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A Review of Hemodynamic Parameters in Cerebral Aneurysm

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Abstract— A cerebral aneurysm refers to a localized enlargement or ballooning that compromises the structural integrity of a blood vessel within the brain. This condition manifests as an abnormal expansion, bulging, or as a small blister-like protrusion (bleb). Understanding the mechanisms behind the onset, development, and rupture of cerebral aneurysms has been instrumental in identifying treatments that reduce the risk of mortality and morbidity. The formation of a cerebral aneurysm is attributed to the weakening and thinning of the arterial wall, making early diagnosis challenging before rupture occurs. A rupture can lead to severe health issues, including brain damage, hemorrhagic stroke, behavioral changes, and disturbances in eye movement. Computational fluid dynamics (CFD) plays a crucial role in studying cerebral aneurysms by simulating blood flow and assessing hemodynamic parameters, which help determine the rupture potential of the vessel. These parameters influence the biological processes of blood flow in brain vessels affected by aneurysms. This paper reviews the key hemodynamic factors that contribute to aneurysm formation, progression, and the associated morphological characteristics, such as size and shape. It focuses on the relationship between these parameters and cerebral aneurysm development.

Keywords—Cerebral aneurysm, Hemodynamics, Wall shear stress, rupture risk, Ansys

1. Introduction

[1] A cerebral aneurysm is a vascular abnormality in the brain's arterial system, characterized by a weakened vessel wall that is susceptible to rupture. Aneurysms can vary in size from under 0.5 mm to over 25 mm. Most aneurysms are saccular, associated with either a thinned or absent media of the tunica, and often correlated with a fragmented or absent internal elastic lamina.

[2] While some aneurysms are fusiform or mycotic, most remain asymptomatic and are discovered incidentally through neuroimaging or autopsy. Over 85% of cerebral aneurysms are located at bifurcation points in the anterior circulation. Their formation and growth are linked to irregular blood flow at these bifurcations, along with factors such as high blood pressure, atherosclerosis, trauma, and genetics. Cerebral aneurysms are relatively common, with approximately 10 out of 100,000 individuals suffering from subarachnoid hemorrhage annually, a condition associated with high rates of morbidity and mortality.

[3] Advancements in neuroradiological imaging have led to an increase in aneurysm detection, but improvements in predicting rupture risk have lagged. Additionally, preventive treatments, whether surgical or endovascular, carry inherent risks. Ideally, treatment would distinguish aneurysms that will rupture from those that will not, leading to more effective interventions. Recent research has focused on

developing statistical models that more accurately predict aneurysm rupture risk.

[4] The size and location of aneurysms in the posterior circulation are well-established risk factors. In recent decades, predictions of rupture risk have improved with a better understanding of hemodynamic factors. These hemodynamic factors, which describe the effect of blood flow dynamics on aneurysms, have become a key area of clinical study. Advances in simulation technology now allow for more precise hemodynamic analyses of cerebral aneurysms. This review aims to summarize the important geometric and hemodynamic parameters involved in the formation, growth, and rupture of cerebral aneurysms.

[5] The geometry of aneurysms—specifically their size and shape—is critical for assessing rupture risk. Unlike hemodynamic factors, size and shape remain constant, though even small changes in these parameters can significantly impact intra-aneurysmal blood flow. Thus, aneurysm geometry is essential for predicting rupture risk. Additionally, the biomechanical properties of blood flow, referred to as hemodynamics, are crucial to understanding the processes that lead to aneurysm initiation, growth, and rupture. Hemodynamics, which studies the movement of blood through the body and vascular structures, has become a focal point in aneurysm research. Fig. 2 illustrates three types of stress on the vessel wall due to blood flow: shear stress (a tangential force along the vessel wall), normal stress (a perpendicular force due to hydrostatic pressure), and tensile stress (a circumferential force acting against the vessel wall)

I. 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

2. Hemodynamic forces and parameters of cerebral aneurysm:

The biomechanical characteristics of blood flow are highly significant, sparking growing interest in the hemodynamic parameters that contribute to the initiation, development, and rupture of cerebral aneurysms. Hemodynamics refers to the study of blood flow dynamics through vessels and other solid structures within the body. Fig. 2 illustrates various types of stresses in a blood vessel, specifically in a straight vessel. These stresses include shear stress, which is a tangential frictional force acting along the vessel wall; normal stress, caused by hydrostatic pressure that acts orthogonally to the vessel wall; and tensile stress, which is the force exerted circumferentially against the vessel wall.

1) 2.1 Wall Shear Stress (WSS)

For years, researchers have extensively studied the role of wall shear stress (WSS) in the initiation, growth, and rupture of cerebral aneurysms. WSS is a dynamic force generated by the movement of viscous blood along the vessel wall and is widely regarded as a key factor in cerebral aneurysm hemodynamics.

Several derived parameters help describe the behavior of WSS. WSS is a tensile force exerted by a viscous fluid as it flows over the surface of a solid structure, in this case, the vessel wall. As blood flows, it induces tangential frictional forces, which are particularly important in the study of pulsatile blood flow. In pulsatile flow, WSS varies throughout the cardiac cycle, and the average WSS over one full cycle is known as the time-averaged WSS where, wss is the instantaneous shear stress vector and T is the duration of one cardiac cycle. Time-averaged WSS is evaluated using the characteristics for an entire time cycle; which is measured in Pa with a normal value from 1.5 to 10 and is calculated based on the accurate time-averaged magnitude of each wall mesh point vector. Blood vessel wall responds to WSS and to wall tension in order to regulate the normal physiological flow rate. Jet flow impinges toward the dome due to the bifurcation and the sudden enlargement of surface area. Using patientspecific computational simulation modeling, it reported that aneurysm rupture occurs in the middle carotid artery when the wall tension overcomes the wall tissue intensity. These researchers investigated the maximum wall tension in the aneurysm dome on the impingement area. At the peak systole point, the wall tension is considerably high near the bifurcation point of the aneurysm neck, and the maximum velocity is reached. A high WSS occurs as the viscosity and velocity of blood flow increase. WSS plays a crucial role in the pathophysiology of cerebral aneurysm. The influence of WSS initiation on the development and rupture impact zone could be distinct. In the last decade, WSS has been investigated in most hemodynamic related research studies. Also, reported that flow velocity and the consequent WSS intensified on the distal side of the neck as the parent vessel's diameter increased. Furthermore, WSS increased with the increasing neck width.

2.2 Pressure:

In our review of cerebral aneurysms, we concentrated on examining pressure as a vital hemodynamic parameter under steady-state conditions. By utilizing computational fluid dynamics (CFD), we evaluated the pressure distribution both within the aneurysm and the adjacent blood vessels to understand the mechanical forces acting on the aneurysm wall. This assessment allowed us to pinpoint regions where higher-pressure levels may increase the risk of rupture. By linking these pressure distributions to aneurysm behavior, we gained critical insights into predicting rupture risk, which is essential for developing effective clinical management strategies. This underscores the importance of pressure data in improving our understanding of cerebral aneurysms and enhancing treatment outcomes.

2.3 Velocity:

In our review of cerebral aneurysms, we concentrated on velocity as a key hemodynamic parameter under steady-state conditions. By employing computational fluid dynamics (CFD), we analyzed the velocity distribution within the aneurysm and surrounding vessels to understand the flow dynamics and pinpoint areas of high and low velocity. These flow patterns revealed regions of flow stagnation or acceleration, which may contribute to aneurysm growth and the risk of rupture. By correlating these velocity profiles with aneurysm behavior, we gained valuable insights into predicting rupture risk and developing informed clinical management strategies, emphasizing the critical importance of velocity data in understanding cerebral aneurysms.

3. METHODOLOGY:

Utilization of Key Hemodynamic Parameters

In our review of cerebral aneurysms, we focused on three key hemodynamic parameters—velocity, wall shear stress (WSS), and pressure—to gain a comprehensive understanding of the mechanisms driving aneurysm initiation, growth, and rupture.

Employment of Computational Fluid Dynamics (CFD) Simulations

We employed CFD simulations to examine blood flow velocity within the aneurysm and surrounding vessels. This analysis enabled us to detect areas of both high and low flow, offering insights into the complex flow dynamics associated with aneurysm progression.

Calculation of Wall Shear Stress (WSS)

Wall shear stress, a key hemodynamic factor linking blood flow forces to vascular responses, was calculated to identify areas experiencing abnormal stress. These regions of abnormal WSS could contribute to endothelial damage, leading to aneurysm development and further progression. Assessment of Pressure Distributions

We assessed pressure distributions to evaluate the mechanical forces acting on the aneurysm wall. This evaluation helped identify regions with elevated pressure, which could increase the likelihood of aneurysm rupture due to the stress imposed on the vessel wall.

Correlation of Hemodynamic Patterns with Aneurysm Behavior

By thoroughly analyzing velocity, WSS, and pressure, we established correlations between specific hemodynamic patterns and aneurysm behavior. These findings provided critical insights into predicting rupture risk and informed clinical management strategies for cerebral aneurysms.

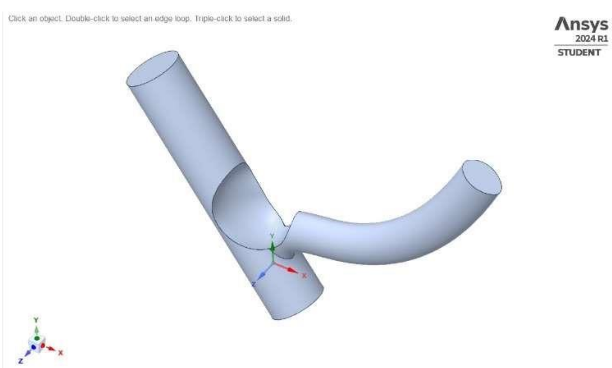

Fig1. CAD model

The Carotid Artery geometry was constructed using SolidWorks 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).

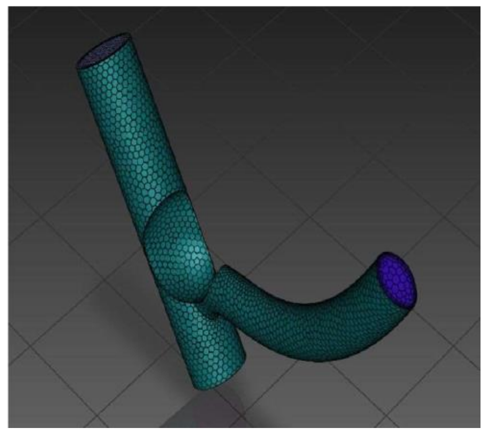

Fig 2. Meshing

After importing the geometry, we proceeded with meshing to prepare the model for simulation.

Boundary Conditions for the Artery

a) Wall:

The arterial wall is a straightforward boundary condition to define. We assigned the wall regions of the model as "wall," following the no-slip condition, which states that the velocity at the wall must be zero. This reflects the physical reality that there is no fluid movement along the wall surface.

b) Inlet:

The inlet velocity was set to a constant value of 0.315 m/s. This specific velocity was chosen to achieve a Reynolds number of 600, ensuring that the flow regime aligns with the desired conditions for our analysis.

c) Outlets:

For the outlets, we used an average pressure of 100 mm Hg (equivalent to approximately 13,332 Pa). This value was determined by averaging a healthy person's diastolic pressure (around 80 mm Hg) and systolic pressure (around 120 mm Hg), representing a typical physiological range.

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4. Results and Analysis

The review of hemodynamic parameters in cerebral aneurysms offers valuable insights into how factors like wall shear stress (WSS), pressure gradients, and velocity profiles impact aneurysm behavior. Computational fluid dynamics (CFD) analysis reveals that low WSS contributes to aneurysm initiation and growth due to endothelial dysfunction, while high WSS is associated with a higher rupture risk, as it applies greater mechanical stress on the aneurysm wall. Elevated pressure gradients across the aneurysm dome, detected through CFD simulations, further increase wall stress and rupture potential, underscoring the crucial role of pressure dynamics in aneurysm stability.

Additionally, CFD analysis indicates that high-velocity inflow jets can significantly elevate rupture risk by causing more damage to the aneurysm wall. The concentrated force of these jets on the wall intensifies structural vulnerabilities, making the aneurysm more prone to rupture. Taken together, these hemodynamic parameters, explored through CFD analysis, provide essential insights into predicting aneurysm behavior and guiding clinical decision-making. This comprehensive approach emphasizes the importance of understanding multiple hemodynamic factors for effectively managing and treating cerebral aneurysms.

	Normal BP 120/80	Elevated 129/80	Hypertension 1 130/80	Hypertension 2 140/90	Hypertension Crisis 180/120
(kg/s) Mass Flow Rate	-1.1031	-1.1031	-1.1031	-1.1031	-1.1031
(N) Drag	-0.12944	-0.1352	-0.1474	-0.1486	-0.1935

	Normal BP 120/80	Elevated 129/80	Hypertension 1 130/80	Hypertension 2 140/90	Hypertension Crisis 180/120
(kg/s) Mass Flow Rate	-9.26	-2.07494	-2.1166	-2.1166	-2.1166
(N) Drag	0.0012	0.0033	0.00507	0.00507	0.0057

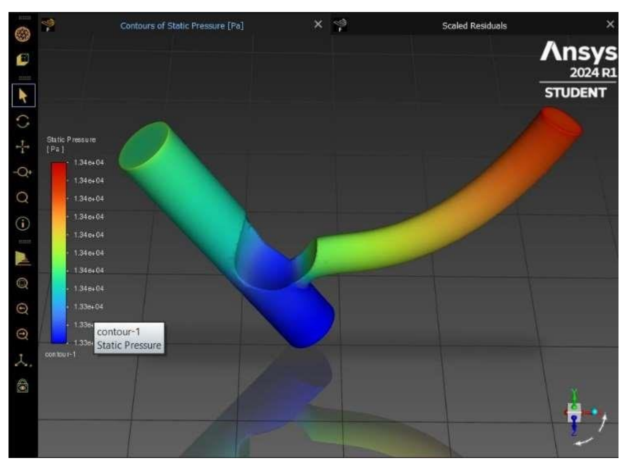

Fig. Contour 1

- The red colouring 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.

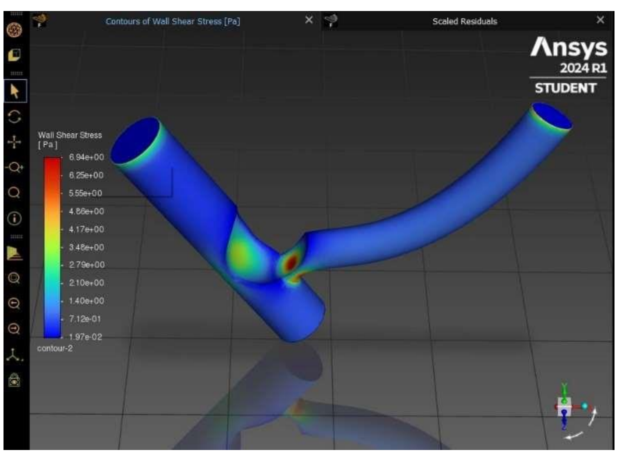

Fig. Contour 1.

- 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.

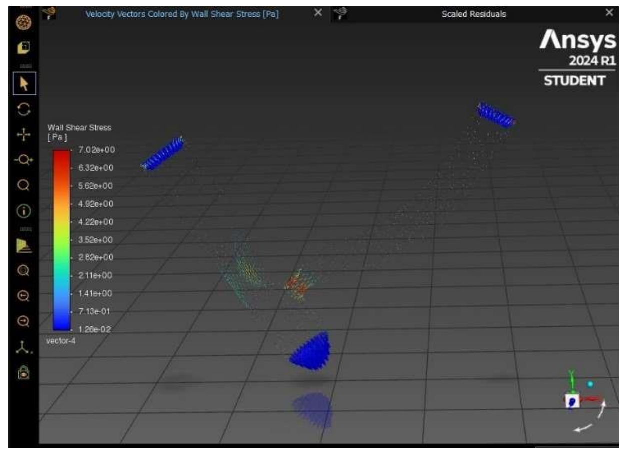

Fig. Vector 1

- 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 colour 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.

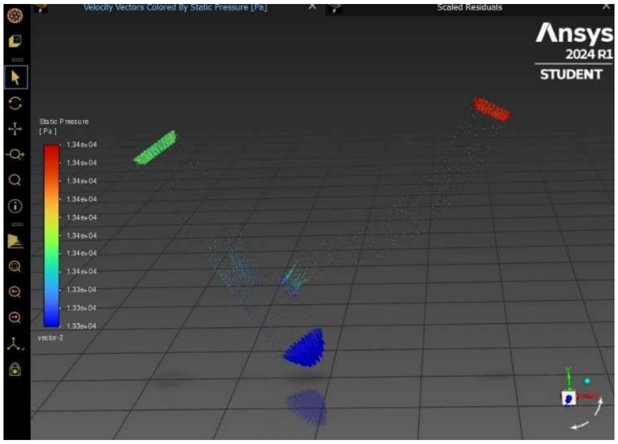

Fig. Vector 2

- When analysing 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 colouring 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 colouring.

5. FUTURE SCOPE:

Integration of Advanced Imaging Techniques:

Utilize cutting-edge imaging methods like 4D flow MRI, high-resolution MRI, and advanced angiographic imaging to achieve a more precise evaluation of hemodynamic parameters in cerebral aneurysms. Additionally, assess the feasibility and potential benefits of combining these techniques to enable a comprehensive analysis of blood flow dynamics.

Patient-Specific Modelling and Simulation:

Emphasize the development of computational models tailored to individual patients for simulating blood flow within cerebral aneurysms. Investigate how machine learning algorithms can improve the precision and efficiency of these models by utilizing imaging data and clinical inputs. Consider the role of personalized hemodynamic analysis in predicting rupture risks and informing treatment plans on a case-by-case basis.

Temporal Analysis of Hemodynamics:

Examine how hemodynamic parameters change over time and their impact on aneurysm growth and rupture. Conduct longitudinal studies to understand the evolution of these parameters throughout the natural course of cerebral aneurysms and in response to treatments.

Incorporation of Hemodynamic Biomarkers:

Identify potential biomarkers related to hemodynamic instability and aneurysm rupture. Explore the integration of hemodynamic factors with clinical, genetic, and biomolecular markers to enhance risk stratification and improve prognostic assessments.

Validation Studies and Clinical Implementation:

Perform validation studies to ensure the accuracy and consistency of hemodynamic data obtained from various imaging and modelling techniques. Develop standardized protocols to incorporate these assessments into routine clinical practice, translating research into effective diagnostic and treatment tools.

Therapeutic Implications:

Examine how specific hemodynamic conditions influence treatment outcomes for both endovascular and surgical interventions. Investigate new therapeutic strategies that target abnormal hemodynamic patterns to prevent aneurysm progression or rupture.

Multidisciplinary Collaborations:

Promote collaboration between researchers, clinicians, engineers, and industry stakeholders to drive advancements in hemodynamic research for cerebral aneurysms. Encourage interdisciplinary research aimed at addressing complex challenges and translating discoveries into clinical applications.

Health Technology Assessment (HTA):

Evaluate the cost-effectiveness and clinical value of incorporating hemodynamic analysis into routine healthcare. Assess the impact of hemodynamic-guided treatments on patient outcomes, resource allocation, and overall healthcare efficiency.

By addressing these future directions, hemodynamic research can contribute to advancing scientific understanding, improving clinical care, and enhancing outcomes for patients with cerebral aneurysms.

6. CONCLUSION:

The role of hemodynamic parameters in the formation, growth, and rupture of cerebral aneurysms can be better understood through the study of blood vessel morphology and flow dynamics. Factors like aneurysm size and shape are key predictors of rupture risk. Hemodynamic forces, particularly wall shear stress (WSS), play a significant role in aneurysm development. Aneurysms are commonly found at vascular bifurcations, where abnormal high or low WSS persists. Of all parameters, WSS has been most extensively studied to predict rupture risk. Future research should aim to correlate these hemodynamic factors with clinical evidence to refine risk assessments and improve patient care.

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