A Review of Hemodynamic Parameters in Cerebral Aneurysm

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Abstract:- A cerebral aneurysm is a localized enlargement of a blood vessel in the brain caused by a weakened vessel wall. It typically appears as a bulge, balloon-like structure, or a small blister. Gaining insight into the mechanisms underlying the formation, growth, and rupture of cerebral aneurysms is crucial for devising treatments to mitigate the risks of mortality and severe complications. These aneurysms arise due to the thinning of arterial walls and are often difficult to detect until they rupture, leading to potentially life-threatening conditions such as hemorrhagic stroke, brain injury, visual impairments, and changes in behavior. Computational fluid dynamics (CFD) has proven valuable in studying cerebral aneurysms by modeling blood flow and analyzing hemodynamic parameters. These parameters play a critical role in assessing rupture risks and influencing biological processes within the affected vessels. This review examines the relationship between key hemodynamic factors and the formation, progression, and rupture of cerebral aneurysms. Additionally, it highlights how these factors are associated with the aneurysm's size, shape, and other morphological characteristics, shedding light on their significance in understanding aneurysm behavior.

Keywords:- *Cerebral Aneurysm, Hemodynamics, Wall Shear Stress, Rupture Risk, Ansys.*

I. INTRODUCTION

A. Definition and Characteristics of Cerebral Aneurysms-

Cerebral aneurysms are abnormalities in the arterial circulation of the brain characterized by a weakened vessel wall that increases the likelihood of rupture. These aneurysms vary in size, ranging from less than 0.5 mm to over 25 mm. Most aneurysms are saccular, commonly associated with a thin or absent tunica media and significantly fragmented or missing internal elastic lamina.

B. Types, Location, and Causes-

While the majority of cerebral aneurysms are saccular, some are fusiform or mycotic in nature. Most remain asymptomatic and are often detected incidentally during neuroimaging or autopsies. Over 85% of cerebral aneurysms are located in the anterior circulation, typically at arterial bifurcations.

C. Advancements in Detection and Treatment Challenges

Neuroradiological advancements have improved the detection rates of cerebral aneurysms; however, predicting rupture risk remains a challenge. Preventive treatments such as surgical and endovascular approaches are not without risks. Identifying aneurysms that are unlikely to rupture, those with rupture potential, and those suitable for intervention has become a critical focus. Consequently, research has turned toward developing statistical models to enhance rupture risk prediction accuracy.

D. Role of Hemodynamic Factors and Technological Advances

Risk factors for aneurysm rupture include the size and location of aneurysms, particularly in the posterior circulation. Over the past two decades, the understanding of hemodynamic factors has significantly advanced rupture risk prediction. Hemodynamic analysis, which examines the effects of blood flow on cerebral aneurysms, has become increasingly important in clinical studies. Advanced simulation software now plays a pivotal role in studying blood flow dynamics and their impact on aneurysm initiation, progression, and rupture.

E. Geometry, Hemodynamic Parameters, and Stress Analysis

- Aneurysm Geometry—specifically size and shape—serves as a critical determinant in treatment strategies. Unlike hemodynamic factors, these geometrical attributes are static but significantly influence intra-aneurysmal blood flow. Even minor changes in size and shape can greatly affect blood flow patterns, underscoring their importance in rupture risk assessment. The biomechanics of blood flow, or hemodynamics, investigates how blood moves through vessels and interacts with their walls. Three primary stresses are associated with blood flow:
- Shear Stress: A tangential force caused by friction on the vessel wall.
- Normal Stress: Arising from hydrostatic pressure, this acts orthogonally on the wall.
- Tensile Stress: A circumferential force exerted against the vessel wall.

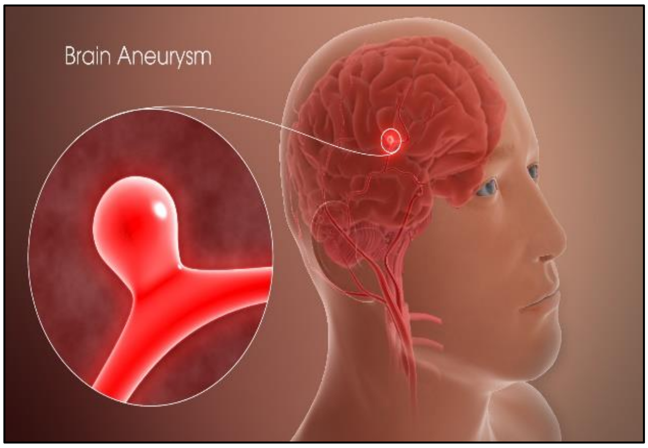

Fig 1: Brain Aneurysm

II. LITERATURE SURVEY

[1] This literature survey reviews the hemodynamic parameters involved in the initiation, growth, and rupture of cerebral aneurysms, emphasizing their role in the pathological processes of these vascular anomalies. By analyzing blood flow simulations, the study identifies key hemodynamic factors that influence the formation and morphological characteristics, such as size and shape, of cerebral aneurysms. The survey highlights the significance of these parameters in predicting rupture risks and their correlation with biological responses in cerebral vessels. It underscores the importance of understanding hemodynamic influences for improving diagnostic and treatment strategies, aiming to reduce mortality and morbidity associated with aneurysm rupture.

A review of hemodynamic parameters in cerebral aneurysm - ScienceDirect

[2] Intracranial aneurysms affect about 2%–3% of the general population. The main risk is rupture, leading to subarachnoid hemorrhage with high mortality and morbidity. Increased detection of unruptured aneurysms has created a treatment dilemma, as their prevalence is high but rupture rates are low (10 per 100,000 person-years). Preventive treatments for unruptured aneurysms carry risks. Recent research aims to improve rupture predictions using statistical models that incorporate hemodynamic factors, alongside traditional risk factors like size and location.

Basic Principles of Hemodynamics and Cerebral Aneurysms - ScienceDirect

[3] This study investigates the relationship between cerebral aneurysm initiation and hemodynamic factors using computational fluid dynamics (CFD) to simulate blood flow in patients' cerebral vessels before aneurysm initiation. Evaluated parameters include pressure, wall shear stress (WSS), wall shear stress gradient (WSSG), oscillatory shear index (OSI), gradient oscillatory number (GON), and wall shear stress divergence (WSSD). Findings indicate that high WSSD regions correlate with aneurysm initiation, suggesting that stretching forces on the vessel wall may play a critical role. Identifying these hemodynamic factors could improve the prediction of aneurysm initiation.

Relationship between hemodynamic parameters and cerebral aneurysm initiation | IEEE Conference Publication | IEEE Xplore

[4] Cerebral aneurysms often form at arterial curvatures and bifurcations exposed to significant hemodynamic forces. This study aimed to examine the hemodynamic environment preceding aneurysm formation. Using 3D reconstructions and finite-volume modeling, researchers analyzed wall shear stress (WSS) and spatial WSS gradient (SWSSG) at future aneurysm sites in three patients. Results showed significantly increased WSS and positive SWSSG at these sites, with WSS values exceeding five times the average and SWSSG peaking at over 40 Pa/mm. These findings suggest that high WSS and SWSSG are critical in aneurysm initiation.

Hemodynamics of Cerebral Aneurysm Initiation: The Role of Wall Shear Stress and Spatial Wall Shear Stress Gradient | American Journal of Neuroradiology (ajnr.org)

[5] The management goal for unruptured intracranial aneurysms aims to identify and treat those at risk of rupture. Computational fluid dynamics (CFD) offers insights into the hemodynamic processes within aneurysms, with models developed to predict rupture risk. However, a review of literature up to 2010 found that parameters such as wall shear stress (WSS), WSS gradient, and aneurysm inflow-angle lack predictive value for clinical use. While CFD simulation techniques have advanced, the ability of patient-specific CFD models to predict rupture risk requires further investigation, incorporating multivariate analysis. As computational power improves, CFD models may eventually become routine in clinical practice.

Current status of computational fluid dynamics for cerebral aneurysms: The clinician's perspective - ScienceDirect

III. HEMODYNAMIC FORCES AND PARAMETERS OF CEREBRAL ANEURYSM

The biomechanical properties of blood flow are essential in understanding cerebral aneurysms, driving growing interest in the hemodynamic factors that influence their initiation, growth, and rupture. Hemodynamics is the study of blood movement and its flow through the body and the solid structures it interacts with, such as blood vessels. Blood flow within a straight vessel exerts three types of stress on the vessel wall. Shear stress arises from friction as blood flows along the wall, acting tangentially and perpendicular to the surface. Normal stress, caused by hydrostatic pressure, applies force orthogonally to the vessel wall. Tensile stress, exerted in a circumferential direction, stretches the vessel wall outward due to internal pressure. These stresses play a critical role in understanding the structural and functional changes in blood vessels related to aneurysms.

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A. Wall Shear Stress (WSS)

For decades, researchers have studied the impact of wall shear stress (WSS) on the development, progression, and rupture of cerebral aneurysms. WSS is a dynamic force generated by the movement of a viscous fluid along the surface of a blood vessel wall and is considered one of the key parameters in cerebral aneurysm hemodynamics.

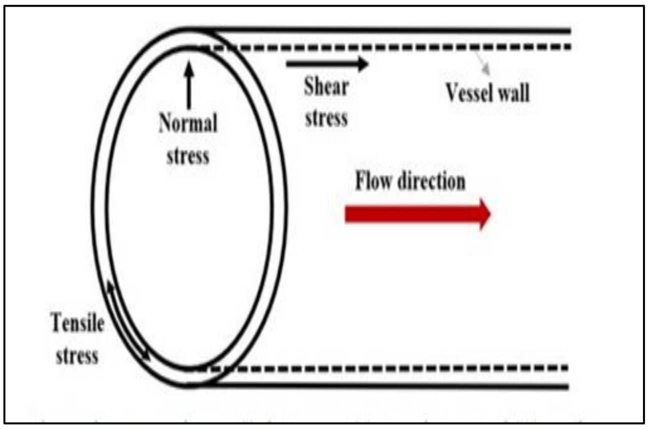

Fig 2: Types of Stresses

Several related parameters have been introduced to characterize WSS. It is defined as a tangential force caused by the friction of a viscous fluid, such as blood, moving over the solid surface of a blood vessel. In pulsatile blood flow, the WSS magnitude during a cardiac cycle is calculated as the time-averaged WSS. The formula for WSS calculation is given as:

$$WSS = \frac{1}{T}\int_{0}^{T} |wss_i| \; dt$$

Time-averaged WSS, measured in Pascals (Pa), typically ranges between 1.5 and 10 Pa and is determined based on the time-averaged magnitude at each mesh point on the vessel wall. Blood vessels adapt to WSS and wall tension to maintain normal physiological blood flow.

Flow patterns in aneurysms differ based on their location and shape. For instance, in saccular aneurysms located at bifurcations, as depicted in Figure 3A, tangential WSS arises as blood flows over the surface. Jet flow directed toward the aneurysm dome causes a sudden increase in surface area, converting kinetic energy into inertial forces, which then reverse the flow. In Figure 3B, wall tension is illustrated as the vertical force generated when jet flow impacts the neck of the aneurysm dome. Computational simulations using patient-specific data have revealed that aneurysm rupture often occurs in the middle cerebral artery when wall tension exceeds the tensile strength of the vessel tissue.

Researchers have observed that at peak systole, wall tension is significantly elevated near the bifurcation of the aneurysm neck, coinciding with maximum blood flow velocity. High WSS is particularly associated with increased blood viscosity and velocity. Moreover, studies have demonstrated that WSS intensifies on the distal side of the aneurysm neck as the diameter of the parent vessel increases. Similarly, aneurysms with wider necks exhibit higher WSS.

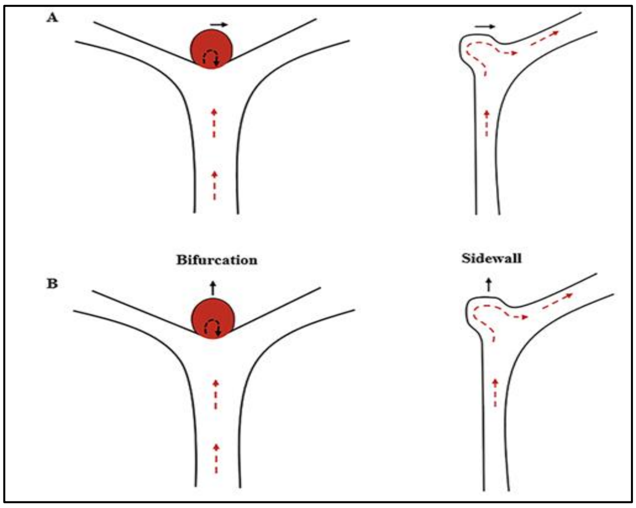

Fig 3: Bifurcation

WSS plays a critical role in the pathophysiology of cerebral aneurysms, with its influence varying across different stages of aneurysm development and rupture. Over the past decade, WSS has been a primary focus of hemodynamic research, providing valuable insights into the biomechanical forces involved in aneurysm behaviour.

B. WSS Gradient (WSSG)

Wall Shear Stress Gradient (WSSG) refers to the variation in the magnitude of the WSS vector along the direction of blood flow over a given distance. The spatial derivative of the flow direction is quantified using WSSG. Additionally, temporal WSSG is employed to evaluate the rate of change in WSS magnitude throughout a cardiac cycle. WSSG is particularly useful for analyzing cerebral aneurysms with intricate vessel geometries and is expressed in Pascals per millimeter (Pa/mm).

C. Pressure:

In our review of cerebral aneurysms, we focused on analyzing pressure as a key hemodynamic parameter under steady-state conditions. Using computational fluid dynamics (CFD), we assessed the pressure distribution within the aneurysm and its surrounding vessels to evaluate the mechanical forces exerted on the aneurysm wall. This analysis helped identify regions susceptible to rupture due to elevated pressure. By correlating these pressure patterns with aneurysm behavior, we gained valuable insights into predicting rupture risk and informing clinical management strategies, highlighting the crucial role of pressure data in understanding cerebral aneurysms.

D. Velocity:

In our review of cerebral aneurysms, we focused on analyzing velocity as a key hemodynamic parameter under steady-state conditions. Using computational fluid dynamics (CFD), we examined the velocity distribution within the aneurysm and its surrounding vessels to understand the flow

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patterns and identify regions of high and low velocity. These velocity patterns provided insights into areas of flow stagnation or acceleration that could contribute to aneurysm growth and rupture. By correlating these velocity profiles with aneurysm behavior, we gained valuable insights into predicting rupture risk and informing clinical management strategies, highlighting the critical role of velocity data in understanding cerebral aneurysms.

IV. METHODOLOGY

- Utilization of Key Hemodynamic Parameters- In our review of cerebral aneurysms, we focused on key hemodynamic parameters such as velocity, wall shear stress (WSS), and pressure to comprehensively understand aneurysm initiation, growth, and rupture.
- Employment of Computational Fluid Dynamics (CFD) Simulations- We employed CFD simulations to analyze blood flow velocity within the aneurysm and its surrounding vessels. This allowed us to identify regions of both high and low flow, providing insights into flow dynamics.
- Calculation of Wall Shear Stress (WSS)-Wall shear stress, a critical factor in linking hemodynamic forces to vascular responses, was calculated. We aimed to determine areas of abnormal stress that could potentially lead to endothelial damage and subsequent aneurysm progression.
- Assessment of Pressure Distributions- Pressure distributions were assessed to evaluate the mechanical forces exerted on the aneurysm wall. This analysis helped identify regions susceptible to rupture based on pressure gradients.
- Correlation of Hemodynamic Patterns with Aneurysm Behavior-Through detailed analyses of velocity, WSS, and pressure, we correlated specific hemodynamic patterns with aneurysm behavior. This correlation provided valuable insights for predicting rupture risk and informing clinical management strategies.

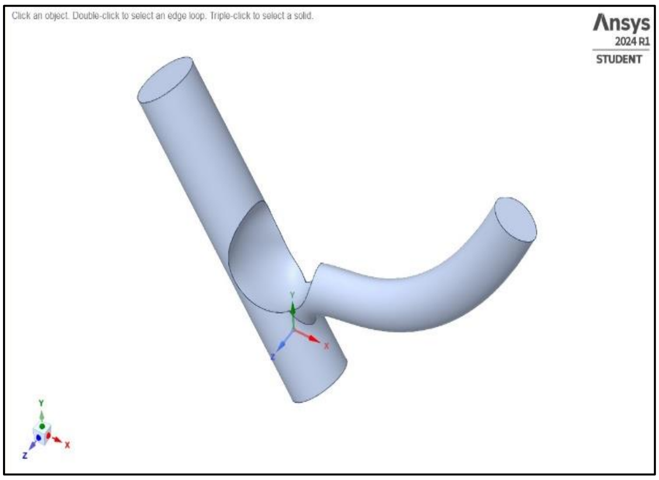

Fig 4: CAD Model

The Carotid Artery geometry was constructed using SolidWork as shown above in Fig 1. After constructing the geometry in SolidWorks it was imported to ANSYS.

➢ *We Conducted Type of Analysis on the Carotid Artery:- Steady State the Boundary Conditions for Flow are:*

- Inlet Velocity of 0.315m/s
- Outlet Pressure of 13332 Pa
- The Artery Walls follow No-Slip Conditions
- The Density of Blood is 1060 kg/m3 and the Viscosity of Blood is 0.0035 Pa-s.
- The Reynold Number is 600 (based on the inlet diameter).

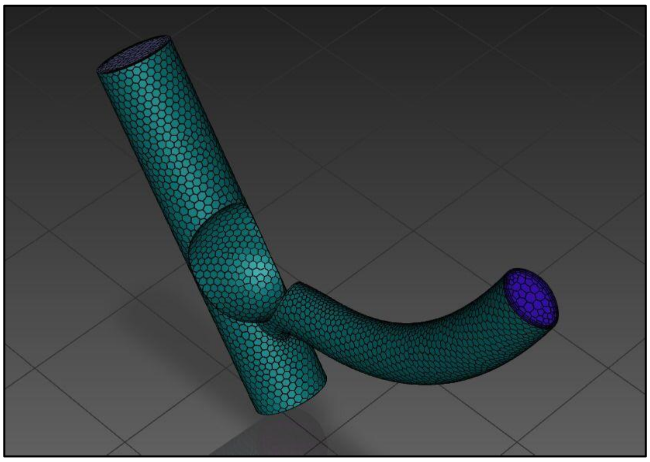

Fig 5: Meshing

➢ *After Importing the Geometry we Conducted the Meshing.* Here, we provided boundary conditions to the Artery.

- Wall: The arterial wall is the most straightforward border condition to determine. We simply need to define the wall regions of this model and set them to “wall.” Physically speaking, the no-slip criterion means that the velocity at the wall must be zero, hence the "wall" condition.
- Inlet: Here our inlet velocity will be a constant 0.315 m/s. This was chosen to give us a Reynolds number of 600.
- Outlets: A healthy person has a diastolic pressure of about 80 mm Hg and a systolic pressure of about 120 mm Hg. Therefore, we determine the static pressure at the outlets to be 100 mm Hg, or roughly 13,332 Pa, by averaging the pressures of the two phases.

V. RESULTS AND ANALYSIS

The review of hemodynamic parameters in cerebral aneurysms reveals critical insights into how wall shear stress, pressure gradients, and velocity profiles influence aneurysm behavior. Computational fluid dynamics (CFD) analysis shows that low wall shear stress (WSS) is associated with aneurysm initiation and growth due to endothelial dysfunction, while high WSS correlates with an increased risk of rupture as it imposes greater mechanical stress on the aneurysm wall. Elevated pressure gradients across the aneurysm dome, identified through CFD simulations, contribute to enhanced wall stress and rupture potential, indicating that pressure dynamics play a significant role in aneurysm stability. Additionally, CFD analysis highlights that high-velocity inflow jets are linked to increased wall damage and rupture risk, as the concentrated impact of blood flow on the aneurysm wall exacerbates structural weaknesses.

Collectively, these hemodynamic parameters, elucidated through CFD analysis, provide valuable insights for assessing aneurysm behavior and guiding clinical management strategies, highlighting the importance of a multifaceted approach to understanding and treating cerebral aneurysms.

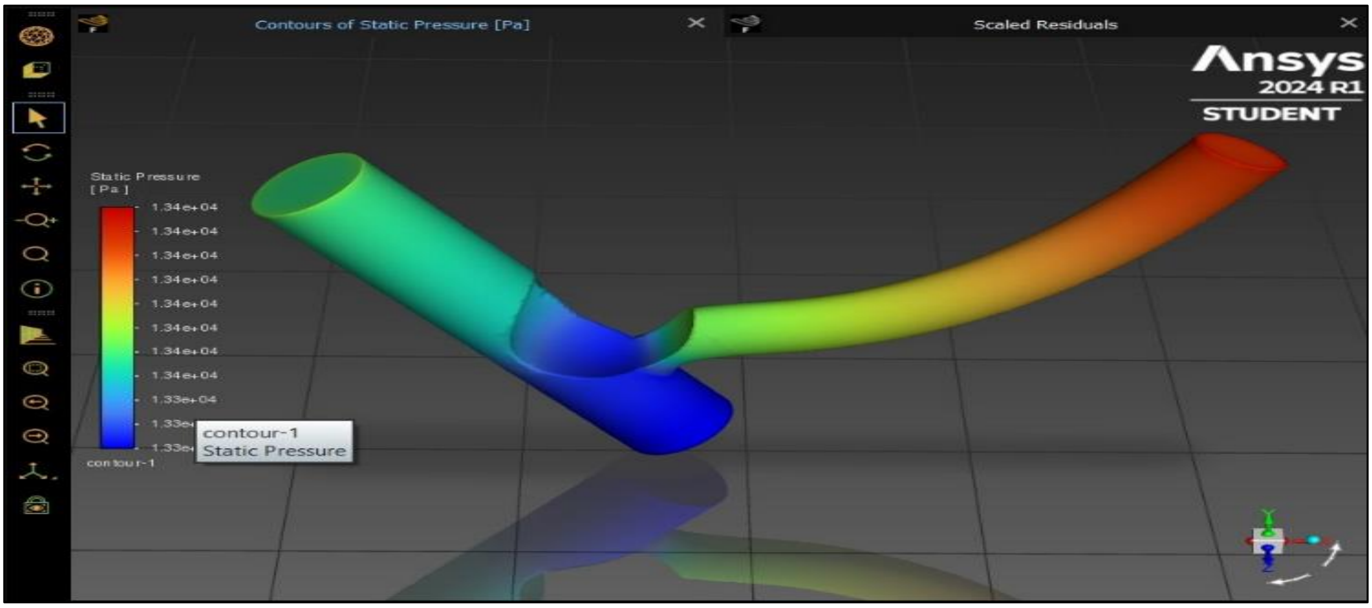

Fig 6: Contour 1

- The red coloring at the inlet artery indicates elevated static pressure levels, reflecting areas where blood flow encounters increased pressure upon entering the arterial system.
- As the visualization shifts from red to blue at the aneurysm's bifurcation point, it indicates a decline in static pressure along the artery. This transition suggests a decrease in pressure as blood moves away from the inlet artery towards the aneurysm bifurcation.
- In summary, this visualization offers insights into the static pressure distribution within the arterial system, highlighting higher pressure levels at the inlet artery and a subsequent decrease in pressure towards the aneurysm's bifurcation point.

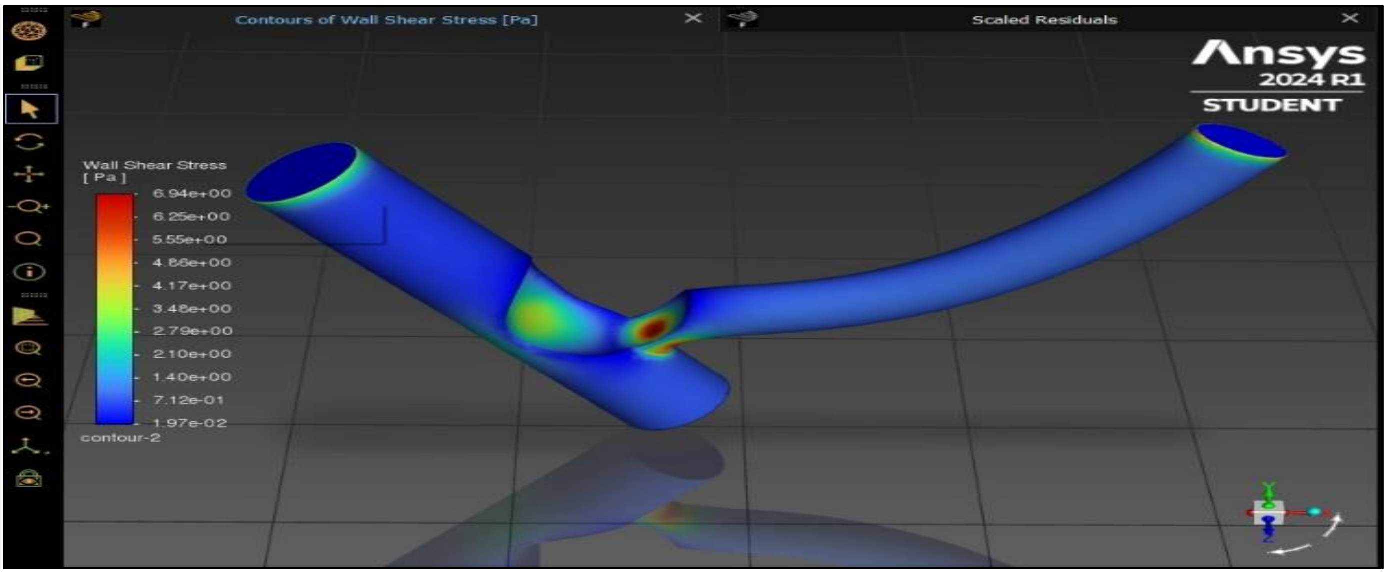

Fig 7: Contour 2

- The blue coloration of the artery suggests lower wall shear stress levels, indicating smoother blood flow conditions with reduced frictional forces on the vessel wall, potentially leading to less mechanical stress on the endothelial lining.
- Conversely, the red coloration at the bifurcated aneurysm point signifies higher wall shear stress levels, especially at the site of the aneurysm's location. This indicates areas with elevated frictional forces or turbulent flow patterns, which may result in greater mechanical strain on the vessel wall.

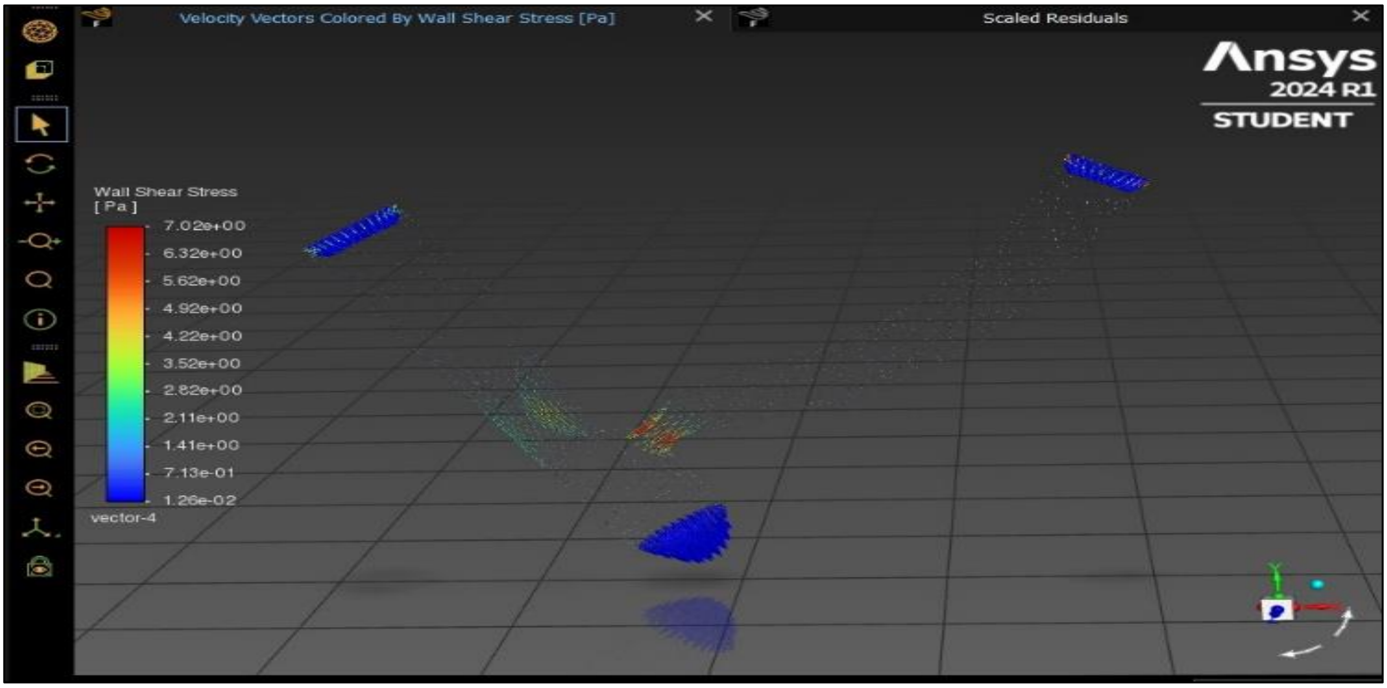

Fig 8: Vector 1

- When examining the velocity vectors as indicated by wall shear stress, a consistent blue hue across the artery indicates generally low levels of shear stress along its walls. This uniform blue color suggests a consistent stress distribution throughout most of the artery.
- However, at the bifurcation points, the vectors shift to red, indicating increased wall shear stress. These areas, where the artery divides due to the aneurysm's presence, experience heightened stress levels or turbulent flow patterns, leading to the change in coloration to red.

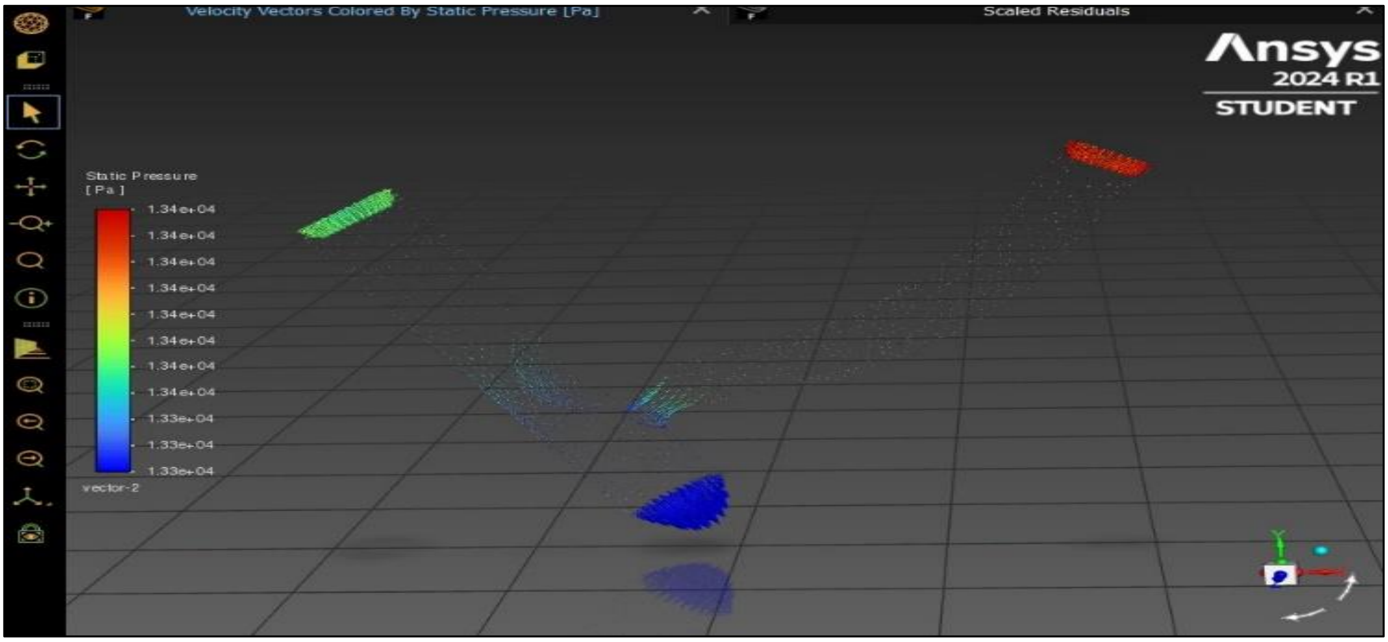

Fig 9: Vector 2

- When analyzing the velocity vectors affected by static pressure, if they remain predominantly blue but change to red at the inlet, it indicates significant pressure variations within the artery.
- Consistent Blue: The ongoing blue shade of the velocity vectors, impacted by static pressure, suggests generally low-pressure levels along the artery's course. This uniform blue hue suggests a consistent pressure distribution throughout most of the artery.
- Red at the Inlet: The red coloring at the inlet indicates regions of increased static pressure. This occurs where blood enters the artery, signifying a rise in pressure, leading to the transition to red coloring.

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VI. FUTURE SCOPE

A. Integration of Advanced Imaging Modalities:

Incorporate emerging imaging techniques such as 4D flow MRI, high-resolution MRI, or advanced angiographic imaging to provide more detailed and accurate assessment of hemodynamic parameters within cerebral aneurysms.

Evaluate the feasibility and potential advantages of combining multiple imaging modalities for a comprehensive analysis of hemodynamics.

B. Patient-specific Modeling and Simulation:

Focus on patient-specific computational modeling approaches to simulate blood flow dynamics within individual cerebral aneurysms.

Explore the use of machine learning algorithms to enhance the accuracy and efficiency of patient-specific modeling based on imaging and clinical data.

Investigate the role of personalized hemodynamic analysis in predicting individualized rupture risk and guiding treatment decisions.

C. Temporal Analysis of Hemodynamics:

Investigate the dynamic changes in hemodynamic parameters over time, including their influence on aneurysm growth and rupture.

Explore longitudinal studies to assess how hemodynamic parameters evolve throughout the natural history of cerebral aneurysms and in response to interventions.

D. Incorporation of Hemodynamic Biomarkers:

Identify potential hemodynamic biomarkers associated with aneurysm instability and rupture.

Investigate the utility of combining hemodynamic parameters with other clinical, genetic, or biomolecular markers to improve risk stratification and prognosis assessment.

E. Validation Studies and Clinical Translation:

Conduct validation studies to assess the reliability and reproducibility of hemodynamic measurements obtained from different imaging and modeling techniques.

Translate research findings into clinical practice by developing standardized protocols for hemodynamic assessment of cerebral aneurysms and integrating them into routine diagnostic and treatment algorithms.

F. Therapeutic Implications:

Explore the impact of hemodynamic parameters on treatment outcomes, including the effectiveness of different endovascular and surgical interventions.

Investigate novel treatment strategies targeting specific hemodynamic abnormalities to prevent aneurysm progression or rupture.

G. Multidisciplinary Collaborations:

Foster collaborations between researchers, clinicians, engineers, and industry partners to leverage expertise from diverse fields in advancing hemodynamic research in cerebral aneurysms.

Encourage interdisciplinary research initiatives aimed at addressing complex challenges and translating scientific discoveries into clinical innovations.

H. Health Technology Assessment (HTA):

Conduct health technology assessments to evaluate the cost-effectiveness and clinical utility of incorporating hemodynamic assessment into routine clinical practice.

Assess the potential impact of implementing hemodynamic-guided interventions on healthcare outcomes, resource utilization, and patient satisfaction.

By exploring these future scopes, a review of hemodynamic parameters within cerebral aneurysms can contribute to advancing scientific knowledge, improving clinical care, and ultimately enhancing patient outcomes in the field of cerebrovascular medicine.

VII. CONCLUSION

The role of hemodynamic parameters in the initiation, growth, and rupture of cerebral aneurysms can be understood by examining blood vessel morphology and hemodynamic behavior. Among these, the size and shape of an aneurysm are crucial predictors of its rupture risk. Hemodynamic forces are thought to play a significant role in the development of cerebral aneurysms, with wall shear stress (WSS) being a central factor. WSS connects blood pressure to the processes of vasodilation and vasoconstriction within vessels. Aneurysms typically form at vascular bifurcation points where persistently abnormal WSS—either excessively high or low—is present. Compared to other hemodynamic parameters, WSS has been extensively studied to assess rupture risks. However, future research should aim to establish stronger correlations between hemodynamic parameters and rupture risks using robust clinical evidence.

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