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Analysis of Blood Flow, Pressure and Velocity in a Stented Abdominal Aortic Aneurysm Model

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Abstract- **This paper describes the analysis of blood flow, pressure and velocity in the abdominal aortic aneurysm (AAA) model, with and without stent graft (SG) placement. The aim of this study is to investigate the effectiveness of using stent graft (SG) in treating abdominal aortic aneurysm (AAA) and to protect the weak wall of an aneurysm sac from rupture. Two 3D-abdominal aortic aneurysm (AAA) models were constructed with and without a linear stent-graft using a computer aided software, Solidworks 2005. Computational fluid dynamic software has been employed to solve for blood flow, sac pressure and velocity of blood in the aneurysm sac and SG. Simulation results indicate that implanting a SG in an AAA can significantly reduce the sac pressure, increase velocity of blood and restore normal blood flow.**

I. INTRODUCTION

Aneurysm is an abnormal bulge or ballooning of weakened artery segments. The artery that grows more than 50% of its normal diameter can burst [1], causing bleeding inside the body. Most aneurysm occurs in the aorta. Aorta is the main artery that carries blood from the heart to the whole body. An aneurysm that occurs in the aorta in the abdomen is called abdominal aortic aneurysm. Many cases of ruptured aneurysm can be prevented with early diagnosis and surgical treatment. The diseased aortic segment can be replaced with a synthetic polymeric graft using traditional open surgery. Alternative to this traditional surgery, a less traumatic treatment called endovascular aneurysm repair (EVAR) has become a preferable treatment among patients due its less traumatic procedure [1-3].

In EVAR, stent graft is inserted into an artery in the groin (upper thigh) and guided to the affected area of the blood vessel and then expanded by ballooning inside the aorta and fastened in place to create a stable channel for blood flow. This graft will protect the aneurysm from the blood pressure, eliminate blood circulation in the aneurysm cavity, ensure normal blood flow and thus prevent the aneurysm wall from rupturing. The stent graft (SG) used is usually a cylindrical wire mesh embedded in synthetic polymeric graft material [2]. This procedure has shown an outstanding success, especially for abdominal aortic aneurysms (AAA) [4], however post-operative failure may occur due to stent migration, stent deflate and blood leakage into the aneurysm cavity, which elevates the sac pressure and may cause aneurysm rupture [1-3].

The demand for a less traumatic EVAR procedure has lead to the improvement of stent graft design and EVAR technique. To understand the engineering features required of a stent graft, some knowledge of the forces, pressure and velocity acting upon the stent graft in AAA is the basic requirement for the ultimate success of EVAR repair. So far, experimental studies and computational work have focused on the analysis of blood flow induced wall stresses of either the AAA or the SG [5]. For example, Fillinger et al.[5, 6] computed the peak wall stresses in realistic AAA configurations and declared the maximum stress to be the most important indicator of AAA rupture. Di Martino et al. [7] and Finol et al. [8] simulated the interactions between blood flow and aneurysm wall to analyze system parameters which are of concern in AAA rupture risk assessment. Raghavan et al. [9] and Thubrikar et al. [10] investigated wall stress distribution on three-dimensionally reconstructed models of human abdominal aortic aneurysms. Chong C.K and How T.V measured the flow patterns in an endovascular SG for abdominal aortic aneurysm repair [11]. Liffman et al. [12], Morris et al. [13], and Mohan et al. [14] investigated numerically or clinically the forces on a bifurcated SG, assuming a rigid SG wall.

Therefore, in this paper the analysis of blood flow, sac pressure and velocity of blood is described in order to fully understand the performance of SG in AAA.

II. METHODS

A. System Geometry

Two 3D-abdominal aortic aneurysm (AAA) models were constructed with and without a linear stent-graft using a computer aided software, Solidworks 2005. The parameters used to construct the 3D models of AAA and SG are listed in Table 1. [1]. Fig 1 shows the 3D asymmetric AAA with and without stent. The SG is assumed to be a uniform 3D linear shell attached to the proximal neck and iliac artery wall.

TABLE I
PARAMETERS USED FOR MODEL CONSTRUCTION

Parameter	Normal artery	Aneurysms	Stent graft
Wall thickness	1.5 mm	1.0 mm	0.2 mm
Diameter	Neck aorta (inner): 17 mm	60 mm	17 mm
Length	Neck aorta & iliac: 30 mm	80 mm	Main body: 60 mm

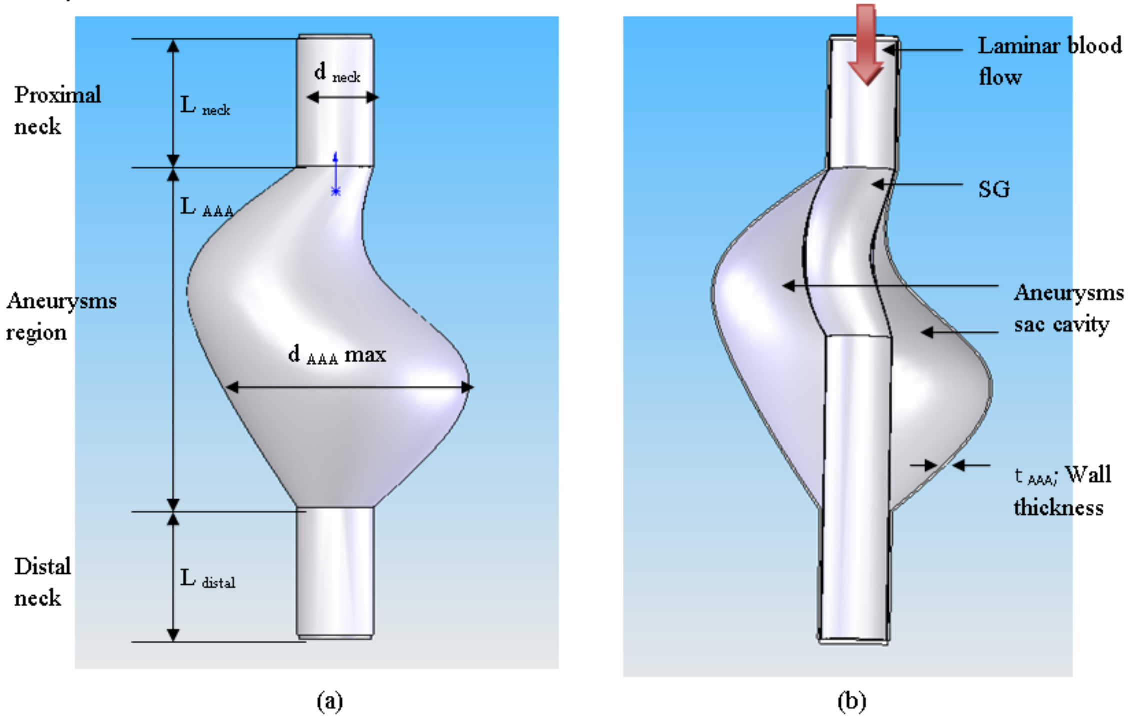


Fig. 1. The 3D models of abdominal aortic aneurysm (AAA), (a) without stent graft (SG), (b) with stent graft (SG) (cross section of model).

B. Simulation

Engineering Fluid Dynamics (EFD) software has been employed to solve for blood flow, sac pressure and velocity of blood in the aneurysm sac and SG. The underlying assumptions for simulating the coupled fluid–structure interactions are listed in Table 2 [1]. The fluid type apply in the AAA simulation is non-newtonian fluid. For the simulation purpose, a steady-state (i.e., nonpulsatile), laminar blood flow was assumed, where the inlet pressure into the stent graft is 100 mmHg or 13,330 Pa and the velocity of the blood into the stent graft was uniform and equal to a peak systolic flow rate of 0.60 m/s [2]. Within the graft, a ‘‘no-slip’’ boundary condition was assumed, i.e., the speed of the blood along the walls of the graft was zero.

TABLE 2
ASSUMPTIONS FOR BLOOD FLOW AND STRUCTURE CHARACTERISTIC

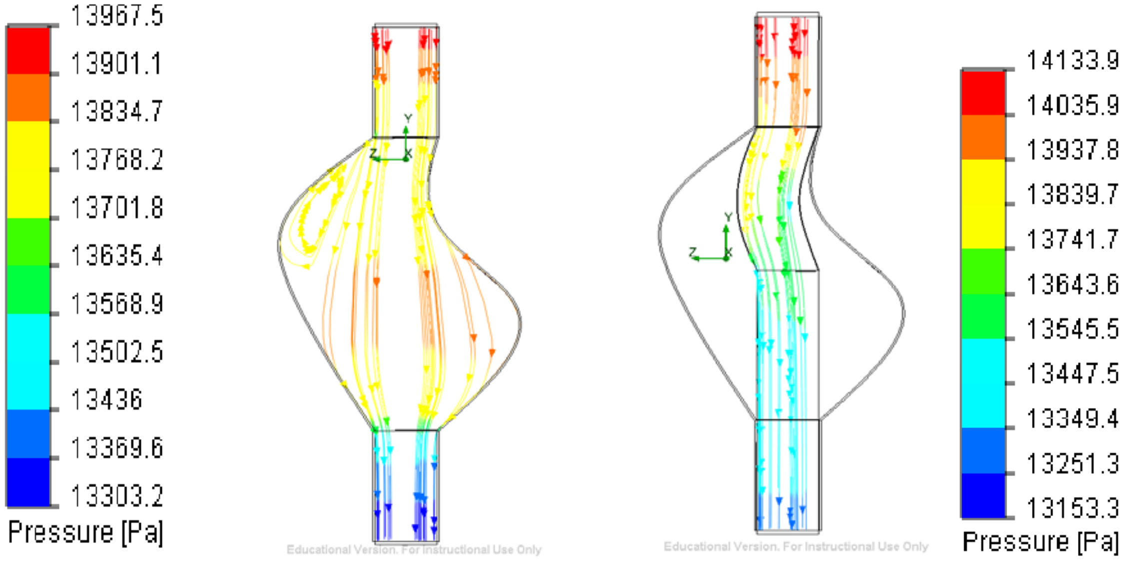
Blood flow	**Structure characteristic (aneurysms & SG)**
Incompresible	Elastic
Non-Newtonion fluid	Incompressible
Laminar blood flow	No tissue growth on walls
No slip at wall	No SG migration
Stagnant blood in cavity	SG consists of equivalently uniform material

III. RESULTS AND DISCUSSION

The blood flow pattern and sac pressure distribution in the both AAA models is shown in Fig. 2 and Fig 3. The pressure inside the unstented AAA models ranged between 13,303 Pa to 13,967.6 Pa whereas in the stented AAA the pressure is between 13,130.9 Pa to 14,123.1 Pa. The highest pressure point for both models is at the proximal neck region because the blood was simulated to enter the aneurysm sack through the face top of this region. The lowest pressure point is distributed at the distal neck of both models. Pressure at the outlet of unstented AAA is higher (13,303.2 Pa) than stented models (13,153.3 Pa) with the pressure difference is 149.9 Pa. The mass and volume flow rate for unstented model is 222.2 $\times10^{-3}$ kg/s and 134.9×10^{-6} m^3/s. The simulation result has demonstrated a slight decrease in the mass and volume flow rate in the stented model where the mass flow rate decrease to 222 $\times10^{-3}$ kg/s and volume flow rate drop to 134.97×10^{-6} m^3/s.

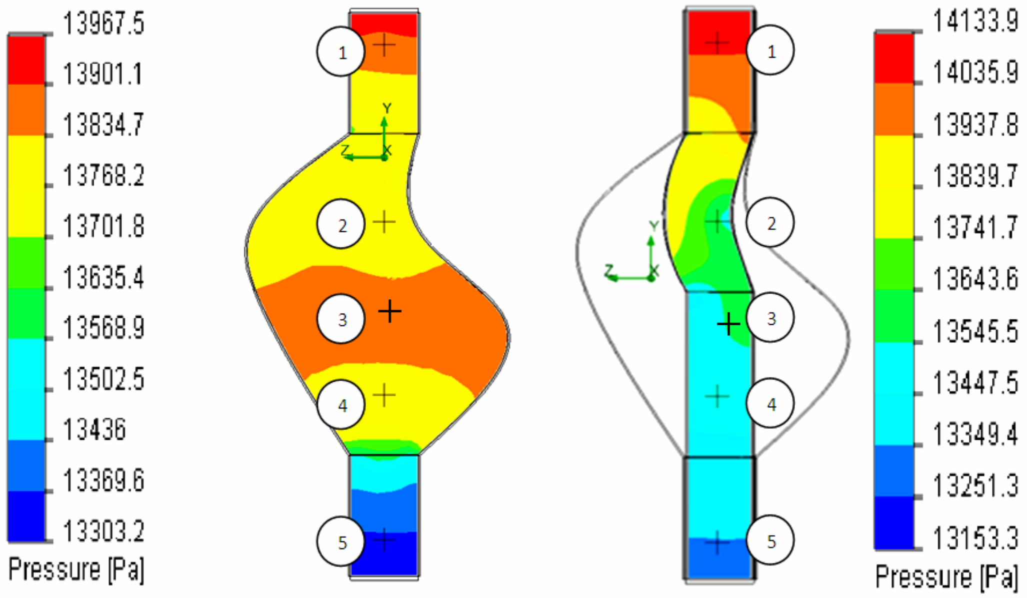
The velocity of blood flow in the unstented AAA ranges between 0 m/s to 747.943 $\times10^{-3}$ m/s while inside the stented AAA the velocity ranges between 0 m/s to 978.225 $\times10^{-3}$ m/s. The simulation has show a significant increase in the velocity of blood when the SG placed inside the AAA. The blue color of contour shows the lower velocity region and the red color is the high velocity region. For the unstented AAA, (see Figure 4 (a) and 5 (a)), the higher velocity of blood flow occurs at the proximal and distal neck of the model. The velocity at the therefore it can be assumed that there is no blood flow at the wall or we can say that the blood is stagnant which result to a high pressure development at the aneurysm wall. Bernoulli's principle states that for an inviscid flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.

The cross sectional area also influenced the velocity and pressure inside the AAA. The unstented AAA has a large cross sectional area compared to the stented AAA, thus the aneurysm wall is found to be about 0 m/s, simulation has proved that the velocity of blood across the aneurysm region decreases resulting in the rise of pressure inside the aneurysm region. Blood flow pattern at point X in Fig. 4 (a) proved that the large space developed in the aneurysm sac and high degree of wall slope will lead to a circulation of blood, velocity drop (V= 0 ~ $2.75\text{x}10^{-3}$ m/s) and increase of pressure, (P =13,818.83 Pa) inside the aneurysm region. This phenomenon will give rise to formation of plaque inside the aneurysm sac.



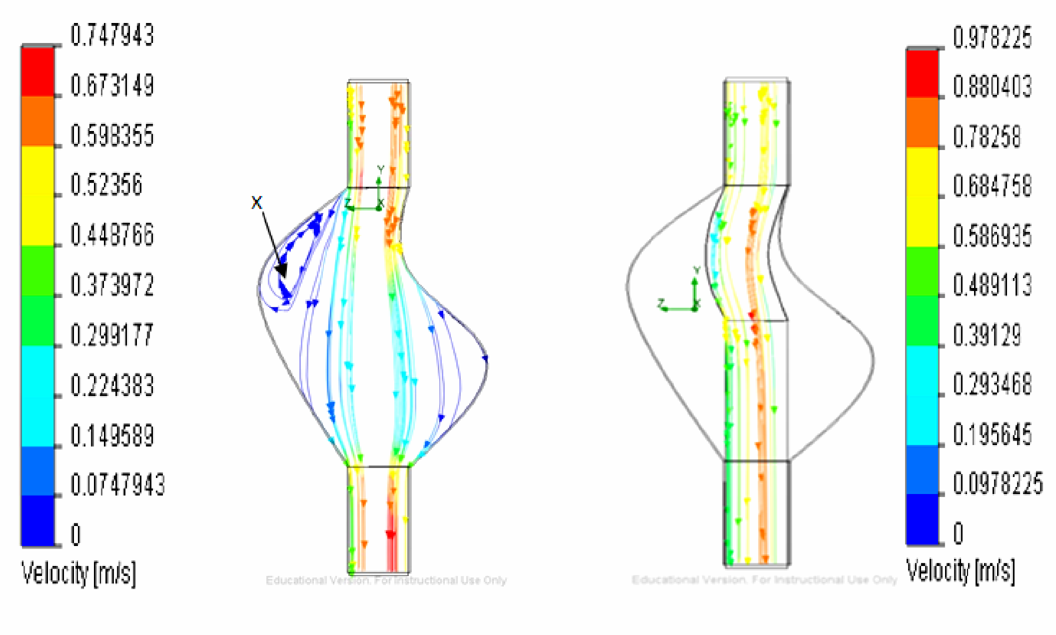
(a) (b)

Fig. 2. Blood flow pattern with pressure distribution in abdominal aortic aneurysm (AAA), (a) without stent graft (SG), (b) with stent graft (SG)



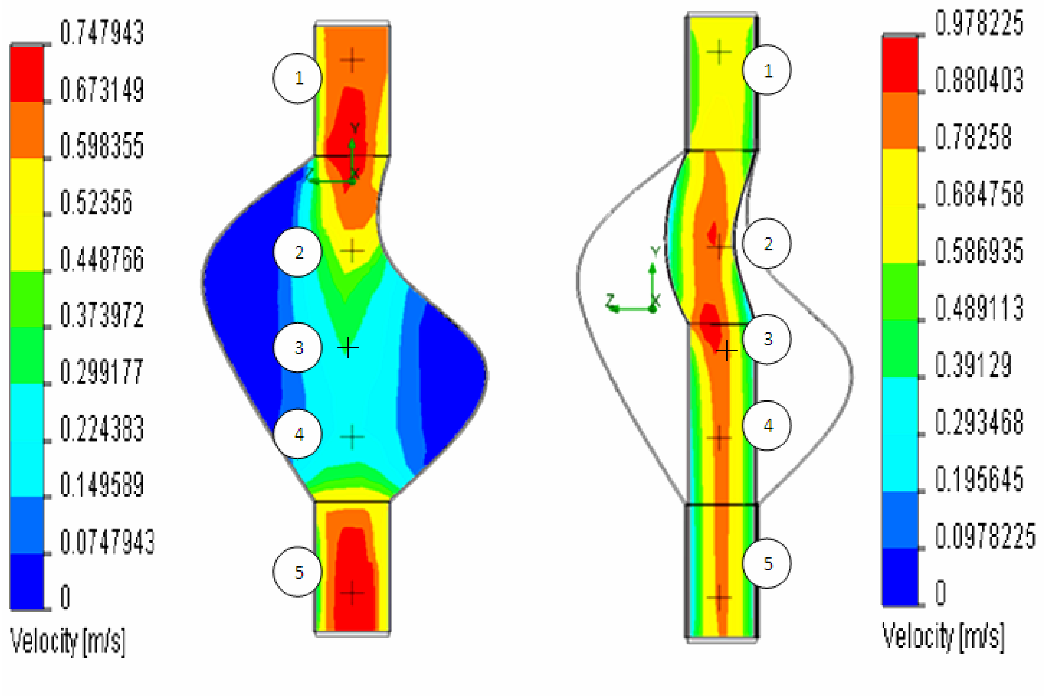
(a) (b)

Fig. 3. Pressure distribution in abdominal aortic aneurysm (AAA), (a) without stent graft (SG), (b) with stent graft (SG)



(a) (b)

Fig. 4. Blood flow pattern with velocity distribution in abdominal aortic aneurysm (AAA), (a) without stent graft (SG), (b) with stent graft (SG)



(a) (b)

Fig. 5. Velocity distribution in abdominal aortic aneurysm (AAA), (a) without stent graft (SG), (b) with stent graft (SG)

Fig. 6. Comparison of pressure at five selected point inside the AAA models.

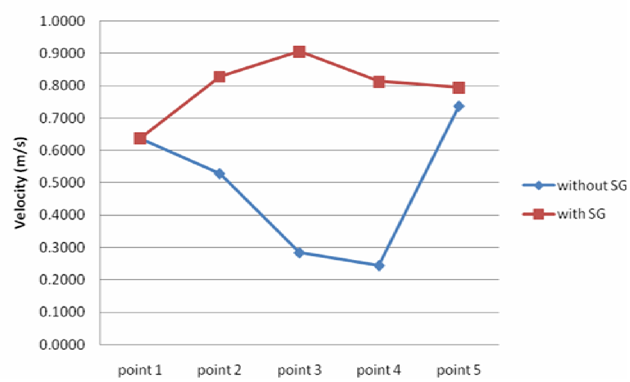


Fig. 7. Comparison of velocity at five selected point inside the AAA models.

In this analysis five fixed points has been taken to monitor the changes of pressure and velocity inside the AAA sac and stent graft (Fig. 6 and Fig. 7). Point 1 located at the proximal region, point 2 to 4 at the aneurysm region and point 5 located at the distal region of the models. Simulation results show that the pressure inside the stented AAA is smaller than the pressure inside the unstented AAA. The average pressure difference at point 2 to 4 is 297.192 Pa. For velocity analysis, there is significant difference between these models where the velocity of blood crosses over the stented AAA is higher than inside the unstented AAA. The average velocity at point 2 to 4 for stented AAA is 0.8492 m/s while for unstented AAA is 0.3531 m/s. The velocity difference between these two models is 0.4961 m/s.

The results obtained from this simulation proved the effectiveness of the SG to increase the velocity of blood that flow through the AAA and reduce the pressure inside the AAA. The placement of SG inside the aneurysm region will restore normal blood flow and prevent the formations of plaque at the aneurysm wall, thus reduce possibility for wall rupture and artery blockage.

There are several limitations of this study that should be addressed. The model of aneurysm constructed was highly simplified due to limitations on geometrical parameters of original stent graft. Most of the parameter used in this simulation are based on the studies conducted by the previous researchers.

V. CONCLUSION

In summary, the simulation results indicate that implanting a SG in an AAA can significantly reduce the sac pressure, increase velocity of blood and restore normal blood flow and therefore reduced the chance of wall rupture. These results are encouraging and point to the huge potential of using computational fluid dynamic simulation for a better understanding of the SG effect in AAA and design advanced structure of SG in order to reduce the post-operation failure.

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