Blood Flow Dynamics in Cerebral Aneurysm - A CFD Simulation

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Submitted by

Shamiul Sarker Shishir (101405)

Md. Abdul Karim Miah (101403)

Under the Guidance of

Prof. Dr. A. K. M. Sadrul Islam

DEPARTMENT OF MECHANICAL AND CHEMICAL ENGINEERING

ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

ORGANISATION OF ISLAMIC TECHNOLOGY (OIC)

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DECLARATION

This is to certify that the work presented in this thesis is an outcome of the study carried out by the authors under the supervision of Dr. A. K. M. Sadrul Islam at IUT Campus, Gazipur, Bangladesh. This is an authentic record of the study carried out as requirement for the award of degree of Bachelor of Science in Mechanical Engineering.

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ABSTRACT

In the present study, the dynamics of blood flow in saccular cerebral aneurysms is investigated. The aneurysm is considered to be located at an arterial bend in human vascular system. The flow field is analyzed computationally by three-dimensional Navier-Stokes equations for laminar flow of incompressible Newtonian fluid. Circular and elliptical necks of different sizes are studied here. The vascular wall is considered rigid for simplicity. Hemodynamic parameters such as streamlines, velocity, vortices, wall shear stress and so on are considered for characterization of flow field. Results showed that the vortex location, stagnation zones and so on are varied significantly with the geometrical parameter of the aneurysm.

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1. Chapter one:

1.1. Cerebral aneurysm:

Cerebral aneurysms (also called brain/intracranial aneurysms) are a cerebrovascular tissue in which weakness in the walls of a cerebral artery causes localized dilation or ballooning in the blood vessel. Over time, the blood flow within the artery pounds against the thinned portion of the wall and aneurysms form silently from wear and tear on the arteries. As the artery wall becomes gradually thinner from the dilation, the blood flow causes the weakened wall to swell outward. This pressure may cause the aneurysm to rupture and allow blood to escape into the space around the brain. A ruptured brain aneurysm commonly requires advanced surgical treatment.

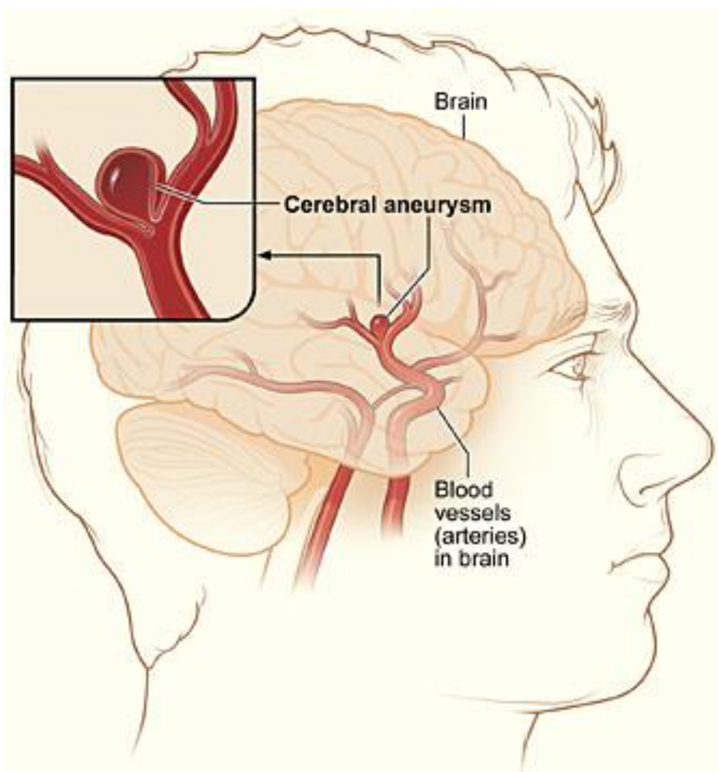


Figure 1: cerebral aneurysm

1.2. How common are aneurysms?

About 1.5 to 5 percent of the general population has or will develop a cerebral aneurysm. About 3 to 5 million people in the United States have cerebral aneurysms, but most are not producing any symptoms. Between 0.5 and 3 percent of people with a brain aneurysm may suffer from bleeding.

1.3. Size:

- Small aneurysms are less than 5 mm (1/4 inch).
- Medium aneurysms are 6–15 mm (1/4 to 3/4 inch).
- Large aneurysms are 16–25 mm (3/4 to 1 1/4 inch).
- Giant aneurysms are larger than 25 mm (1 1/4 inch).

1.4. Shape:

- Aneurysms can be Saccular (sac-like) with a well-defined neck
- Saccular with a wide neck
- Fusiform (spindle shaped) without a distinct neck

1.5. Saccular aneurysm:

A saccular aneurysm is the most common type of aneurysm and account for 80% to 90% of all intracranial aneurysms and are the most common cause of non-traumatic subarachnoid hemorrhage (SAH). It is also known as a "berry" aneurysm because of its shape. The berry aneurysm looks like a sac or berry forming at the bifuraction or the "Y" segment of arteries. It has a neck and stem. These small, berry-like projections occur at arterial bifurcations and branches of the large arteries at the base of the brain, known as the Circle of Willis.

Figure 2: saccular aneurysm

1.6. Fusiform aneurysm:

The fusiform aneurysm is a less common type of aneurysm. It looks like an out pouching of an arterial wall on both sides of the artery or like a blood vessel that is expanded in all directions. The fusiform aneurysm does not have a stem and it seldom ruptures.

Figure 3: fusiform aneurysm

1.7. Location:

An aneurysm is usually located along the major arteries deep within brain structures. When approaching an aneurysm during surgery, normal brain tissue must be carefully spread apart to expose it. Aneurysms can occur in the front part of the brain (anterior circulation) or the back part of the brain (posterior circulation).

1.8. If one aneurysm forms, will others form?

Having one aneurysm means there's a 15 to 20 percent chance of having one or more other aneurysms.

1.9. What causes a cerebral aneurysm :

Intracerebral aneurysms can result from trauma, infection, or neoplastic disease. Most aneurysms, however, result from a developmental abnormality of the inside lining or intima of an artery with abnormal thinning of the vessel at the site of origin. It appears there may be a genetic predisposition to the development of intracerebral aneurysms; the existence in some families runs as high as 10%, approximately 10 times higher than that found in the general population.   There are several other causes of intracerebral aneurysms .For example, they can result from infected embolic material from a bacterial infection on one of the heart valves being deposited on one of the arteries in the brain (mycotic aneuryms).

1.10. Symptoms:

Prior to rupture, saccular aneurysms are usually asymptomatic. However, an expanding aneurysm can have a "mass" effect causing problems with double vision, loss of vision, numbness in the face, an enlarged pupil size, or a drooping eyelid. Usually patients who have an aneurysm rupture experience sudden onset of a severe headache, often described as "the worst headache of my life", frequently accompanied by transient loss of consciousness and sometimes vomiting. A stiff neck often follows. Rupture of an aneurysm usually occur while the person is active rather than during sleep. Occasionally, patients experience a warning or "sentinel" headache which is attributed to a smaller leakage of blood usually preceding a major bleed by several hours to days later. These milder headaches are often associated with nausea and vomiting and are often mistaken for migraine headaches.

2. Chapter two

2.1. Risk factors of cerebral aneurysm:

Risk factors that doctors and researchers believe contribute to the formation of brain aneurysms:

- Smoking
- High blood pressure or hypertension
- Congenital resulting from inborn abnormality in artery wall
- Family history of brain aneurysms

- Age over 40
- Gender, women compared with men have an increased incidence of aneurysms at a ratio of 3:2
- Other disorders: Ehlers-Danlos Syndrome, Polycystic Kidney Disease, Marfan Syndrome, and Fibromuscular Dysplasia(FMD)
- Presence of an arteriovenous malformation (AVM)
- Drug use, particularly cocaine
- Infection
- Tumors
- Traumatic head injury

Risk factors that doctors and researchers believe contribute to the rupture of brain aneurysms:

- Smoking
- High blood pressure or hypertension

2.2. Dangers of cerebral aneurysm:

Aneurysms may burst and bleed into the brain, causing serious complications, including hemorrhagic stroke, permanent nerve damage, or death.

- about 15% of patients die before reaching the hospital
- 40% will not survive the first two weeks, despite the best available care
- Of the remaining 60%, more than half will be permanently disabled perhaps 20% will return to their pre-rupture employment and level of function

2.3. Factors involved in rupture:

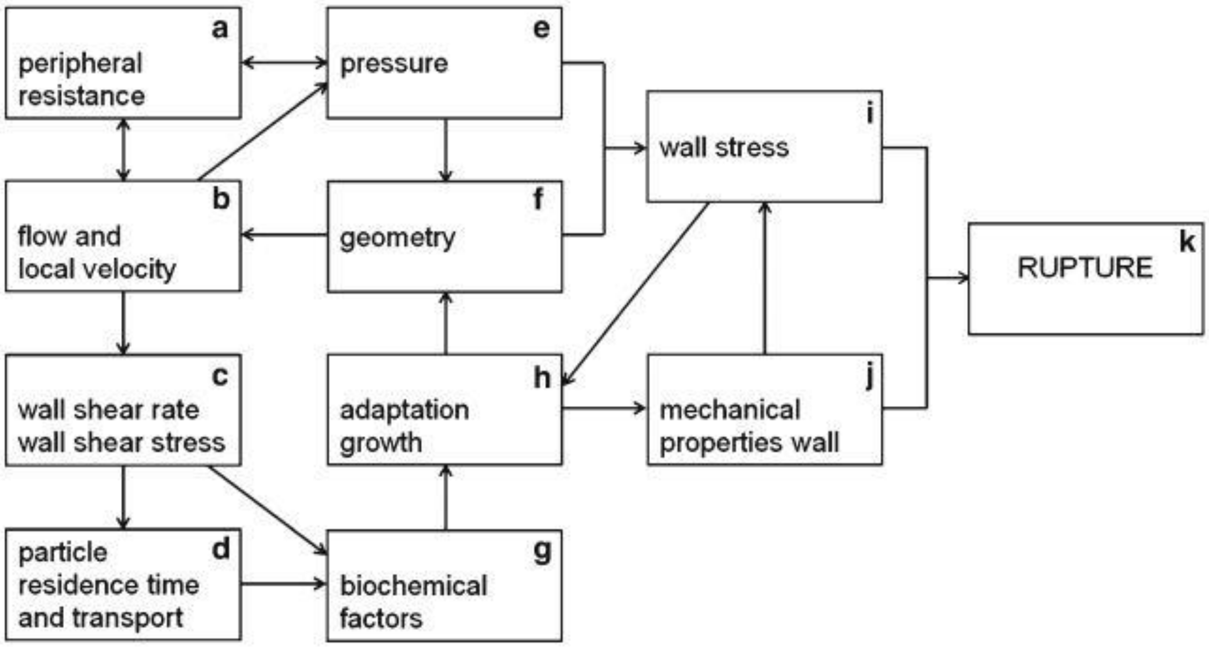


Figure 4: schematic representation of factors involved in aneurysm rupture

The rupture risk is determined by the loading state and the mechanical properties of the arterial wall, which are both related to the hemodynamics. The loading state, i.e., wall stress (i), depends on the mechanical properties of the arterial wall (j), the aneurysmal geometry (f) and the intra-aneurysmal pressure (e). The pressure is determined by the flow (b) through the parent artery and the peripheral resistance (a). The local geometry, which slightly varies with the pressure due to the distensibility of the arterial wall, has a major effect on the intra-aneurysmal flow patterns (b). However, this geometry is also affected by the flow via biochemical cascades that control the adaptation of the arterial wall. The flow-induced wall shear rate (c) is known to affect particle residence times (d). Moreover, changes in shear-stress (c) magnitude and direction alter the permeability of the arterial wall and the transport (d) between the lumen and wall. Endothelial cells are sensitive to these hemodynamical changes, resulting in the activation of biochemical factors (h) that control the adaptation of the arterial wall (g). Altogether, this adaptation may become pathological and may cause weakening of the arterial wall, which, under the influence of wall stress, may result in aneurysm growth. In the event of rupture (k), the mechanical properties of the arterial wall have been altered by the degradation process such that the stress in the wall exceeds its strength.

3. Chapter three

3.1. Simulation with CFD (Boundary conditions):

- At the arterial wall and the wall of aneurysm, no-slip boundary conditions are applied.
- Steady state condition is applied.
- Flow considered as laminar.
- Mean blood flow through 4 mm parent artery was chosen to be 3.6 ml per second.
- Pressure outlet is applied.
- Velocity inlet is considered.

3.2. Properties of fluid used in simulation:

In the simulation, property of the fluid used is in conformity with blood.

Density=1400 kg/m^3 Viscosity=3.5 mPa-s.

3.3. ANEURYSM MODEL:

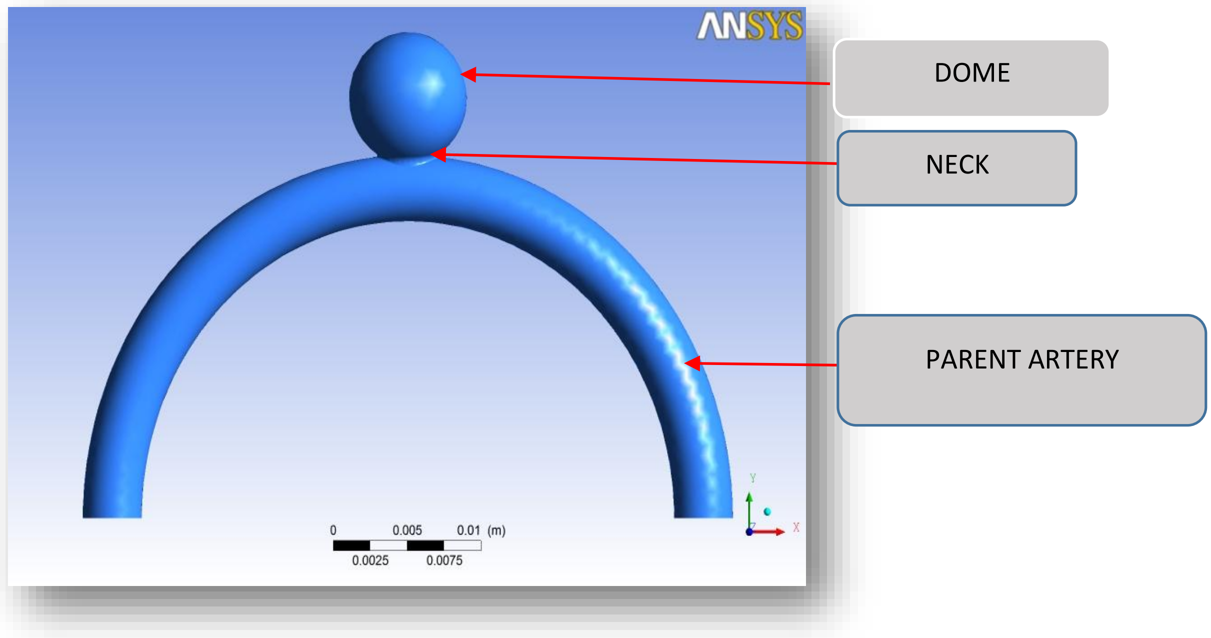
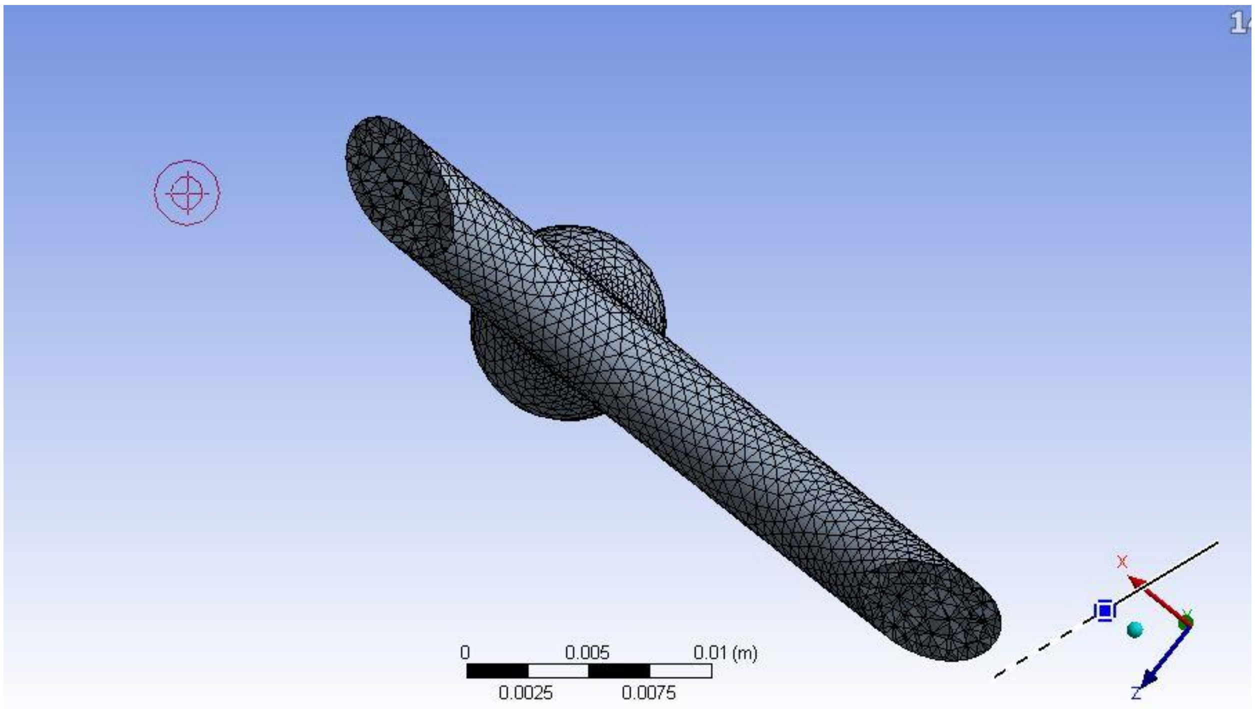


Figure 5: aneurysm model

- The diameter of the parent artery is 4mm.
- The diameter of the dome is 8 mm.
- Different shapes and sizes of neck are studied.
- Inner radius of parent artery is 18 mm.
- Dome is 25.5 mm from base.

3.4. CFD MESHING:



Statistics	
Nodes	17917
Elements	90488
Mesh Metric	None

Figure 6: mesh of the model

- Here we have done Ansys default meshing.
- We have taken more cells at proximity and curvature.
- Total element is 90488.

3.5. Flow pattern inside dome:

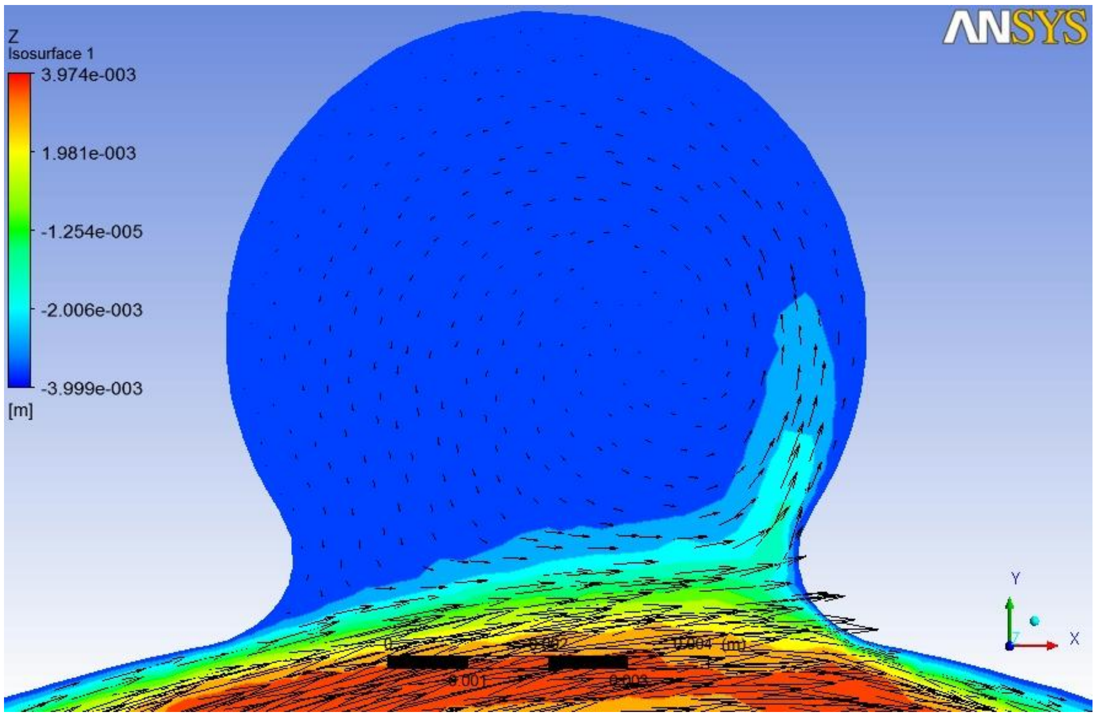


Figure 7: vortex inside aneurysm dome

- Circular vortex is formed inside the dome.
- Maximum wall stress is formed in the wall at outflow.
- Vortex inside the dome has negligible flow.

4. Chapter four

4.1. Geometry factors involved in flow pattern:

- Here we have discussed flow patterns in aneurysms with circular and elliptical necks.
- The ratio of aneurysm dome diameter with the neck diameter (Dome : Neck) has been changed and compared.
- The geometry of cerebral aneurysm is highly patient dependent.
- For the elliptical neck the minor diameter is taken as constant.

4.2. Wall shear stress of aneurysm (elliptical neck):

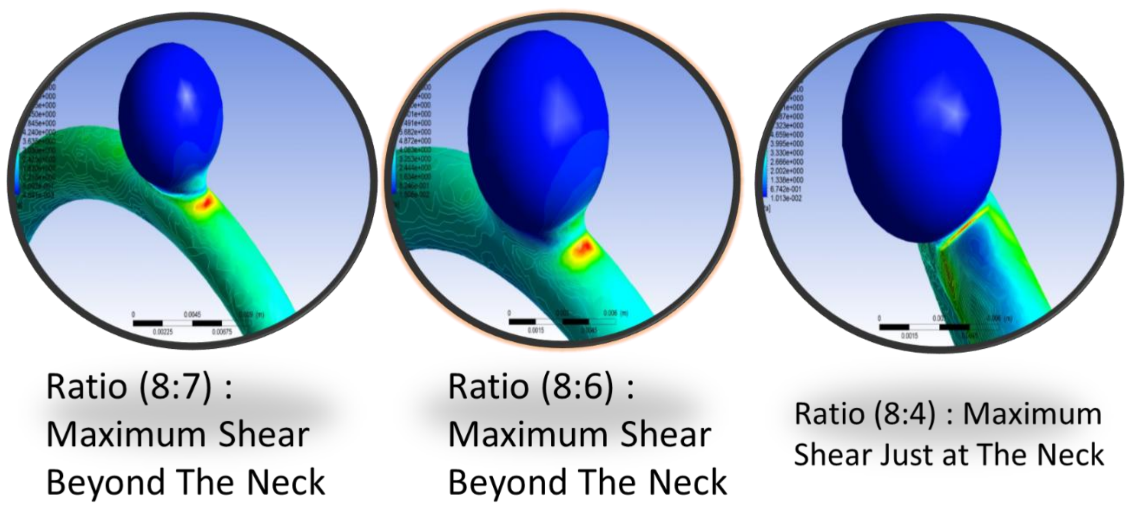


Figure 8: comparison of wall shear stress in aneurysm (elliptical)

- The red color shows region of maximum shear stress.
- Maximum shear stress develops near the neck in outflow region.
- Inside the dome shear stress is nil.

4.3. Velocity Contour And Vector Comparison (YZ Plane Of Aneurysm):

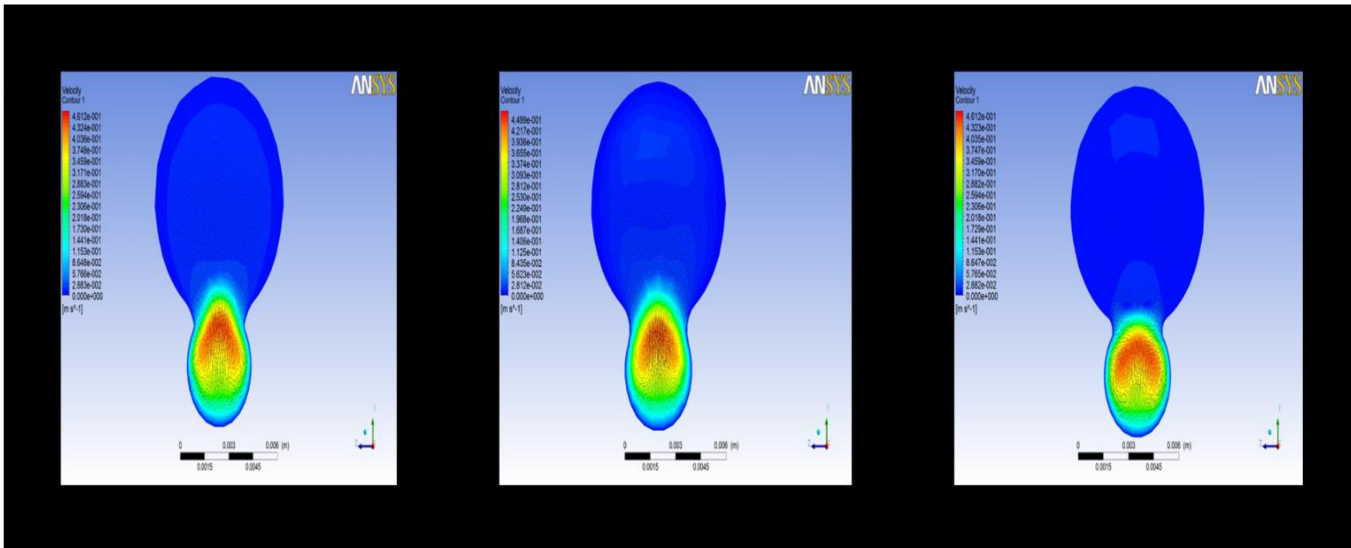


Figure 9: comparison of velocity in aneurysm in yz plane (elliptical neck)

- The red colored region shows maximum velocity zone.
- With close look we can see that two vortices are there just below the neck.
- The aneurysmal neck shows a high velocity gradient where the aneurysmal vortex and the flow in the parent artery meet

4.4. Velocity contour and vector comparison (XY plane):

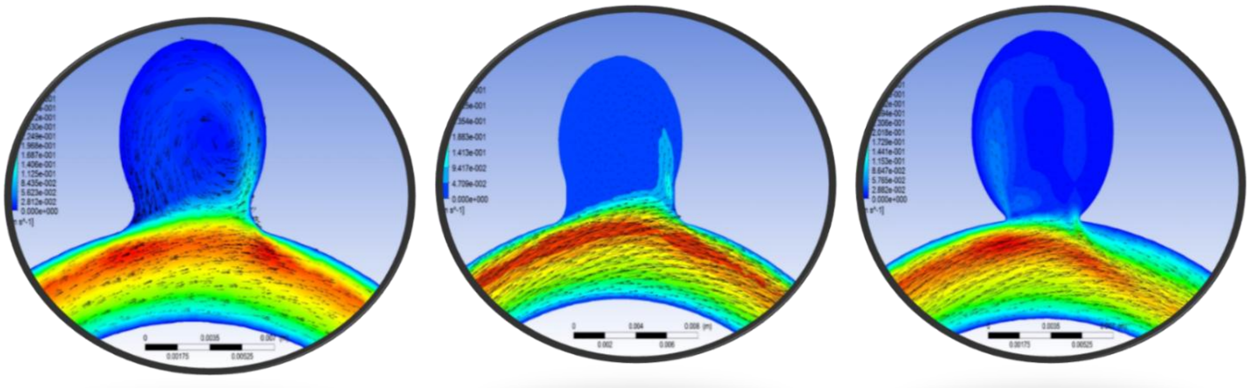


Figure 10: comparison of velocity in xy plane (elliptical neck)

- Flow velocity inside the dome is very less.
- With greater neck diameter the flow inside dome increases.
- The velocity of flow in parent artery is more in large neck diameter.
- Vortex strength at ratio (8:7) is highest. More blood flow is there in the dome

4.5. Velocity vector and contour comparison at aneurysm dome (ZX plane):

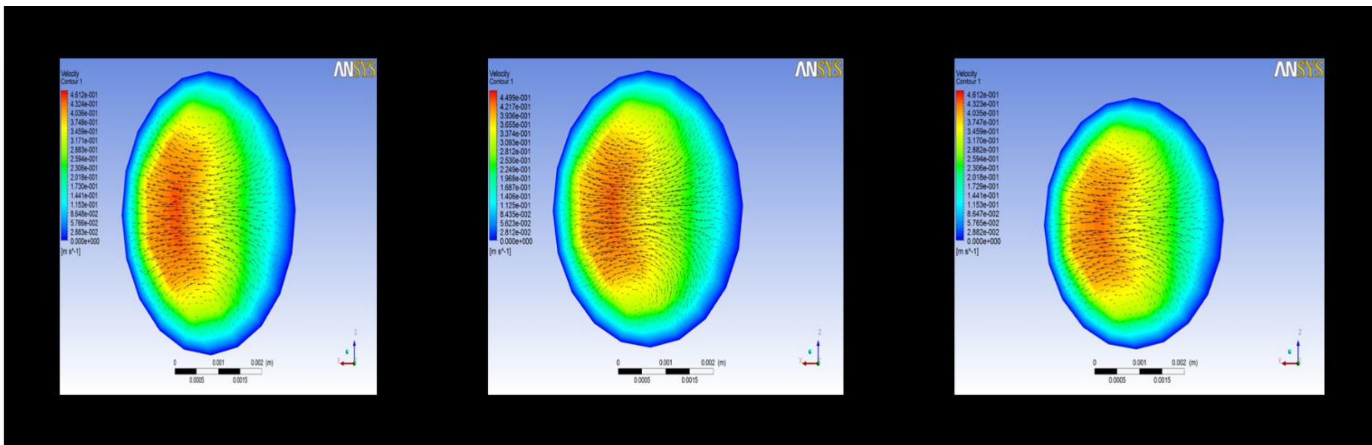


Figure 11: comparison of velocity in aneurysm dome (elliptical neck)

- Velocity is maximum at the (8:7) ratio
- Velocity is not uniform throughout the dome.
- Flow is greater at the side of aneurysm dome.

4.6. Streamline comparison for 500 stream lines and determining the position and no of vortices:

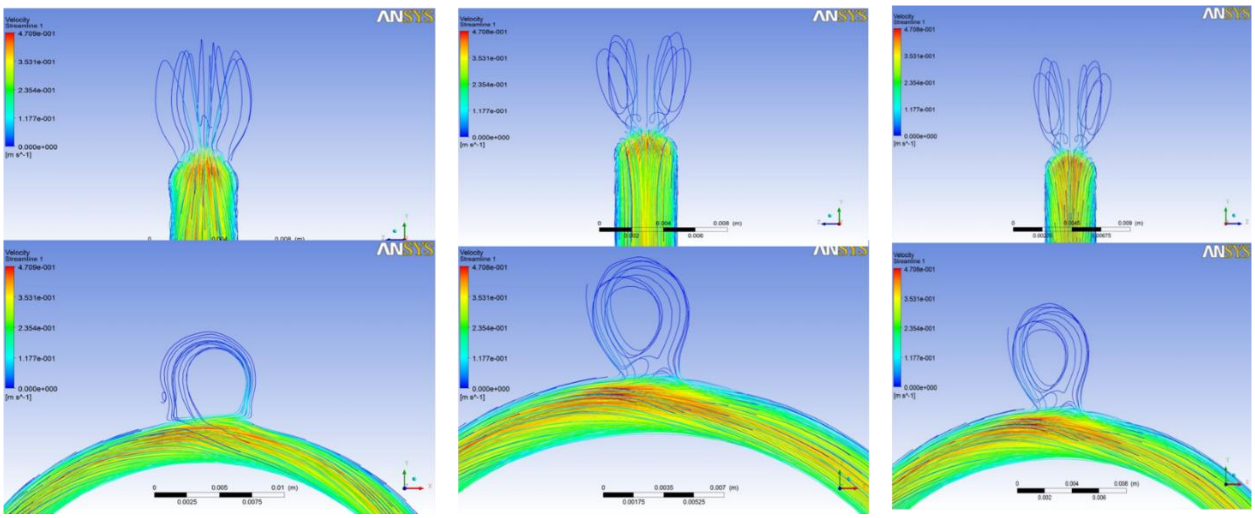


Figure 12: comparison of streamlines (elliptical neck)

- Out of 500 streamlines only 5-8 entered inside the dome.
- The velocity is very less inside the dome.
- There is a vortex created inside the dome.

4.7. Wall shear stress in cerebral aneurysm (Circular Neck):

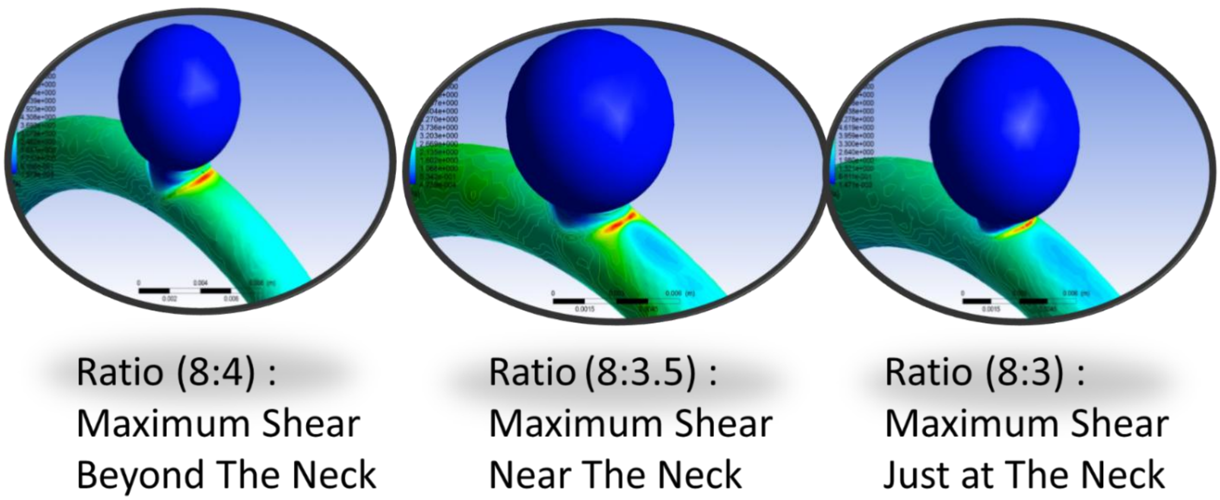


Figure 13: comparison of wall shear stress in aneurysm (circular neck)

- The red color shows region of maximum shear stress.
- Maximum shear stress develops near the neck in outflow region.
- Inside the dome shear stress is nil.
- Even in the neck there is no shear stress.

4.8. Velocity contour and vector comparison (XY plane):

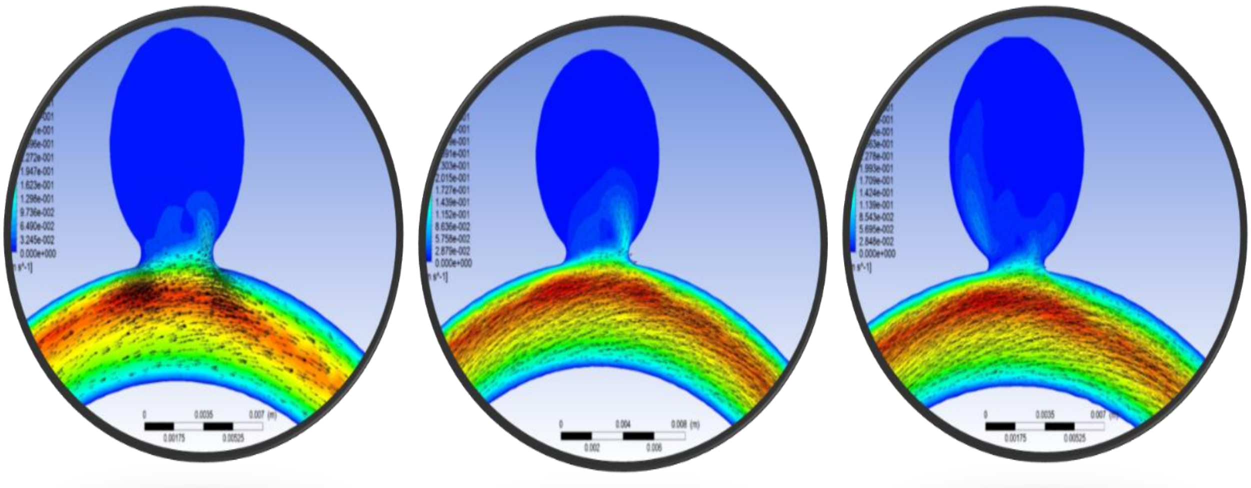


Figure 14: comparison of velocity in xy plane (circular neck)

- There is a reverse vortex in the (8:3) ratio.
- Maximum flow in the (8:4) ratio
- Flow velocity inside the dome is very less.
- With greater neck diameter the flow inside dome increases.
- The velocity of flow in parent artery is more in large neck diameter.
- Vortex strength at ratio (8:4) is highest. More blood flow is there in the dome

4.9. Velocity contour and vector comparison (YZ Plane of Aneurysm:

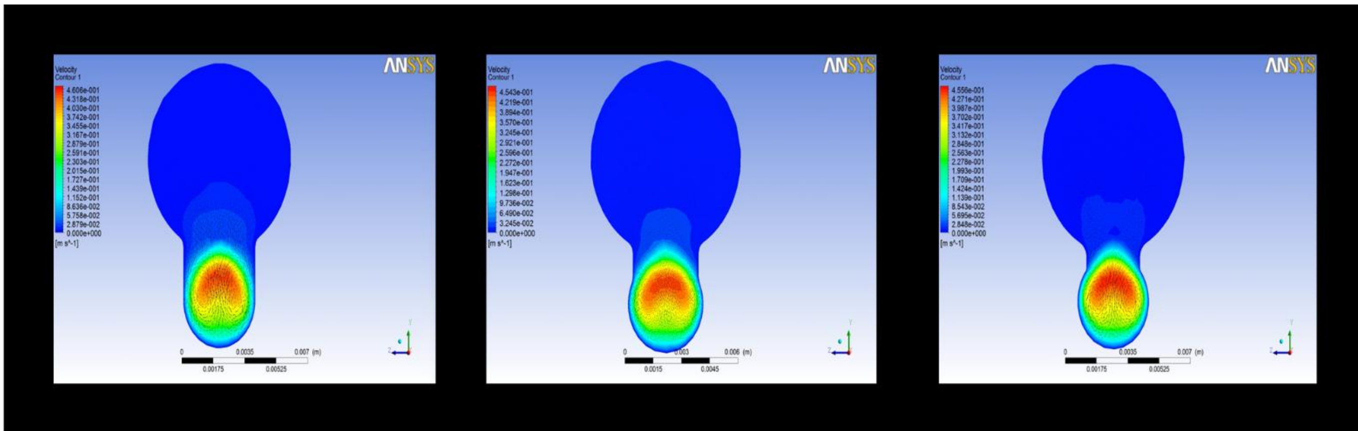


Figure 15: comparison of velocity in aneurysm in yz plane (circular neck)

- The aneurysmal neck shows a high velocity gradient where the aneurysmal vortex and the flow in the parent artery meet.
- Flow velocity inside the dome is very less.
- With greater neck diameter the flow inside dome increases.
- The velocity of flow in parent artery is more in large neck diameter.

4.10. Velocity vector and contour comparison at aneurysm dome (ZX plane):

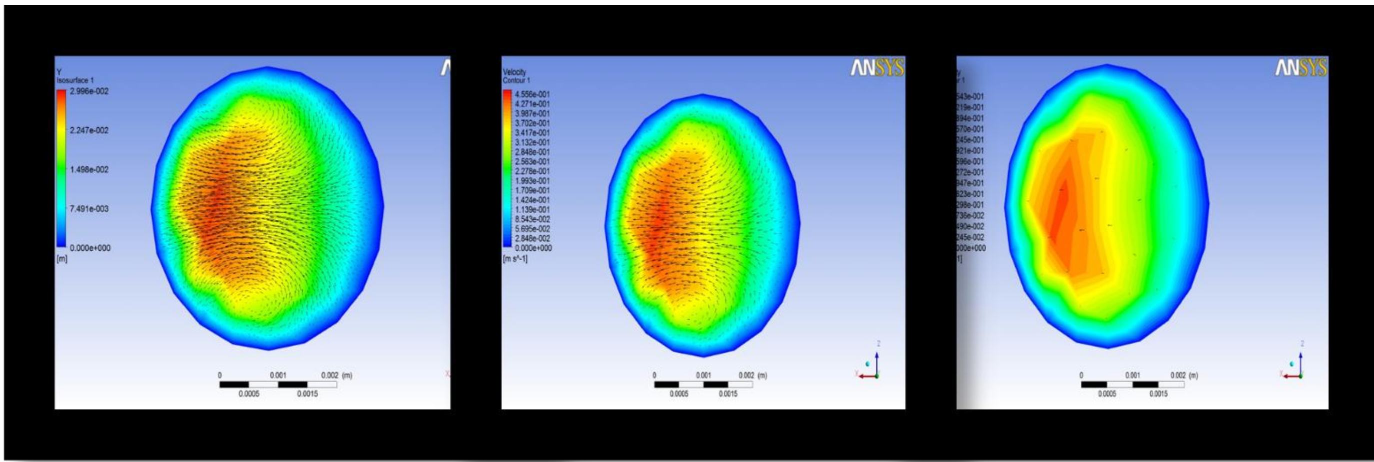


Figure 16: comparison of velocity in aneurysm dome (circular neck)

- Velocity is maximum at the (8:4) ratio.
- Velocity is not uniform throughout the dome.
- Flow is maximum in the aneurysm with large neck.

4.11. Streamline for circular neck:

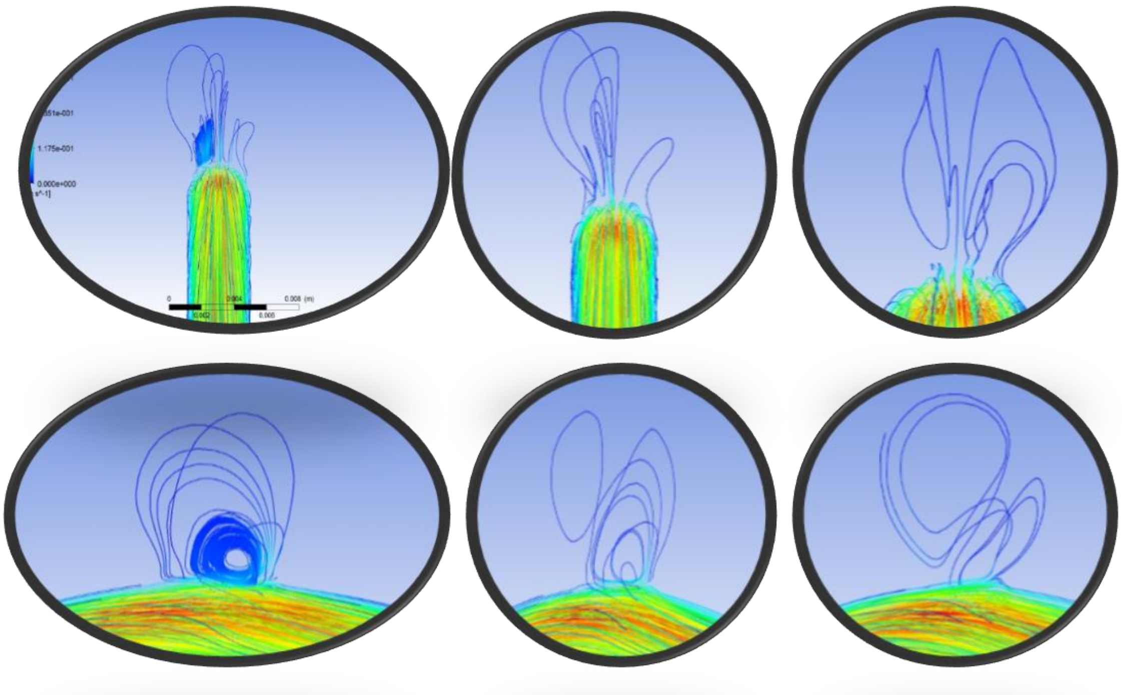


Figure 17: comparison of streamlines (circular neck)

- Out of 500 streamlines only 5-8 entered inside the dome.
- The velocity is very less inside the dome.
- There is a vortex created inside the dome.
- When the ratio is 8:4 the vortex strength is highest and it formed at the neck.
- More flow is there when the ratio is high.

4.12. Tabulation For Elliptical Neck:

Dome Diameter (D)	Neck Diameter (N)	D/N	Maximum Shear Stress(Pa)
8	7	8/7	12.97
8	6	8/6	10.63
8	4	8/4	9.68

4.13. Tabulation For Circular Neck:

Dome Diameter (D)	Neck Diameter (N)	D/N	Maximum Shear Stress(Pa)
8	4	8/4	10.65
8	3.5	8/3.5	9.68
8	3	8/3	8.59

5. Chapter five

5.1. Conclusion:

- From the above comparisons it has been noticed that the aneurysms with comparatively higher neck diameter has high shear stress.
- The patients having aneurysms with higher neck diameter must be treated immediately.
- Aneurysm with elliptical neck has high risk of rapture.
- Again with lower neck diameter the highest shear stress develops just at the neck.
- The cells at the neck is thinner compared to parent artery, so with lower neck diameter there is high risk of rapture.

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