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An Analysis of Blood Flow through Constricted Arteries

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ABSTRACT: The circulatory system, a marvel of biological engineering, is essential for sustaining life. At the heart of this intricate system lies the arterial network, responsible for delivering oxygenated blood to vital organs and tissues. However, this system is not without its vulnerabilities. Arterial constrictions, whether due to atherosclerosis, plaque build-up, or other factors, can significantly impede blood flow, potentially leading to serious health complications. Understanding the intricate structure and function of arteries is fundamental to appreciating how constrictions within these vessels can significantly impact blood flow. This paper reviews the existing literature on about this interplay and emphasizes on the existing research gaps.

Keywords: Atherosclerosis, arterial constriction, blood flow, arteries.

INTRODUCTION

The study of blood flow in constricted arteries is of paramount importance in the field of cardiovascular research. Constrictions, whether caused by atherosclerosis, plaque buildup, or other factors, can have severe consequences on human health. William Harvey's ground breaking work on blood circulation in the 17th century laid the foundation for the study of hemodynamics. While Harvey's work focused on the broader context of circulation, it was a critical starting point for understanding the principles governing blood flow (Pagel, 1951).

The 19th century witnessed significant advancements in the understanding of hemodynamics and fluid mechanics. Researchers began to appreciate the role of fluid dynamics in cardiovascular health. The present study emphasizes on the development of the study of Blood Flow and focuses on the existing research gaps.

Historical Development of the Study of Blood Flow in Constricted Arteries

Poiseuille's experiments laid the foundation for understanding the relationship between vessel diameter and blood. The work highlighted the significance of resistance in blood vessels, which is now described by Poiseuille's law (Poiseuille, Jean Leonard Marie). These developments laid the groundwork for the study of blood flow in constricted vessels.

The early to mid-20th century saw an increase in clinical observations of arterial constrictions and their impact on patients. The association between constricted arteries and diseases like hypertension and atherosclerosis became more apparent (Deming, 1968 and Dustan, 1974). Research efforts were directed toward understanding the pathological mechanisms behind arterial constriction, which ultimately influenced the study of blood flow in these conditions. The latter half of the 20th century marked a significant turning point in the study of blood flow in constricted arteries. Advances in computing technology and numerical methods allowed for the development of sophisticated computational models. These models began to incorporate the intricacies of arterial geometry and blood rheology, allowing for more accurate simulations of constricted blood flow. Computational Fluid Dynamics (CFD) emerged as a powerful tool for understanding the hemodynamics of constricted arteries, offering insights into diagnostics and treatment planning (Basri, 2016; Perktold & Hofer 2010; Taylor *et al*., 1996; Taylor & Humphrey 2009 and Tu, 2015).

The 21st century has witnessed a shift towards multiscale modeling and patient specific simulations. Researchers have recognized that arterial constriction and its effects on blood flow are highly individualized (Claassen *et al*., 2021; Segal, 2005). By combining advanced imaging techniques with computational modeling, it has become possible to create patient-specific simulations. These models provide insights into the influence of arterial geometry, stenosis severity, and other factors on blood flow patterns. Exploration of microvascular blood flow is vital for comprehending tissue perfusion and exchange of nutrients (Pries & Secomb 2008).

Mathematical and Computational Models of Blood Flow

Mathematical and computational models have become indispensable tools for exploring the complexities of blood flow in arteries. These models offer insights into the intricate fluid dynamics and biomechanical behaviours of blood in health and disease. Blood flow modeling is essential for understanding arterial function, diagnosing cardiovascular diseases, and optimizing treatments. It is particularly critical in studying conditions such as atherosclerosis, aneurysms, and stenoses. The mathematical and computational foundations of these models sheds light on their applications in understanding two-layered blood flow in constricted arteries (Fasano & Sequeira 2017; Taylor & Draney 2004 and Tu *et al.,* 2015).

The Navier-Stokes equations serve as the cornerstone of mathematical modeling in fluid dynamics. When applied to blood flow in arteries, these equations provide insights into the velocity, pressure, and shear stress distributions. However, solving the full Navier-Stokes equations for blood flow can be computationally intensive, especially in complex geometries. Depending on factors such as Reynolds number, blood flow can exhibit laminar or turbulent characteristics. Mathematical models can help predict the transition from laminar to turbulent flow, which is relevant in constricted arteries and stenotic lesions.

Two-Layered Blood Flow in Arteries

Arterial walls consist of two primary layers—the intima and media. The intima is in direct contact with the blood, while the media is a thicker layer composed of smooth muscle cells and elastin. These two layers have different mechanical properties and behaviours, which can significantly affect blood flow dynamics. The two-layered nature of arteries influences shear stress distributions along the arterial wall. The interface between the intima and media plays a crucial role in determining shear stress patterns and, in turn, the behaviour of endothelial cells.

The interaction between the two-layered arterial wall and stenotic lesions influences flow patterns, pressure gradients, and wall shear stress. Understanding these dynamics is essential for assessing the impact of stenosis on blood flow. Boundary layer theory postulates that a thin, slower-moving layer of blood forms near the endothelial surface due to the no-slip condition. This theory has implications for understanding shear stress distributions in arteries and how they relate to the presence of stenosis. Various hypotheses propose that the two-layered nature of blood flow in arteries influences endothelial cell function (Davies, 2009; Pries *et al.,* 2000). The differential shear stress experienced by the intima and media layers may play a role in endothelial cell responses, including mechanotransduction and the development of atherosclerotic plaques.

With the advent of computational methods and technological advancements, the study of inclined stenosed tubes experienced a significant boost. The inclination factor in tube geometry added a new dimension to the mathematical models, making the study of inclined stenosed tubes both challenging and intriguing. Researchers began to explore the complexities arising from inclined configurations, recognizing the impact of gravitational forces on fluid flow and the altered dynamics compared to horizontal tubes (Abubakar & Adeoye 2020; Bakheet *et al*., 2016; Mandal, 2005; Nallpu *et al*., 2018; Shahzadi & Nadeem 2017; Vajravelu *et al.*, 2005 and Verma & Srivastava 2013)

Magnetic Field Influence on Blood Flow

Magnetic fields have emerged as a non-invasive tool with the potential to manipulate blood flow within the circulatory system. This area of research holds promise for novel diagnostic and therapeutic approaches. Magnetic fields can be applied externally, offering a means to exert control over the movement of blood without the need for invasive procedures. One significant application of magnetic fields in hemodynamics is the control of drug delivery. Magnetic nanoparticles, when introduced into the bloodstream, can be directed to specific target sites using external magnetic fields (Pankhurst *et al*., 2003; Pankhurst *et al.*, 2009; Patrick *et al.*, 2017 and Stride *et al*., 2009). This technique has opened up possibilities for precisely delivering therapeutic agents to diseased tissues, reducing side effects, and enhancing treatment efficacy. Additionally, magnetic fields have been explored for their potential to enhance targeted drug delivery within the circulatory system (Poon, 2014; Poon *et al.*, 2017). The ability to guide therapeutic agents to specific regions of the vascular network offers considerable potential for improving the treatment of vascular diseases and cancers.

Couple Stress Fluid Models

Conventional fluid dynamics models treat blood as a Newtonian fluid, simplifying its behaviour as an incompressible fluid with constant viscosity. However, this simplified representation fails to capture the intricate microscale interactions that occur within the blood, particularly in the presence of complex geometries such as stenosed tubes. To address these limitations, researchers have turned to more sophisticated models, such as those based on couple stress fluid mechanics. A couple stress fluid model is characterized by its ability to account for the rotational deformations that occur within blood at the microscale. Blood is not a homogeneous, continuous fluid but rather comprises discrete components, including red and white blood cells, platelets, and plasma. These components interact and deform in response to fluid shear, exhibiting complex behaviour. Modeling blood as a couple stress fluid allows us to capture these intricate microstructural effects (Reddy, 2013).

The use of couple stress fluid models has provided valuable insights into blood behaviour in scenarios involving intricate geometries, including stenosed tubes. Furthermore, the couple stress fluid model allows us to explore the influence of microstructural parameters, such as the couple stress coefficient, on flow behaviour.

CONCLUSIONS

The review enables us to investigate how variations in parameters affect the rheological properties of blood and, consequently, the flow patterns in stenosed tubes. Such investigations offer valuable insights into the factors governing blood behaviour in complex geometries. However, there are existing gaps in analysing the blood flow through constricted arteries and how the complexities in flow behaviour could impact the health at microstructure levels.

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