Proceedings of the ECCOMAS Thematic International Conference on Simulation and Modeling of Biological Flows (SIMBIO 2011)
September 21-23, 2011, VUB, Brussels, Belgium

Flow Analysis with Stent Placement in the Cerebral Aneurysm

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Abstract

After surgery, the aneurysm recurrence may happen. In the worst scenario, the patient not only suffers from repeated treatment but also may even die due to the unsecured aneurysm or the treatment itself. Although there are wide variety of surgical or endovascular therapeutic options for the treatment of these difficult aneurysms, none of the current technique is complete successful. However, we could not possibly know which treatment is superior to the others unless we really try it. Therefore, the CFD analysis to aneurysm has been considered as an evaluation tool for treatment of aneurysm and can provide hemodynamic information to clinicians to make an optimal therapeutic choice.

We simulated the case with a helix stent traversing the aneurysmal in a side aneurysm using CFD. Furthermore, we simulated the cases of a straight pipe and several bending ones (with curvature θ of 15˚ ,30 ˚ , and 45˚) to study the effects of helix stent placement across side wall aneurysm pore. Figure 1 shows the cerebral aneurysm model and the mesh of the artery. Hence, this study focuses on flow fields inside a stented cerebrovascular aneurysm model at different angle to curved vessel in order to provide a better understanding of the pertinent hemodynamic factors for the reference of the endovascular treatment. Results are presented in terms of the main and secondary flow velocity vector fields, the inflow rates into the aneurysm and the intra-aneurysmal wall shear stress and pressure. In general, if the blocking ratio is 30%, the blood in aneurysm may stop flowing and form clot. Based on the comparisons of the computed results of the different angle model, the flow pass into the aneurysm can be known. Large flow may cause aneurysm to rupture or recurrence; however, the cerebral surgery is not a time bomb. If we can judge whether the local stent is suitable for a patient according to the flow field from CFD analysis, the unnecessary surgery treatment to the patients with aneurysm can be avoided and the risk can be reduced.

Keywords: aneurysm, stent, parent vessel, Hemodynamic

Introduction

Cerebral aneurysms are pathologic dilations of the arterial wall that frequently occurred at or near arterial bifurcations. The prevalence of cerebral aneurysm in Western population is 3%-5%. Cerebral aneurysms are the cause of spontaneous subarachnoid hemorrhage in 65%-85% of cases. During the initial period of cerebral aneurysm morbidity, anti-hypertensive drugs is useful to alleviate the impact on the artery inner wall caused by blood. When cerebral aneurysm ruptures, it must be treated by surgery. The available treatment options for brain aneurysms includes surgical clipping and intravascular stenting [1 - 2] . In treating aneurysms intravascular stenting [3] is thought as a better option compared with clipping treatment. This is because craniotomy with clipping cannot completely seal off an aneurysm with a wide or calcified orifice and generally has the risk of surgical complications. Besides, the intravascular stenting can serve as a complementary approach for treating saccular aneurysms with wide opening and fusiform aneurysms in which the packing materials are likely to extent or migrate from the aneurysm into the parent vessel. Stenting across the aneurysmal orifice could sufficiently prevent the aneurysm from rupture [3-6]. After 7 days of the metal stent placement in dogs for the treatment of the internal carotid aneurysm [6] , also demonstrated an effective occlusion of the aneurysm based on brain angiography.

Hemodynamic factors such as blood flow velocity, wall shear stress (WSS) and pressure have influences on the growth and the rupture of aneurysms. From flow dynamic point of view, an aneurysm arising from a parent vessel is similar to a cavity in a pipe wall. The inflow rate into the aneurysm depends partly on the curvature of the parent vessel. For a straight parent vessel the inflow into the lateral aneurysm is typically less than 1% of the parent vessel's volume flow rate [7] and is mainly driven by viscous diffusion (with an approximately null inflow angle) since flow in the cerebral artery is laminar and tangential to the aneurysmal pouch [8].

After surgery, the aneurysm recurrence may happen, in the worst scenario, the patient not only suffers from repeated treatment and may even die from the unsecured aneurysm or the treatment itself. Although there are wide variety of surgical or endovascular therapeutic options for the treatment of these difficult aneurysms, none of the current technique is complete successful. However, we could not possibly know which treatment is superior to the others unless we really try it. Therefore, the aneurysmal CFD analysis has been considered as part of the evaluation tools for treatment of aneurysm and can guide hemodynamic information to clinicians making an optimal therapeutic choice.

In the research, we simulated the case with a helix stent traversing the aneurysmal in a side aneurysm using CFD and focuses on more realistic artery curves which provide an inertia-dominated inflow into the aneurysm (with a finite inflow angle [9]). Moreover, the curvature of the parent vessel will induce helical flow that further complicates the nature of inflow. As a result, the placement of stents in the 'curved' arteries harboring lateral aneurysms (figure 1) for intravascular treatment to effectively alter the local hemodynamics, promote the formation of thrombus inside the aneurysm, and, in turn, exclude the aneurysm from cardiac circulation becomes more interesting and critical.

Furthermore, we simulated the cases of a straight pipe and several bending ones (with curvature θ of 15˚,30˚, and 45˚) to study the effects of helix stent placement across side wall aneurysm pore. Hence, this study focuses on flow fields inside a stented cerebrovascular aneurysm model at different angle to curved vessel in order to provide a better understanding of the pertinent hemodynamic factors for the reference of the endovascular treatment.

Materials and Numerical Methods

The parent vessel with an inner diameter of 5 mm (D) simulating human internal Cerebral artery is depicted in figure 1. Θ is an angle between axis direct to the dome along the aneurismal centerline and axis along parent vessel centerline. The diameters of the aneurysmal orifice, neck and fundus were l =1.4D, n = 1D and f = 1.5D, respectively, and the distance between orifice and dome measured h = 2D. The helical stent depicted in figure 1 was 15 mm (L) long.

A 30-mm long (L in Fig.1) stainless wire with a diameter of d=0.5 mm was coiled around a threaded steel rod of 9 mm in diameter. The effect of the stent on the inflow into the aneurysm can be characterized by the blocking ratio defined as:

$$C_\alpha = \frac{Nd}{L} \qquad (1)$$

where N is the number of filaments (or stent loops). The porosity can then be expressed as 1-C_a. In this study, the value of C_a was fixed at 30%.

We assumed the blood flow is laminar in the cerebral artery and neglected the gravity effect. Besides, there was no phase change occurrence. We assumed the blood is incompressible. The governing equations, continuity equation and momentum equation, were used to calculate the velocity and pressure of the flow.

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \qquad (2)$$

Momentum Equation:

$$\frac{\partial}{\partial t}(\rho U) + \nabla \cdot (\rho U \times U) = -\nabla P + \nabla \cdot \tau + S_M \qquad (3)$$

The terms of time could be eliminated due to the steady condition. $\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$, $\mathbf{U} = (U_x, U_y, U_z)$, in which u, v, w are the velocities in x, y, z directions respectively. P, μ, ρ and τ are the pressure, viscosity, density and strain rate respectively. S_M is source term. Under the Newtonian flow assumption, the density and viscosity of the blood are 1,080 kg/m^3 and 3.88×10^{-3} kg/m•s, respectively.

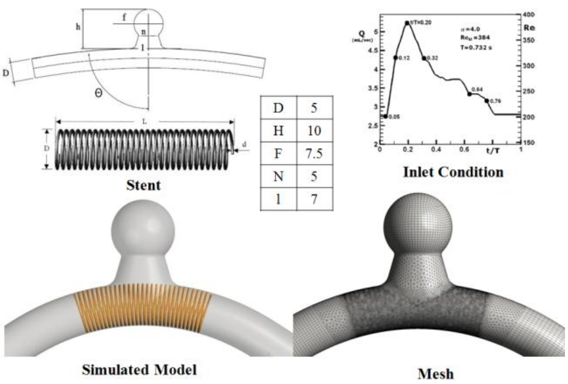

Fig.1 Configuration, dimensions, grid distribution and arterial inlet reference station.

For numerical simulation, the 3D mesh was constructed with the 3D geometry model using the ANSYS ICEMCFD (Ansys, Berkeley, CA),see Fig1. The computational grid comprises about 1 , 4 00,000 unstructured tetrahedral and hexahedral grids. We used commercial package ANSYS CFX (Ansys, Berkeley, CA) to solve the Navier-Stokes equations with a second-order accuracy scheme. ANSYS CFX solvers are based on the finite volume method. IBM P690 in NCHC (National Center for High Performance Computing) was taken as the computing hardware and using 8 CPUs.

The objective of this research is to observe the flow field near the cerebral aneurysm under the stable flow condition. The variation of the pulsatile volume flow rate with time over the cross-section of the inlet reference station.[10] See Fig.1.The outlet condition is set as a reference pressure, 0 Pa. All vascular walls were considered as rigid, with a no-slip condition.

Results and Discussion

When the stent embolization treatment is proceeding, the doctor placed stent across the aneurysmal orifice could sufficiently reduce the blood flow and make the aneurysm closed, furthermore, to prevent the aneurysm from rupture. Four time point (t/T=0.05,0.2,0.36 and 0.72), were selected to characterize the pulsatile flow field in the aneurysm. Figure 2-5 depicts the velocity vector fields inside the aneurysm for without stent placement in four degree of curvature of the parent vessel at four time point (t/T=0.05,0.2,0.36 and 0.72). In case of the degree of curvature of the parent vessel being zero ($\theta=0^\circ$), the blood flows into the aneurysm along the wall with a low velocity (See Figure 2-5). On the other hand, in case of the degree of curvature of the artery being 15˚ or 30˚, the velocity of blood into the aneurysm is higher compared with the above case ($\theta=0^\circ$). When compared to the straight parent vessel ($\theta=0^\circ$), the velocity are increased to 101% to 374% and 167% to 504% at the four time point for the case of $\theta=15^\circ$ and $\theta=30^\circ$,respectively. Rate percentage (%) compare to $\Theta=0^o$ of all case in table.1.

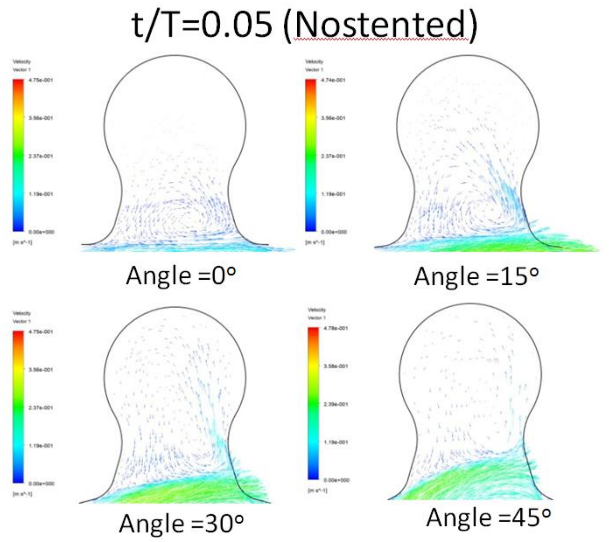

Fig. 2 Intra-aneurysmal velocity vector fields without stent placement in four degree of curvature of the parent vessel at t/T=0.05.

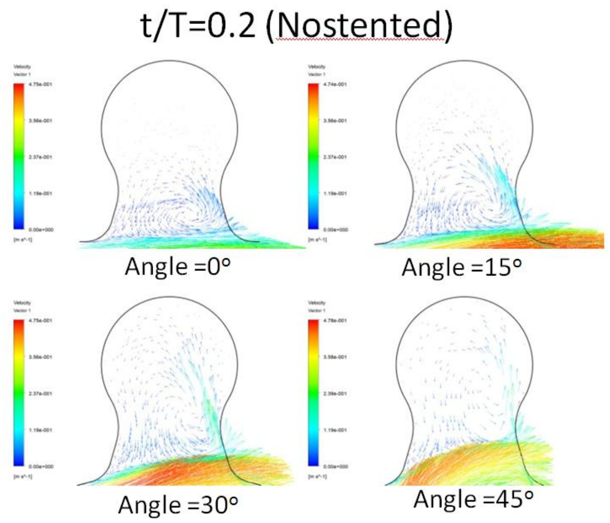

Fig.3 Intra-aneurysmal velocity vector fields without stent placement in four degree of curvature of the parent vessel at t/T=0.2.

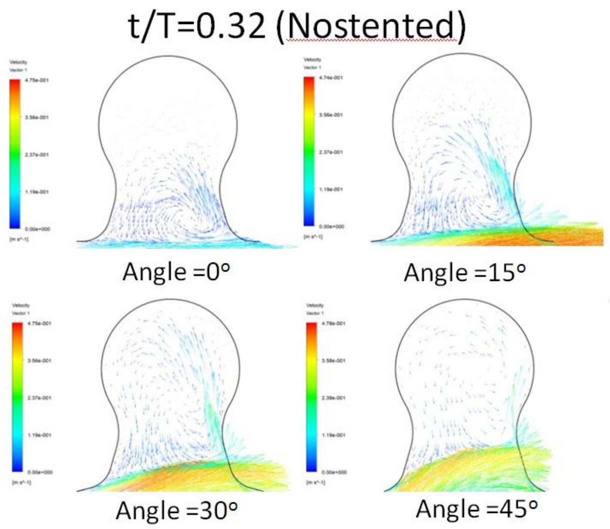

Fig.4 Intra-aneurysmal velocity vector fields without stent placement in four degree of curvature of the parent vessel at t/T=0.32.

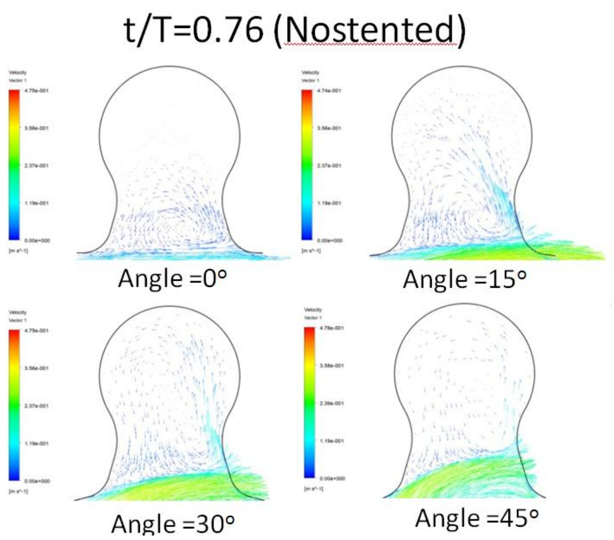

Fig.5 Intra-aneurysmal velocity vector fields without stent placement in four degree of curvature of the parent vessel at t/T=0.76.

Table.1

	Rate percentage (%) compare to ϴ=0°			
Angle of parent vessel	t/T=0.05	t/T=0.2	t/T=0.32	t/T=0.76
ϴ=0°	--	--	--	--
ϴ=15°	192	101	374	265
ϴ=30°	307	167	504	374
ϴ=45°	295	157	494	364

In case with helix stent placement, the velocity of the blood in the aneurysm becomes smaller than the case without stent placement. Figure 6-9 depicts the velocity vector fields inside the aneurysm for with stent placement in four degree of curvature of the parent vessel at four time point (t/T=0.05,0.2,0.36 and 0.72).

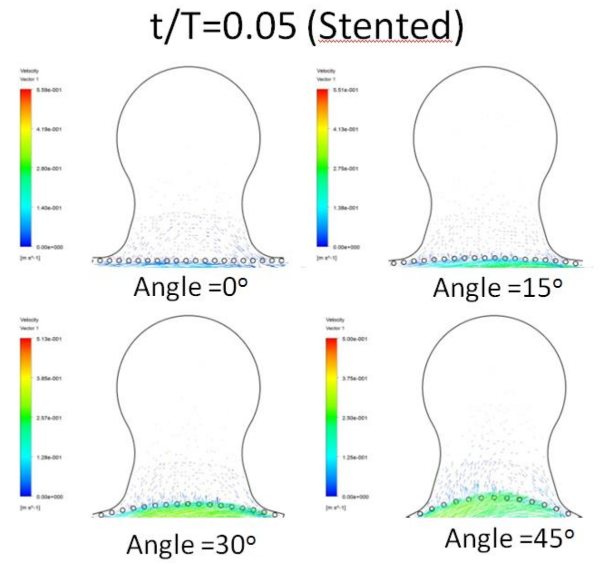

Fig.6 Intra-aneurysmal velocity vector fields with stent placement in four degree of curvature of the parent vessel at t/T=0.05.

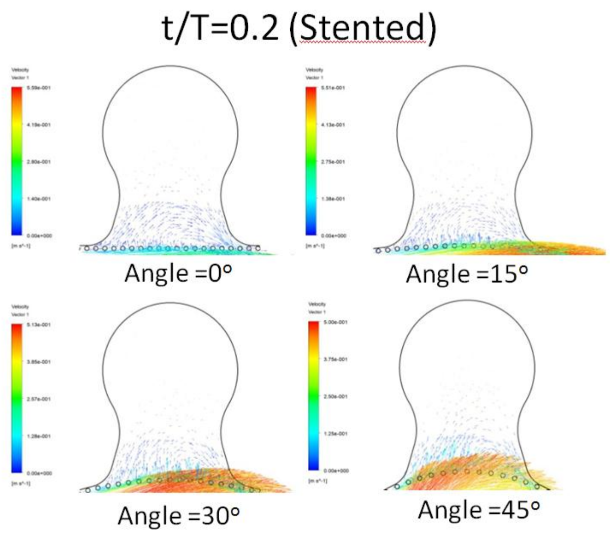

Fig.7 Intra-aneurysmal velocity vector fields with stent placement in four degree of curvature of the parent vessel at t/T=0.2.

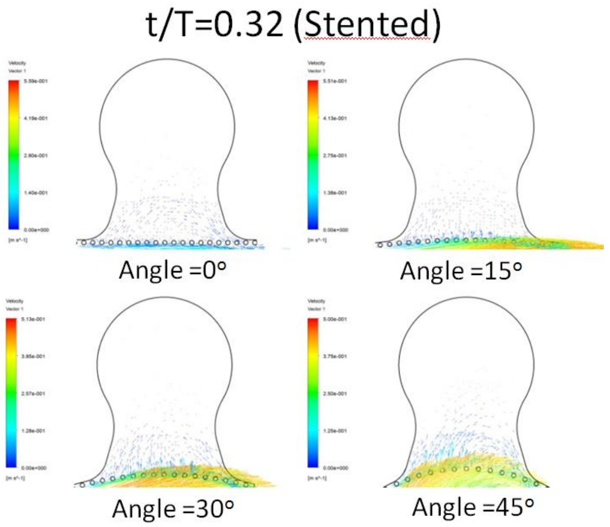

Fig.8 Intra-aneurysmal velocity vector fields with stent placement in four degree of curvature of the parent vessel at t/T=0.32.

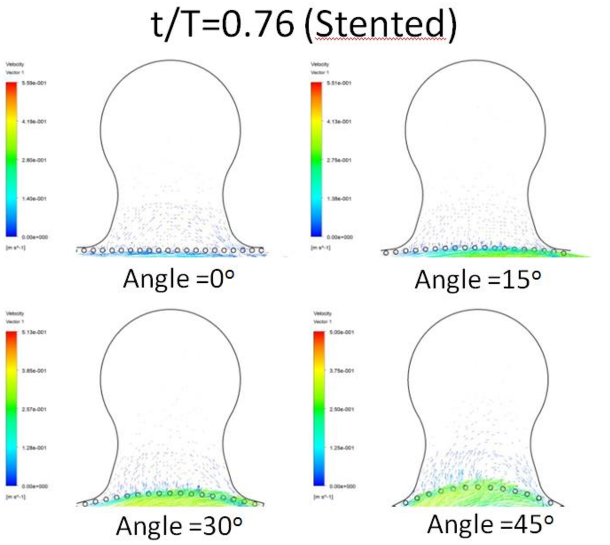

Fig.9 Intra-aneurysmal velocity vector fields with stent placement in four degree of curvature of the parent vessel at t/T=0.76.

Besides the qualitative analysis of the flow field, it is worthy to quantitative analyze of the flow rate Q into the aneurysm. A higher flow rate into the aneurysm implies the blood in the aneurysm subjected stronger disturbance. Therefore, the risk of the aneurysm calcified is reduced. Refer to Fig.10, Q_a and Q_{max} represent the flow rate into the aneurysm and the maximum flow rate in the parent vessel, respectively. The figure shows the ratio, Q_a / Q_{max}, of impulse flow at t/T=0.2 (where T is the period of the impulse flow) in the case of a stent embedded or not into the parent vessel under the parent vessel with different angle. The ratio decreases when a stent is embedded and a maximum ratio is obtained when the angle is 15^0 in either case. The ratio decreases slightly when the angle is above 30^0 due to the impulse flow. In the case without a stent, the simulation results show the percentage of the ratio is raised by 45.68%, 42.15% and 18.81% under the angle of 15^0, 30^0 and 45^0 compared to the angle of 0^0, respectively. In the case of 0^0, the percentage of flow rate with a stent compared to that without a stent is decreased by 36.77%, and decreased by 25.24%, 25.87% and 15.47% in the cases of 15^0, 30^0 and 45^0, respectively. The stent has a better effect when the angle is less than 30^0 which is consistent to the steady case.

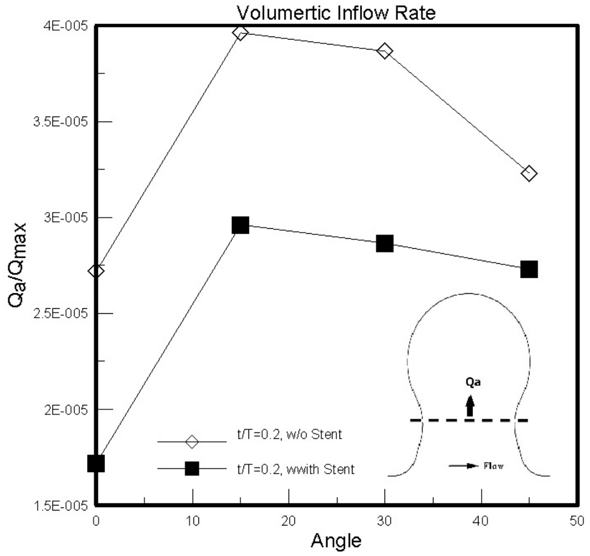

Fig.10 Volume flow rate (Q_a / Q_{max}) in four degree of curvature of the parent vessel at t/T=0.2.

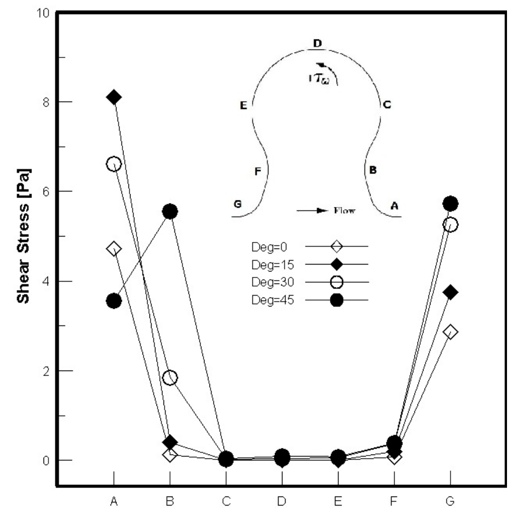

Fig.11 Wall shear stress (WSS) with stent placement in four degree of curvature of the parent vessel at t/T=0.2.

The wall shear stress (WSS) increases with the blood velocity within the aneurysm increases. Because a higher WSS makes the aneurysm grow, it is better to decrease the WSS when a stent was embedded at the neck of the aneurysm. Based on the simulation results and the previous discussions, the WSS gets higher with the ratio, Q_a / Q_{max}, of the flow rate into the aneurysm is larger in case of a larger angle. Fig. 11 shows the WSS distribution under different angle at t/T=0.2. As the figure shows, a xy-plane and seven points (A-G) were taken and sampled to study the WSS distribution. The WSS is relative small in case of 45^0. When the angle of the parent vessel is 45^0, it forms a particular direction of the blood flow into the aneurysm which leads the amount of blood at point A decreases, and therefore the velocity and WSS at point A decrease. Refer to points B to G, a higher WSS appears at point B and G and the WSS increases with the angle increases. At point C, D and E located at the internal part of the aneurysm, the blood amount is less and the WSS is low.

Refer to Fig. 12, the figure shows the WSS at the position Z*=0 in case of a stent embedded. Based on the results, the larger WSS appears at point A and point G. However, the WSS within the aneurysm is relative small. When the angle of parent vessel is 0^0, the WSS is decreased by 77.69% and 89.75% at point A and G, respectively. When the angle of parent vessel is 15^0, the WSS is decreased by 43.73% and 43.39% at point A and G, respectively. When the angle of parent vessel is 30^0, the WSS is decreased by 98.71% and 98.30% at point A and G, respectively. When the angle of parent vessel is 45^0, the WSS is decreased by 88.96% and 95.09% at point A and G, respectively. The results suggest a stent provide the better effect when the angle of parent vessel is 30^0.

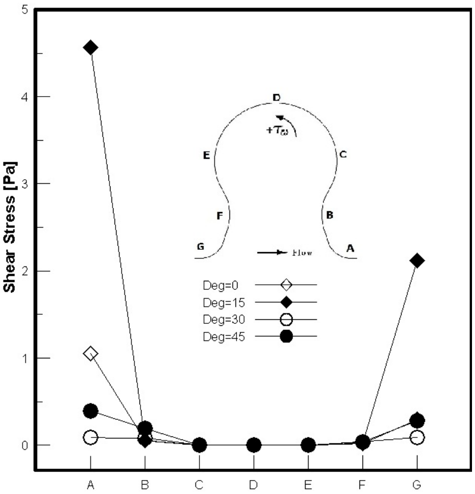

Fig.12 Wall shear stress (WSS) without stent placement in four degree of curvature of the parent vessel at t/T=0.2.

Conclusions

The research studies the effects of the angle of the parent vessel and the stent on the flow field within the aneurysm. We analyzed the flow field, the flow rate into the aneurysm and the WSS within the aneurysm. We propose the following conclusions based on the above results and discussions:

1. The velocity field appears a significant difference between a stent embedded or not. The embedded stent disturbs the flow field and causes a different vortex at the entrance of the aneurysm. Furthermore, it leads a decreasing flow rate into the aneurysm. The WSS within the aneurysm in the case with a stent is decreased, too.

2. The maximum velocity in the case of 30^0 without a stent is 42.3cm/s. The ratio of the maximum velocity in the aneurysm in the case of 30^0 to the case of 0^0 is 1.2(t/T=0.12) to 5(t/T=0.32) under the impulse flow. The maximum velocity in the case of 45^0 with a stent is 47.4cm/s. The ratio of the maximum velocity in the aneurysm in the case of 45^0 to the case of 0^0 is 2.9(t/T=0.12) to 10.9(t/T=0.64) under the impulse flow.

3. The WSS at the neck of the aneurysm is larger than that in the aneurysm whether there is a stent. In the case of 30^0 with a stent, the WSS is decreased by 99% compared to the case without a stent under the steady flow and impulse flow.

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