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Nonlinear model on pulsatile flow of blood through a porous bifurcated arterial stenosis in the presence of magnetic field and periodic body acceleration

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ABSTRACT

Background and objective: Background and Objective: The motivation of cardiovascular modeling is to understand the haemodynamic and mechanical factors in the diagnosis and treatment of cardiovascular diseases. Several investigations have been carried out by many authors to understand the flow properties of blood in modelling blood flows in the circulatory system. In the present article, the pulsatile flow of Herschel–Bulkley fluid through a bifurcated arterial stenosis in a porous medium with magnetic field and periodic body acceleration has been investigated in view of understanding the role of rheological behaviour of blood, stenotic height, bifurcation angle, magnetic field and porosity of wall in the initiation and proliferation of cardiovascular diseases.

Methods: The governing equations involving shear stress are solved numerically using finite difference schemes and the shear stress values in parent and daughter arteries are obtained using MATLAB software. The constitutive equation of Herschel–Bulkley fluid is highly nonlinear and using the equation, velocity distribution has been obtained. From the obtained velocity distribution, the numerical solutions of wall shear stress and flow resistance are found.

Results: The plug core radius is, for the first time, computed for various stenotic heights and it is found that the magnetic field and porosity increase the plug core radius. The wall shear stress and flow resistance increase as stenotic height, yield stress, power law index, consistency and Hartmann number increase and decrease with increase in Darcy number and half of the bifurcation angle. It is significant to note that when the value of yield stress is increased from 0.1 to 0.2, the plug core radius is increased by 7.3%. In the presence of yield stress in blood, the applied magnetic field causes 33.87% increase in the plug core radius.

Conclusion: The mathematical model clearly shows that the increase in wall shear stress affects the aggregation of human platelets and rearranging the alignment of endothelial cells near the arterial wall. This implies that the wall shear stress is to be brought down below its critical level by increasing the values of Darcy number and half of the bifurcation angle. Further, the nature of increased flow resistance reduces the amount of blood supply to the vital organs which ultimately leads to a sudden death. This information is useful for bio-medical engineering in developing bio-medical instruments for a great potential treatment modalities inturn, prevent the causes of stroke, heart attack and renal failure.

1. Introduction

Blood is a complex non-Newtonian fluid and weighs 7% of the human body. Blood is a fluid that flows through arteries and veins and transports enzymes, hormones, oxygen and carbon dioxide between the lungs and cells of the tissues. Blood cells form a continuous structure in a blood volume at rest. To break the continuous structure, a finite stress is needed which is known as the yield stress. Blood flow in the circulatory system is in general pulsatile due to the systolic and diastolic pumping. Fluid dynamic principles have been applied successfully in recent years to understand physiological flows in particular the blood flow through arteries.

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The prevalence of cardiovascular diseases is the largest cause of death in the world. The primary aim of cardiovascular modeling is to understand the haemodynamic and mechanical factors that play an important role in the diagnosis and treatment of cardiovascular diseases. It is essential to understand the flow properties of blood such as pulsatility, bifurcation, variations in pressure in modelling blood flows in the circulatory system. Aortic stenosis is an abnormal narrowing of the aortic valve due to the deposition of fatty substances resisting delivery of blood from the heart to the body. As a result, blood supply to the corresponding organs is reduced. Stenosis in an artery may cause cough, chest pain, tiredness, palpitations, fainting, breathing problems, weakness and dizziness. Atherosclerosis disease affects the circulation through arterial stenosis. As blood flow encounters the stenotic region in an artery, velocity increases to maintain constant blood flow.

Several investigations have been carried out in [1–6] and found that understanding of fluid dynamic and rheological properties of blood through stenosed arteries is necessary in analysis of cardiovascular diseases. Many investigators (El- Shahed [7], El-Shehawey et al. [8], Sharma et al. [9], Chaturani and Ponnalagarsamy [10]) analysed the flow of blood considering it as a Newtonian fluid. Charm and Kurland [11], Whitmore [12] and Lih [13] have shown that blood being a suspension of cells behave as a non-Newtonian fluid at low shear rate. Mandal [14], Mandal and Chakravarthy [15] analysed the flow of blood assuming it as a non-Newtonian fluid. Bali and Awasthi [16] analyzed the effect of external magnetic field on blood flow in stenotic artery. They observed that the resistance to flow increases with stenosis height. Mathur and Jain [17] studied the effects of magnetic field and body acceleration on the pulsatile flow of blood through stenosed arteries. Mathur and Jain [18] studied the effects of stenosis in an artery by considering the blood as power-law fluid and pointed out that the pressure drop and shear stress increases as the stenosis size increases. Blood flow through a tapered artery with a stenosis by assuming blood as a power law fluid has been studied in [19,20].

Dash et al. [21] analysed the flow of Casson fluid in a tube with porous medium. The effects of permeability factor and yield stress on shear stress distribution, plug core radius, flow rate and frictional resistance are also examined in [21]. Siddiqui et al. [22] studied the effects of stenosis, pusatility and non-Newtonian characteristics of blood assuming it as Casson fluid. Sankar and Nagar [23] developed mathematical models to study the steady flow of Casson fluid in a circular tube filled with homogenous porous medium. They observed that velocity decreases with increase in yield stress of the fluid. Aroesty and Gross [24] have developed a model on pulsatile flow of blood through narrow uniform arteries by assuming it as Casson fluid. Chaturani and Ponalagusamy [25] studied the pulsatile flow of Casson fluid through arterial stenosis using the perturbation method. The flow of blood through a narrow artery with bell-shaped stenosis treating blood as a Casson fluid has been analysed by Venkatesan et al. [26].

Bifurcation takes place in arteries before they become capillaries. Botwin [27] analysed the effect of pulsatility on flow of blood through bifurcated artery with stenosis. Siouffi et al. [28] observed experimentally the effects of unsteadiness on flow of blood through a bifurcated arterial stenosis. Chakravarty and Mandal [29] investigated the pulsatile flow of blood in a bifurcated arterial stenosis treating blood as Newtonian fluid. Sachin et al. [30] obtained velocity and shear stress distributions numerically for the flow of Casson fluid through a bifurcated artery with stenosis. The MHD principles are used to decelerate the blood flow through arteries and hence used as an effective tool in the treatment of several cardiovascular diseases. When charge particles pass through a strong magnetic field at a high speed, a force defined as Lorentz force has been developed which resist the flow of blood. Static magnetic fields are used in MRI, in decreasing healing time for fractures and in nerve regeneration. It is, therefore, worthful to investigate the pulsatile flow of blood by taking into account the influence of transverse magnetic field.

The Herschel–Bulkley fluid is a non-Newtonian fluid in which there exists a non-linear relationship between stress and strain experienced by the fluid. It is characterized by three parameters, the consistency, the power law index and the yield stress. It possesses both shear thinning and shear thickening properties. Herschel-Bulkley fluids are often used to describe rheological properties of drilling fluids, blood etc. Minced fish paste and raisin paste obey Herschel–Bulkley fluid model. Sacks et al. [31] have experimentally shown that blood behaves as both Bingham-plastic and pseudo plastic fluid- Herschel Bulkley fluid with fluid behavior index less than unity. Blair and Spanner [32] found that the behavior of blood is very close to Herschel–Bulkley fluid. Chaturani and Ponnalagarsamy [33] have pointed out that blood behaves like Herschel – Bulkley fluid rather than power - law and Bingham - plastic fluids and obtained the values of power-law index, consistency index and yield stress for normal blood and diseased blood (Myocardial Infarction) using experimental data.

The steady flow of Herschel – Bulkley fluid through stenosed arteries has been investigated in [34–36]. Sankar and Hemalatha [37] analysed the pulsatile flow of blood through stenosed arteries assuming blood as Herschel–Bulkley fluid. Tu and Deville [38] have numerically solved the pulsatile flow of Herschel–Bulkley fluid through stenosed arteries. Ponalagusamy et al. [39] investigated the effects of pulsatility and rheological behaviour of blood through stenosed artery. Further analytic expressions for velocity, wall shear stress, flow rate and flow resistance are obtained in [39]. Priyadharshini and Ponalagusamy [40] analysed the flow of blood through tapered arterial stenosis with dilatation treating blood as Herschel-Bulkley fluid. The velocity profiles of Newtonian, power-law, Bingham-plastic, Herschel– Bulkley fluids are compared with the experimental results in [40] and found that blood behaves as Herschel–Bulkley fluid. From the above arguments, it is meaningful to consider blood as Herschel–Bulkley fluid.

Huilgol and You [41] solved the flow problems of Bingham, Casson and Herschel - Bulkley fluids in circular and square cross - sections of pipes using augmented Lagrangian method. Herschel–Bulkley fluid has wide applications in bio medicine, industries and engineering. Wang and Gordaninejad [42] compared experimental results and theoretical results of Herschel–Bulkley fluid model and Bingham-plastic fluid and observed that the results of Herschel–Bulkley fluid are more accurate than Bingham-plastic model. They concluded that the Herschel–Bulkley fluid is more suitable for viscoplastic flow with yield stress and hence it serves as an important tool in designing fluid dampers. Herschel–Bulkley fluid is used in the development of blood oxygenators [6]. Due to its shear-thinning and shear-thickening properties, it is widely used in polymer industries. It is often used as lubricant in bearing [43]. Herschel-Bulkley fluid finds its application in petroleum industries in describing the non-Newtonian rheological behavior of drilling fluids [44].

The aim of the present study is to develop a mathematical model on pulsatile flow of blood through a porous bifurcated artery with stenosis in the presence of applied magnetic field and periodic body acceleration. The blood in the artery is assumed as a Herschel-Bulkley fluid which is characterized by three parameters namely yield stress, power law index or flow behavior index and consistency. The velocity distribution, wall shear stress, flow resistance and plug core radius are obtained by numerical computation. The effects of pulsatility, yield stress, flow behavior index, consistency, magnetic field, porosity and periodic body acceleration on velocity, wall shear stress and flow resistance are brought out.