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Biomedical Simulation of Non-Newtonian Fluid Dynamics in Cardiovascular Systems: A Finite Volume Method Approach to Pulsatile Flow and Atherosclerosis Analysis

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ABSTRACT

The study of non-Newtonian fluid dynamics within cardiovascular systems is critical for understanding the complex interactions between blood flow and arterial health. This research focuses on the application of the Finite Volume Method (FVM) to simulate non-Newtonian fluid behavior under pulsatile flow conditions, mimicking the heartbeat. The objective is to analyze the effects of varying viscosity properties and flow patterns on the development and progression of atherosclerosis. By employing computational simulations, we investigate the rheological properties of blood, characterized as a non-Newtonian fluid, and its impact on shear stress distribution and arterial wall interaction. The simulation framework incorporates advanced non-Newtonian models, including Power-law and Carreau-Yasuda models, to accurately represent blood viscosity variations. Pulsatile flow dynamics are modeled to replicate physiological conditions, providing insights into the mechanical forces exerted on arterial walls and their role in atherosclerotic plaque formation. The results highlight critical areas of high shear stress and low shear rate, which correlate with regions prone to atherosclerosis. This study's findings contribute to a deeper understanding of cardiovascular fluid mechanics and offer potential implications for medical diagnostics and treatment strategies for atherosclerosis. The application of the FVM in this context demonstrates its robustness in handling complex fluid behaviors and geometries, paving the way for more sophisticated simulations in biomedical engineering.

1. INTRODUCTION

In the realm of fluid dynamics, the study of non-Newtonian fluids has garnered significant attention due to their complex flow behavior, which deviates from the simple linear relationship between shear stress and shear rate observed in Newtonian fluids. Non-Newtonian fluids, such as blood, exhibit a range of behaviors including shear-thinning, shear-thickening, and viscoelasticity, making their analysis crucial for understanding various biological and industrial processes. The complexity of non-Newtonian fluids lies in their viscosity, which is not a constant but rather a function of the shear rate. This dependency poses challenges for accurately predicting flow behavior, especially in intricate geometries like those found in the human cardiovascular system. One of the prevalent models used to describe the viscosity of non-Newtonian fluids is the Carreau-Yasuda model, which effectively captures the shear-thinning nature of fluids like blood. The Carreau-Yasuda model provides a more accurate representation of blood viscosity by incorporating parameters that adjust the fluid's behavior across different shear rates, thus enabling a more realistic simulation of blood flow in physiological conditions [1].

The effect of viscosity on blood flow is profound, influencing both macroscopic and microscopic dynamics within the cardiovascular system. Blood, being a shear-thinning fluid, experiences a decrease in viscosity with increasing shear rates, which is particularly relevant in the context of pulsatile flow induced by the heartbeat [2, 3]. The pulsatile nature of blood flow means that the velocity and shear rates within arteries are continuously fluctuating, leading to complex temporal and spatial variations in viscosity. These variations play a critical role in determining the hemodynamic forces exerted on the arterial walls, which are crucial for understanding the progression of diseases such as atherosclerosis. Atherosclerosis, characterized by the buildup