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Pulsatile magneto-hydrodynamic blood flows through porous blood vessels using a third grade non-Newtonian fluids model

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ABSTRACT

In this paper, the unsteady pulsatile magneto-hydrodynamic blood flows through porous arteries concerning the influence of externally imposed periodic body acceleration and a periodic pressure gradient are numerically simulated. Blood is taken into account as the third-grade non-Newtonian fluid. Besides the numerical solution, for small Womersley parameter (such as blood flow through arterioles and capillaries), the analytical perturbation method is used to solve the nonlinear governing equations. Consequently, analytical expressions for the velocity profile, wall shear stress, and blood flow rate are obtained. Excellent agreement between the analytical and numerical predictions is evident. Also, the effects of body acceleration, magnetic field, third-grade non-Newtonian parameter, pressure gradient, and porosity on the flow behaviors are examined. Some important conclusions are that, when the Womersley parameter is low, viscous forces tend to dominate the flow, velocity profiles are parabolic in shape, and the center-line velocity oscillates in phase with the driving pressure gradient. In addition, by increasing the pressure gradient, the mean value of the velocity profile increases and the amplitude of the velocity remains constant. Also, when non-Newtonian effect increases, the amplitude of the velocity profile.

1. Introduction

Blood is known as one of the most important heterogeneous multi-phase mixtures in nature that delivers necessary substances such as nutrients and oxygen to the cells and transports metabolic waste products away from those same cells. Generally, blood is composed of plasma (contains water, glucose, dissipated proteins, mineral ions, hormones, carbon dioxide), blood cells (red blood cells 'RBCs' and white blood cells 'WBCs'), platelets, etc. In spite of the fact that plasma behaves as a Newtonian fluid, it is commonly accepted that the hematocrit (the volume percentage of RBCs in blood, which is normally 45% for men and 40% for women) exhibits shear-thinning behavior and therefore, must be modeled as a non-Newtonian fluid [1].

Some numerical studies in blood flow simulation, such as Ogulu and Bestman [2], Ogulu and Amos [3], and Ellahi et al. [4] have considered blood as a Newtonian fluid. For example, Ellahi et al. [4] performed a theoretical study for Newtonian blood flow of nanofluid through composite stenosed arteries with permeable walls. They simplified the highly nonlinear momentum equations of nanofluid model by considering the

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mild stenosis case. The hypothesis of Newtonian blood is valid for large blood vessels (arteries and veins), but when the diameter of the blood vessel is the same order of magnitude as the red blood cells and corpuscles (such as arterioles and capillaries), it is widely accepted that the non-Newtonian nature of blood has to be taken into account. Using non-Newtonian model for blood can be seen in the works of Majhi and Nair [5], Haldar and Andersson [6], Prakash and Ogulu [7], Moyers-Gonzalez et al. [8], Massoudi and Phuoc [9], Cherry and Eatona [10], Alimohamadi and Imani [11], Moawed et al. [12], Ellahi et al. [13–15], Akbar et al. [16], Caballero and Lain [17], and to name but a few. For example, Ellahi et al. [13] presented mathematical models for blood flow of Jeffrey fluid (a non-Newtonian fluid having shear thinning property) via nanoparticles in the tapered stenosed atherosclerotic arteries. In their studies, the effect of catheter and the influence of heat and mass transfer of nanoparticles on blood flow behaviors were revealed. Ellahi et al. [14] investigated the unsteady and incompressible arterial blood flow of non-Newtonian fluid (micropolar fluid) through composite stenosis. They developed analytical solutions of velocity and volumetric flow flux in terms of modified Bessel functions. Ellahi et al. [15] examined the heat and mass transfer on blood flow of non-Newtonian fluid (micropolar fluid) through a tapered stenosed artery of permeable walls. They evaluated the exact solutions for velocity, temperature and concentration profiles. And Akbar et al. [16] performed a theoretical study on the unsteady blood flow of a Williamson fluid (which represents the behavior of pseudo-plastic materials, particularly of polymer solutions and powder suspensions in Newtonian fluids) through composite stenosed arteries with permeable walls. They simplified the highly non-linear momentum equations of the Williamson fluid model by considering the mild stenosis case.

Also, the physical properties of the non-Newtonian blood have been presented in many published papers such as Fowkes et al. [18], Baieth [19], Ghasemi et al. [20] and so forth. One of the approved non-Newtonian models, in simulating the blood flow is the third-grade non-Newtonian model. There are a lot of numerical studies on blood flow simulation in which, the researchers utilized the third-grade non-Newtonian fluid in the blood modeling such as Majhi and Usha [21], Majhi and Nair [5], Hayat et al. [22,23], Zeeshan and Ellahi [24], Hatami et al. [25], Ghasemi et al. [20], and to name but a few. For example, Hayat et al. [22] carried out an analysis for MHD flow and heat transfer characteristics in a third grade fluid between two porous plates (with the application of blood flow in the coronary arteries). Zeeshan and Ellahi [24] studied the fully developed flow of an incompressible, thermodynamically compatible third-grade non-Newtonian MHD fluid in a pipe with porous space and partial slip (by considering the application of blood flow in the arteries). And Ghasemi et al. [20] simulated the steady-flow of a third-grade non-Newtonian blood in porous arteries in presence of magnetic field using analytical and numerical methods.

Blood flow in the human cardiovascular system is caused by the pumping action of the heart. The heart is a muscular organ in humans and other animals, which produces a pulsatile pressure gradient throughout the system (popularly known as a pressure pulse which physicians check at the wrist). Pressure and flow rate are characteristic in pulsatile shapes that vary in different parts of the arterial system [26,27]. Thus, several researchers have studied the pulsatile flow of blood in blood vessels. Clark [28] presented the experimental results of the pulsatile flow in a laboratory model of aortic stenosis taking the Reynolds number appropriate to aortic flow. Chaturani and Palanisamy [29] proposed a mathematical model to study the pulsatile flow of blood (by treating blood as a Power-law fluid) through rigid circular tubes under the influence of periodic body acceleration. Majhi and Nair [5] studied the pulsatile flow of blood subjected to externally imposed periodic body acceleration by assuming blood as a third grade fluid. They investigated numerically the effects of the body acceleration on the velocity, the flow rate and the wall shear stress for femoral and coronary arteries. Sarkar and Jayaraman [30] studied the flow pattern of pulsatile Newtonian blood flow in a catheterized stenosed artery through a mathematical model. Their study took into account the effect of the movement of the flexible catheter influenced by the pulsatile nature of the flow. Elshehawey et al. [31] examined pulsatile flow of blood (Newtonian model) through a porous medium under the influence of body acceleration. Craciunescu and Clegg [32] investigated the influence of the blood pulsation rate on the temperature distribution and energy transport for four typical blood vessel sizes: aorta, large arteries, terminal arterial branches, and arterioles. In their numerical works, blood was considered as a Newtonian fluid. Long et al. [33] performed numerical simulations of 3-D pulsatile Newtonian blood flow in straight tube stenosis to investigate the post-stenotic flow phenomena by means of commercial CFD package CFX4 (AEA Technology). El-Shahed [34] studied pulsatile flow of Newtonian blood through a stenosed porous medium under the influence of body acceleration. He obtained analytical expressions for axial velocity, fluid acceleration, flow rate and shear stress. Khanafer et al. [35] conducted a numerical study to determine the influence of pulsatile laminar flow and heating protocol on temperature distribution in a blood vessel and tumor tissue receiving hyperthermia treatment. They modeled the arterial wall as macroscopically homogeneous porous media and the blood as an incompressible Newtonian fluid. Ogulu and Amos [3] modeled pulsatile Newtonian blood flow within a homogeneous porous cardiovascular system in the presence of a magnetic field and time-dependent suction. Their studies showed an increase in the wall shear stress when the porosity of the medium was increased. Nagarani and Sarojamma [36] developed a mathematical model of pulsatile blood flow (using the non-Newtonian Casson fluid) through small blood vessels. They used perturbation method to solve the governing equations by assuming that the Womersley frequency parameter is small. Massoudi and Phuoc [9] examined the unsteady pulsatile flow of blood in an artery, where the effects of body acceleration were included. They modeled the blood as a modified second-grade fluid where the viscosity and the normal stress coefficients depend on the shear rate. Siddiqui et al. [37] mathematically investigated the effects of non-Newtonian nature of blood and pulsatility on flow through narrow arteries by considering two types of non-Newtonian fluid models, i.e. Herschel–Bulkley fluid model and Casson fluid model. They reported that the mean and steady flow rates decrease as the yield stress increases. Shit and Roy [38] interrogated the effect of externally imposed