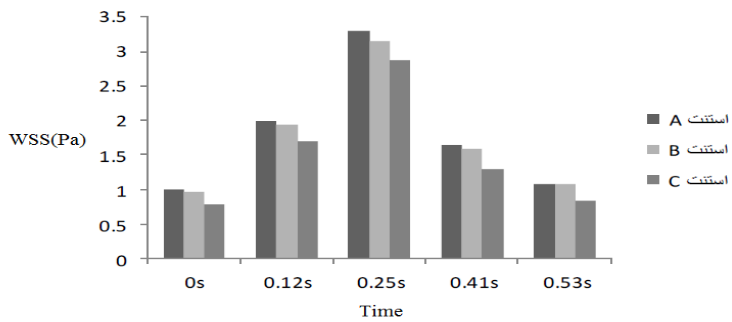
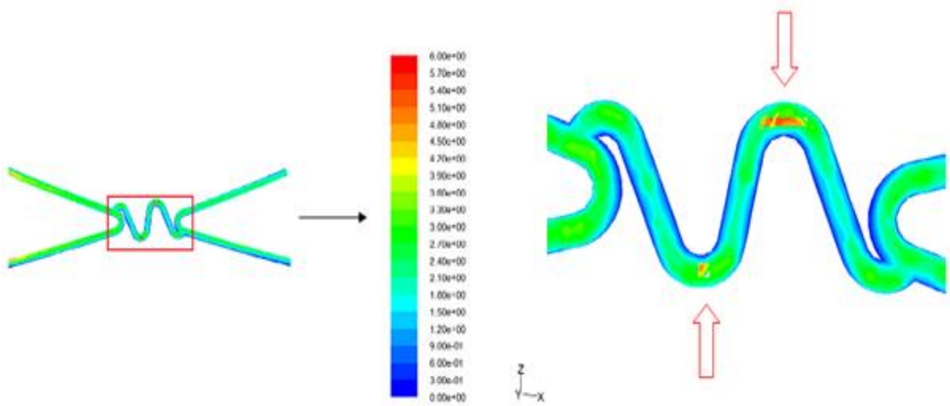
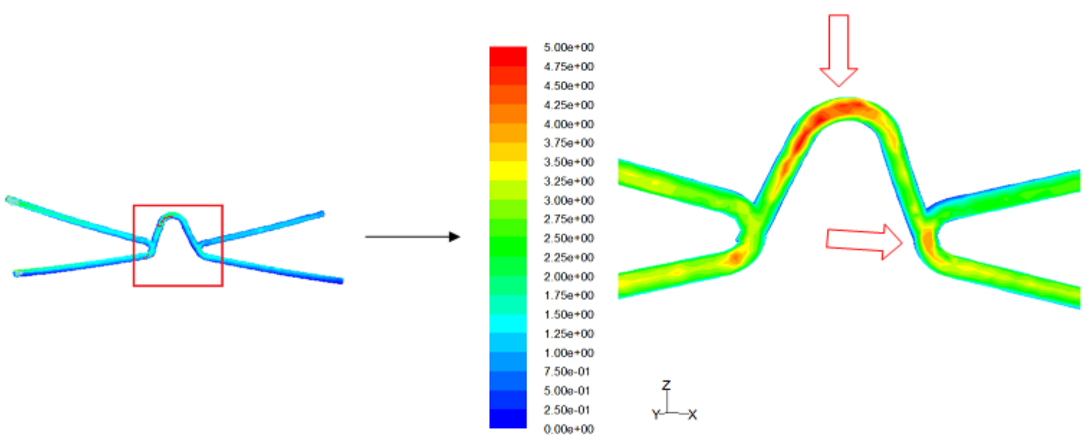


Figure 8. Comparing the maximum wall shear stress in the vessel area for three stent models

Figure 9 shows the spatial WSS distribution on the stent area in three models, as it has been specifiedby arrow in figures, the curved parts of stent strut and connectors have the highest WSS andin fact, they are places having the highest concentration of stresses.



A



B

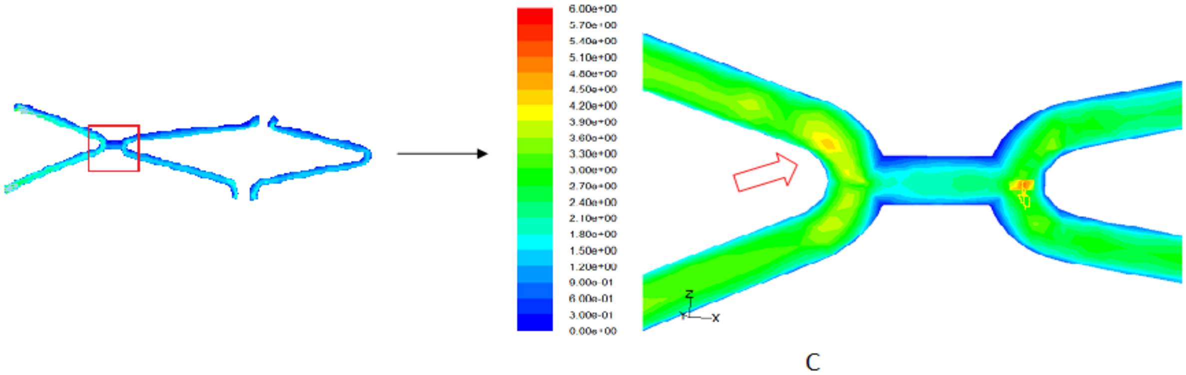
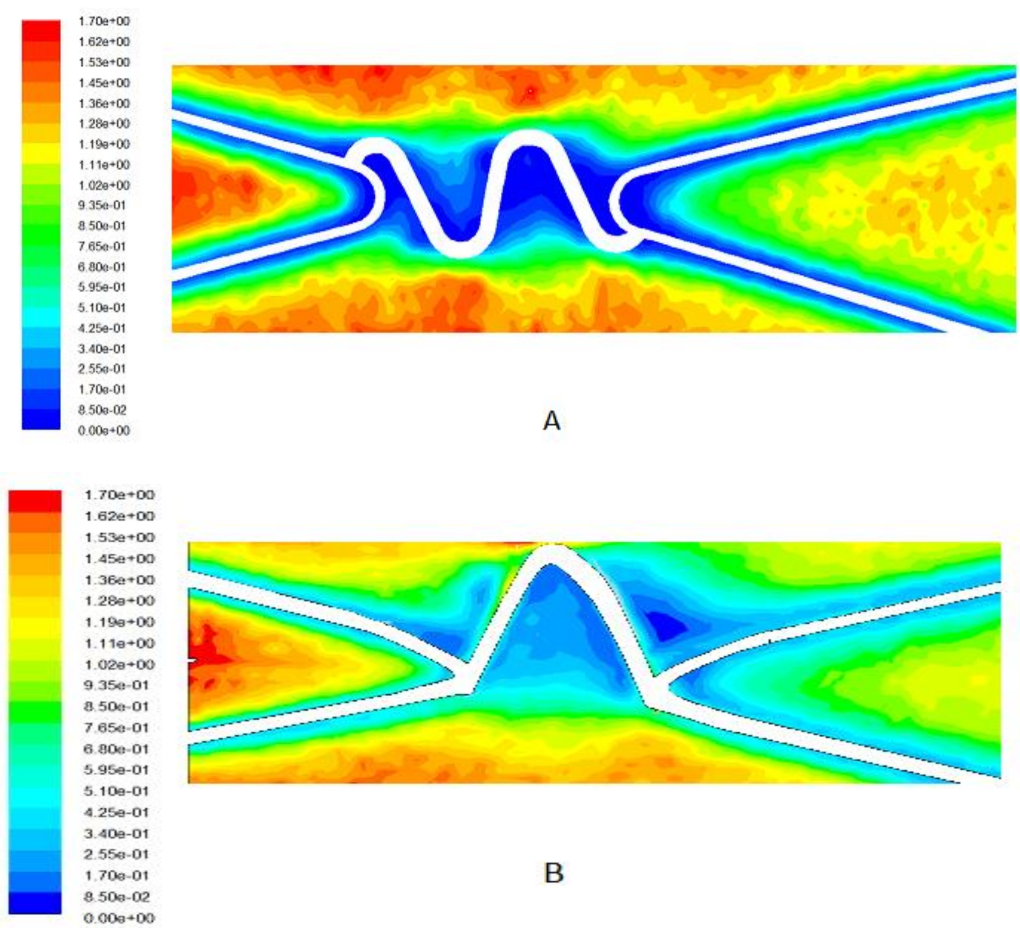


Figure 9. The spatial distribution of wall shear stress on the stent area in three models

Figure 10 shows the spatial WSS distribution on vessel area in three models. These patterns are similar for all models in theway that as we move toward the center of vessel area from the area near strutting, the WSS amount increases. The distribution is fairly consistent with previous study conducted by (LaDisa et al., 2003), [9].



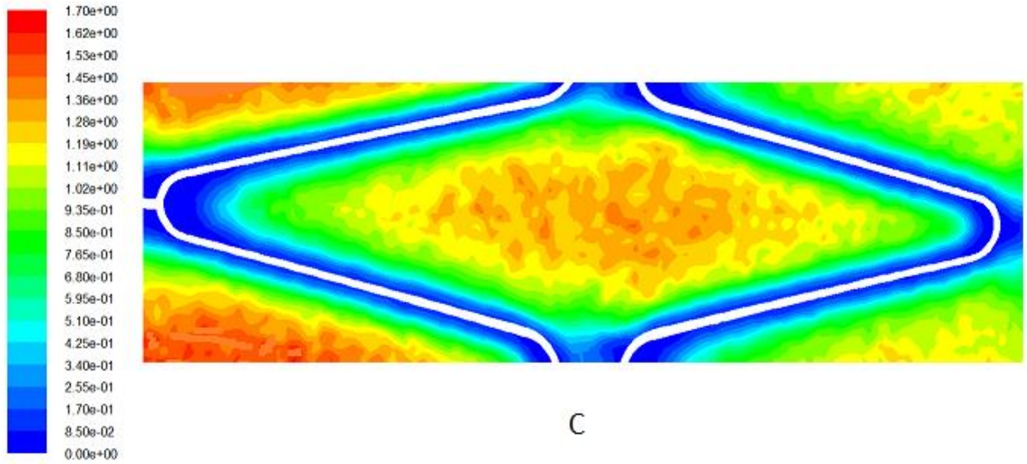


Figure 10. (A) a sample of modeled vessel area, (B)The spatial distribution of wall shear stress on vessel area in three models

Figures

DISCUSSION

In the present study, for a more appropriate judgment on the various plans of stent, the thickness of each threestent models were taken the same so that the comparison among them becomemore accurate and logical. For threestent models, comparing the extent of areas with WSS < 0.5Pashowed that the stent A has the lowest area and as a result, has less ability to increase the thickness of NIH and is more desirable than the other stents.However, it is obvious thatthe difference between stents is not very significant thatone reason may be using a unit stent and another reason is the same thickness of stents.We believe that removing these restrictions lead to a larger difference on the final status.

In the stented area, observing the spatialWSSdistributionon the surface of wall vessel had the result that the greatest amount of WSS is in the area center of the vessel wall.

Stent A having the largest area among connectors has more area of high WSS. Asit isshownin figure 10, low WSScompared to other places was the most near stent strut and connectors and in the stent Acompared to the other two stents, this area was higher. Due to itsregular geometry form, the model of stentChas more uniform spatial distributionof WSS than theother two models. According to the stent area, the maximum WSS amount focused on the stent strutin whichareas are in the subject of blood flow and finally, the curved struts have higher WSS than the right one.

Abbreviations

CFD	Computational fluid dynamics
μ	Blood viscosity
NIH	NeoIntimal Hyperplasia
ρ	Blood density
P	stress
WSS	Wall shear stress
Wo	Womersle number

CONCULSION

Given that there are no clinical tests generally comparing the *restenosis* rate for all these models, the computational fluid dynamics has been used todeterminethe best model of stent. The accuracy of CFD results depends on the computational domain and the size of calculated mesh. For this simulation,norepeated struttingwas considered to save the sizeand time of computational mesh.Thus, the stent geometry is only an approximation; hence, results may be different from the actual geometry. In this study, the flow characteristic has been shown as an unstable pulsatile flow that is expected to be an indicator of the flow pattern in the body. Given that stent A has the lowest WSS area of <0.5 Paand also the maximum area of high WSS, it is expected to have low tendency for increasing NIH and as a result, to be the most desirable stent in comparison with other models. Considering that the small differences may, however,be significant in vessel, the other factors affecting thevessel reaction to stents should be recognized.

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