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Effects of Hematocrit level on Blood flow through a tapered and overlapping stenosed Artery with Porousity

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ABSTRACT

This present study discusses the effects of hematocrit level on wall shear stress and flow resistance in a tapered and overlapping stenosed artery with porousity. The equation governing the flow in a tapered overlapping stenosed artery was solved for dimensionless resistance to flow and wall shear stress. The results highlight that the resistance to flow increases with increase in either stenosis height or artery shapes while the influence of hematocrit level has slight decrease. The effects of Darcy number and slip parameter due to permeability of the wall was discussed.

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1. Introduction

The circulatory system is an organ system that allows blood to circulate and transport nutrients (such as amino acids and electrolytes), oxygen, hormones, blood cells, carbon-dioxide to and from the cells in the body to provide nourishment and help in fighting diseases, stabilize temperature and PH, and maintain homeostasis. The condition where the artery becomes narrowed and hardened due to the deposition of excessive fatty components (cholesterol) and abnormal intravascular growth which results in the formation of the stenosis is called the atherosclerosis. The atherosclerotic cardiovascular disease is the usual cause of heart attacks, strokes and peripheral vascular disease. This has been the major causes of health problems and death in this 21st century globally. The world health organization (WHO) gave an estimation of 17.9 million of people who died from atherosclerotic cardiovascular disease in 2016, which represent 31% of all global deaths, 85% are due to heart attack and stroke, so it is very important to study the blood flow through the tapered and overlapping stenosed artery with a permeable wall.

Taylor [1], found that at low shear (less than $100s^{-1}$) rate blood behaves as a non-Newtonian pulsatile flow and at high shear rate ($1000s^{-1}$) blood exhibits Newtonian characteristic in large arteries like aorta. Low shear rate is observed in stenosis and blood flow through stenosed artery to behave like non-Newtonian characteristics (Leondes, [2]). Ellahi et al. [3] have studied a mathematical model of non-Newtonian fluid to investigate the eff ect of composite stenosis through the permeable artery analytically. They observed that the flow impedance (resistance) increases by increasing the stenosis height and decreases by increasing the slip parameter and length. As one gets older, fats, cholesterol and calcium can collect in the arteries and form plaque. The buildup plague makes it difficult for blood to flow through ones artery and it might results to partially or totally blockage of arterial blood flow. Studies showed that an endothelium which is semi permeable can form the inner cellular lining of blood vessels which played vital roles on permeability of the artery. Many researchers such as (Mofrad et al. [4]; Nerem, [5]; Byoung Kwon et al. [6]) contributed on this issue. The wall shear stress is of great significance on the blood flow through the arteries and plays a vital role in remodeling the arterial wall (Mofrad et al. [4]). Nerem [5] and Byoung Kwon et al.[6] drew special attentions to low wall shear stress which can be regarded as risk factor in the growth of atherosclerotic plaque. Pralhad et al. [7] compared the blood flow between stenosed arteries and

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normal arteries and noticed that the resistance to flow was much higher in the case of stenosed arteries. Srivastav [8] and Mishra et al. [9] studied the Newtonian blood flow through a stenosed artery with permeable wall and got resistance and wall shear stress graphically. They have shown that the resistance increased as the stenosis height increasing and wall shear stress was downwardly concave.

Chakravarty and Mandal [10], studied the Mathematical modelling of blood flow through an overlapping arterial stenosis observed that the flow rate becomes inversely proportional to the resistive impedance arising out of the stenotic flow in vivo, the severity of the overlapping stenosis affects the wall shear stress becomes inversely proportional to the amplitude of the pressure gradient.

The hematocrit measures the volume of red blood cells compared to the total blood volume (red blood cells and plasma). The normal hematocrit for men is 40% to 54%; for women it is 36% to 48%. This value can be determined directly by microhematocrit centrifugation or calculated indirectly. Automated cell counters calculate the hematocrit by multiplying the red cell number (in millions/mm3) by the mean cell volume (MCV, infemtoliters). When so assayed, it is subject to the vagaries inherent in obtaining an accurate measurement of the MCV. by Kenneth et. al. [11]. Hematocrit affects blood viscosity and therefore resistance to flow. Srivastava [12] investigated the resistance and wall shear stress with the stenosis height and hematocrit in the catheterized stenosed artery and concluded that the resistance is increased with stenosis height and hematocrit.

Singh and Singh [13], studied the effect of hematocrit on wall shear stress for blood flow through tapered artery. They observed that wall shear stress reduces for increasing Hematocrit percentage and it is increases as stenosis height and porous parameter whereas it decreasing values of velocity of blood and slope of tapered artery. Abubakar J.U. et al. [14], studied the effects of radiative heat and magnetic field on blood flow in an inclined tapered stenosed porous artery. They observed that the volumetric flow rate will increase more in the converging region than in the non-tapered and diverging regions of the artery.

Malek et al. [15], studied the effects of Hematocrit level on the blood flow through stenosed Artery; observed that resistant increases with the increasing of hematocrit level and stenosis and that skin friction increase with increasing of stenosis height and decreases with the decreasing of stenosis height. Malek and Haque [16], studied hematocrit level on blood flow through a stenosed artery with permeable wall, they observed that the resistance of flow increases for increasing of stenosis height where the hematocrit level($35\% - 45\%$) has significant effects, the effects of hematocrit, slip parameter and Darcy number have been focused on wall shear stress of the inner surface of the artery which has a fashion of downward concave for increasing of the z-axis of the artery.

In all the above discussed studies, to the best knowledge of the author, the effect of hematocrit level on blood flow through a tapered and overlapping stenosed with permeable wall has not been studied. Therefore, the objective of the present work is to investigate the effect of hematocrit level, slip parameter and Darcy number on resistance of blood flow and wall shear stress in presence of tapered and overlapping stenosed artery when the blood flow is considered as power law fluid using Walburn-Schnek model [17]. The problems were solved analytically.

2. Formulation of the problem

All The study consider the laminar, incompressible and non-Newtonian flow of blood through axisymmetric one-dimensional tapered and overlapping stenosed artery. Any material point in the fluid is representing by the cylindrical polar coordinate (r,θ,z), where z measures along the axis of the artery and that of r and θ measure along the radial and circumferential directions respectively.

The mathematical expression that corresponds to the geometry (Figure 1) of the present problem is given by

$$\frac{R(z)}{R_0} = \begin{cases} \left(\frac{mz}{R_0}+1\right) - \frac{\delta cos\emptyset}{R_0 L_0}(z-d) \\ \left\{11 - \frac{94}{3L_0} + \frac{32}{L_0^2(z-d)^2} - \frac{32}{3L_0^3}(z-d)^3\right\} \\ ,d \le z \le d + \frac{3L_0}{2} \\ \left(\frac{mz}{R_0}+1\right),\ otherwise, \end{cases} \tag{1}$$

Where R(z) denotes the radius of the tapered arterial segment in the constricted region, R_0 is the constant radius of the normal artery in the non-stenotic region, φ is the angle of tapering, $\frac{3L_0}{2}$ is the length of overlapping stenosis, d is the location of the stenosis, δcosφ is taken to be the critical height of the overlapping stenosis and m(tanφ) represents the slope of the tapered vessel. Ex-poring the possibility of the different shapes of the artery, it can be categorized as converging tapering (φ<0), non-tapered artery (φ = 0) and the diverging tapering (φ>0).

3. Mathematical Formulation

The equation governing one dimensional blood flow was expressed by Young [18] and Malek et. al [16] as

$$\frac{dp}{dz} = \frac{1}{r}\frac{\partial(r\tau)}{\partial r} \tag{2}$$

Where p, τ, r represent the pressure, shear stress of blood, and radius of the artery respectively.

The constitutive equation of blood in its non-Newtonian form based on significant level of hematocrit and shear rate is expressed by Walburn-Schneck [17] as follows:

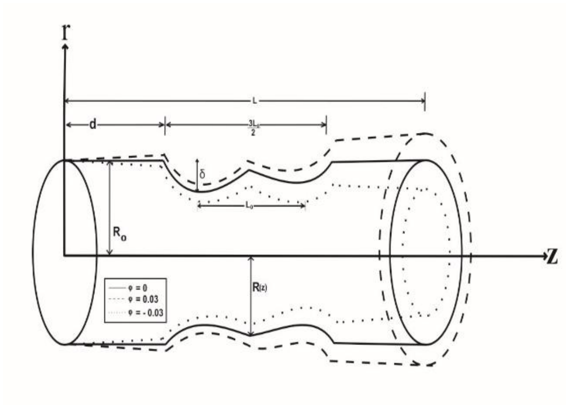

Figure 1. Schematic diagram of overlapping stenosed artery.

$$\tau = a_1 exp(a_2 H + \frac{a_3}{H^2})\dot{\gamma}^{(1-a_4 H)} \tag{3}$$

Where $\dot{\gamma}$ and H are the shear strain rate and hematocrit level on the blood, respectively and a_1, a_2, a_3 and a_4 are constant corresponding to 0.000797, 0.0608, 377.7515 and 0.00499 for whole blood analysis. $\dot{\gamma} = -\frac{du}{dr}$, u is the axial velocity of blood.

4. Boundary Conditions

A formulation for the flow of blood through artery of permeable wall with slip velocity is given by Beavers et. al [19] and Shailesh et. al [20] as

$$\frac{\partial u}{\partial r} = 0 \qquad at \quad r = 0 \tag{4}$$

$$u = v_c \qquad at \quad r = R(z) \tag{5}$$

$$\frac{\partial u}{\partial r} = \frac{\alpha}{\sqrt{D_a}}(v_c - v_f) \qquad at \quad r = R(z) \tag{6}$$

where $v_f = -\frac{D_a}{\mu}\frac{dp}{dz}$ is the velocity in the permeable boundary and v_c is the slip velocity. α and D_a are the dimensionless quantity depending on the slip parameter and Darcy number, respectively.

5. Analysis

In solving Equation (2), one re-writes the equation as

$$\frac{\partial(r\tau)}{\partial r} = r\frac{dp}{dz} \tag{7}$$

Integrating Equation (7) and using boundary condition (4), one obtains

$$\tau = (\frac{r}{2})\ \frac{\partial p}{\partial z} \tag{8}$$

The flow in large artery satisfies Newtonian flow, hence:

$$\tau = \mu\ \frac{\partial u}{\partial r} \tag{9}$$

Where μ is the viscosity of the blood.

Substituting Equation (3) into Equation (8) in view of Equation (9), the expression for the velocity subject to the boundary condition (5) is

$$u = [a_1 exp(a_2 H + \frac{a_3}{H^2})]^{\frac{1}{(-a_4 H)}}\mu^{\frac{1}{(-a_4 H)}}(r - R) + v_c \tag{10}$$

From equation (8), applying the boundary condition (6), the slip velocity vc can be determined as

$$v_c = \frac{D_a}{2\mu\alpha}\frac{dp}{dz}[R\ -\ 2\alpha D_a] \tag{11}$$

The volumetric flow flux, Q is thus defined as

$$Q = 2\pi\int_0^{R(z)} urdr \tag{12}$$

Which is modified by Equation (10) and (11). Finally, the modified volumetric flow flux becomes

$$Q = -\frac{\pi T}{3}R^3 + \frac{\pi\sqrt{D_a}}{2\mu\alpha}\frac{dp}{dz}[R^3 - 2\pi R^2\sqrt{D_a}] \tag{13}$$

where

$$T = [a_1 exp(a_2 H + \frac{a_3}{H^2})]^{\frac{1}{(a_4 H)}}\mu^{\frac{1}{(-a_4 H)}}$$

After simplifying the Equation (13) then,

$$\frac{dp}{dz} = \frac{Q + \frac{\pi}{3}TR_0^3\left(\frac{R(z)}{R_0}\right)^3}{\frac{\pi\sqrt{D_a}}{\mu\alpha}[{R_0}^3(\frac{R(z)}{R_0})^3\ -\ 2\alpha\sqrt{D_a}{R_0}^2\left(\frac{R(z)}{R_0}\right)^2]} \tag{14}$$

Equation (14) is the pressure gradient of blood due to stenosis in the artery. Integrating Equation (14) from p = p_0 at z = 0 and p =p_1 at z = L, is the resistance of the flow as

$$p_1 - p_0 = \int_0^L \frac{Q + \frac{\pi}{3}TR_0^3(\frac{R(z)}{R_0})^3}{\frac{\pi\sqrt{D_a}}{\mu\alpha}[{R_0}^3(\frac{R(z)}{R_0})^3\ -\ 2\alpha\sqrt{D_a}R_0^2(\frac{R(z)}{R_0})^2]}dz \tag{15}$$

The resistance to flow λ given by Somchai Sriyab [21] and Malek et. al. [16] as

$$\lambda = \frac{p_1 - p_0}{Q}$$

$$\lambda = \int_0^L \frac{1 + \frac{\pi}{3Q}TR_0^3(\frac{R(z)}{R_0})^3}{\frac{\pi\sqrt{D_a}}{\mu\alpha}[R_0^3(\frac{R(z)}{R_0})^3\ -\ 2\alpha\sqrt{D_a}R_0^2(\frac{R(z)}{R_0})^2]}dz \tag{16}$$

and

$$\lambda = \int_0^d \frac{1 + \frac{\pi}{3Q}TR_0^3(\frac{R(z)}{R_0})^3}{\omega}dz + \int_d^{\frac{3L_0}{2}+d} \frac{1 + \frac{\pi}{3Q}TR_0^3(\frac{R(z)}{R_0})^3}{\omega}dz + \int_{\frac{3L_0}{2}+d}^L \frac{1 + \frac{\pi}{3Q}TR_0^3(\frac{R(z)}{R_0})^3}{\omega}dz \tag{17}$$

Where $\omega = \frac{\pi\sqrt{D_a}}{\mu\alpha}[R_0^3(\frac{R(z)}{R_0})^3\ -\ 2\alpha\sqrt{D_a}R_0^2(\frac{R(z)}{R_0})^2]$.

The stenosis is present in the region $d \le z \le d + \frac{3L_0}{2}$. If there is no stenosis $\frac{R(z)}{R_0}$ equal to $(\frac{mz}{R_0} + 1)$ from Equation (1). Therefore,

$$\lambda = \int_0^d \frac{(1+\rho)}{\zeta} dz + \int_d^{\frac{3L_0}{2}+d} \frac{1}{\frac{\pi\sqrt{D_a}}{\mu\alpha}[R_0^3(\frac{R(z)}{R_0})^3 + \frac{\pi}{3Q}TR_0^3\left(\frac{R(z)}{R_0}\right)^3 - 2\alpha\sqrt{D_a}R_0^2\left(\frac{R(z)}{R_0}\right)^2]} dz + \int_{\frac{3L_0}{2}+d}^{L} \frac{(1+\rho)}{\zeta} dz \quad (18)$$

where $\zeta = \frac{\pi\sqrt{D_a}}{\mu\alpha}[R_0^3(\frac{mz}{R_0}+1)^3 - 2\alpha\sqrt{D_a}R_0^2(\frac{mz}{R_0}+1)^2]$, $\rho = \frac{\pi}{3Q}TR_0^3(\frac{mz}{R_0}+1)^3$.

By integrating Equation (16) with no stenosis, the resistance to flow λN is given by

$$\lambda_N = \int_0^L \frac{1}{\frac{\pi\sqrt{D_a}}{\mu\alpha}[R_0^3(\frac{mz}{R_0}+1)^3 + \frac{\pi}{3Q}TR_0^3(\frac{mz}{R_0}+1)^3 - 2\alpha\sqrt{D_a}R_0^2(\frac{mz}{R_0}+1)^2]} dz \quad (19)$$

The resistance to flow in dimensionless form can be given as

$$\bar{\lambda} = \frac{\lambda}{\lambda_N} \quad (20)$$

The wall shear stress can be expressed as

$$\tau_R = -(\frac{R}{2})\frac{\partial p}{\partial z} = -\left\{\frac{Q + \frac{\pi}{3}TR_0^3(\frac{R(z)}{R_0})^3}{\frac{2\pi\sqrt{D_a}}{\mu\alpha}[R_0^2(\frac{R(z)}{R_0})^2 - 2\alpha\sqrt{D_a}R_0(\frac{R(z)}{R_0})]}\right\} \quad (21)$$

Also, in the absence of stenosis in the artery $\frac{R(z)}{R_0} = (\frac{mz}{R_0} + 1)$, then, one can expressed Equation (21) as

$$\tau_N = -\left\{\frac{Q}{\frac{2\pi\sqrt{D_a}}{\mu\alpha}[R_0^2(\frac{mz}{R_0}+1)^2 + \frac{\pi}{3}TR_0^3(\frac{mz}{R_0}+1)^3 - 2\alpha\sqrt{D_a}R_0(\frac{mz}{R_0}+1)]}\right\} \quad (22)$$

The wall shear stress can be given in dimensionless form as

$$\bar{\tau} = \frac{\tau_R}{\tau_N} \quad (23)$$

The analytical evaluation of the second integral on the right hand side of Equation (18) is a formidable task and therefore shall be evaluated numerically, whereas the evaluation of first and third integrals are straight forward. The resistance to flow and wall shear stress in the stenosed artery for different parameters such as hematocrit, viscosity of blood, slip parameter, e.t,c., can be determined through Equations (18) - (20).

6. Numerical results and discussion

In this section, calculation of the effects of blood flow parameters have been shown. From Srivastav [8], Malek A. et al [16] and others the values for the parameters are taken. The values of the parameters are considered with its range as H = 40% − 50%, Q=0.1, L=5, L_0 = 2, d=1, R_0 = 1, $\frac{\delta}{R_0}$= 0.1 − 0.5, α = 0.1−0.2, $\sqrt{D_a}$ = 0.1−0.2. μ is the blood viscosity and defined as the inherent resistance of blood to flow. The blood viscosity for normal adult is given as 0.3 and reported in units of millipoise.

Determination of Resistance to blood flow through the vessels depends on the size of the vessels and the resistance is dependent on radius of the blood vessels. Hence, a narrow blood vessel will resist blood flow than a wider vessel as described by Poiseuille's equation that shows an inverse relationship between the blood flow rate and blood vessel resistance. The resistance of blood flow in the presence of overlapping stenosis in a tapered porous artery, on level of hematocrit constitutive non-Newtonian expression of blood flow is given by Equation (18) analytically. Graphical presentations of resistance are plotted in Figure (2) - (6) for different values of hematocrit level, slip parameter and Darcy number respectively. Figure 2 shows the variation of resistance to flow along the stenosis height with artery shapes for different value of hematocrit level. It is shown that the resistance to flow is increasing with an increase in stenosis height and hematocrit level produces no significant change. Also, resistance to flow rise with an increase in the value of angle φ. Hence, diverging tapering produces upper bound resistance while converging tapering results in lower bound resistance. Figures 3 shows the variation of resistance to flow along the stenosis height with artery shapes for different value of slip parameter. It depicts that resistance to flow rises with an increase in values of angle φ. Hence, diverging tapering produces upper bound resistance while converging tapering results in lower bound resistance. A rise in slip parameter α speedup the resistance to flow. Figure (4) - (6) show the variation of resistance to flow along the stenosis height with artery shapes for different value of Darcy number. As Darcy number increases, the resistance to flow decreases for angle (φ=0) non-tapering, (φ=0.03) diverging tapering and (φ=-0.03) converging tapering.

Figure (7) - (9) show the variation of resistance in dimensionless form along the stenosis height with artery shapes for different value of Darcy number. One observes that as Darcy number increases, the resistance to flow increases for angle (φ=0) non-tapering, (φ=0.03) diverging tapering and (φ=-0.03) converging tapering. Figure (10) - (12) show the variation of resistance in dimensionless form along the stenosis height with artery shapes for different values of slip parameter. There is slight significant decrease in resistance as slip parameter increases for both diverging tapering and non-tapering respectively while for converging tapering it shows no significant difference.

The tangential force at the endothelial surface produced by blood moving through artery is called the wall shear stress. The magnitude of wall shear stress is directly proportional to blood flow and blood viscosity, and inversely proportional to the cube of the radius (Masuda et al., [22]). Thus, a small change in the radius of a vessel will have a great effect on wall shear stress as show in Figure (13) - (16).

It has been noted that wall shear stress plays a critical role in the gradual development and destabilization of atherosclerotic plaques. The effects of stenosis height, hematocrit level, slip parameter and Darcy number on wall shear stress of the permeable tapered and overlapping stenosed arterial wall along the horizontal axis are expressed by Equations (21) and (23). The results have been presented in Figures (13) - (16) against the horizontal axis. It is observed that where there is no stenosis, there is no significant different for hematocrit level, slip parameter and Darcy number on wall shear stress in the artery. However, at stenosis region, as angle (φ) decreases, the shear stress ($\bar{\tau}$) also increases. Figure 14 shows the variation of wall shear stress in dimensionless form along z with artery shapes for different value of slip parameter.

Furthermore, Figure 16 which shows the variation of wall shear stress in dimensionless form along z with artery shapes for different value of stenosis height. It is also observed that wall shear stress significantly depends on stenosis height. The wall shear stress is increasing with an increase in stenosis height and a decrease in angle (φ). Table 1 shows the resistance to flow with variation of Hematocrit level H and stenosis height ($\frac{\delta}{R_0}$) when φ= 0.03. It depicts that resistance to flow slightly decreases with an increase in values of hematocrit level H (35% - 60%) and as stenosis height developed.

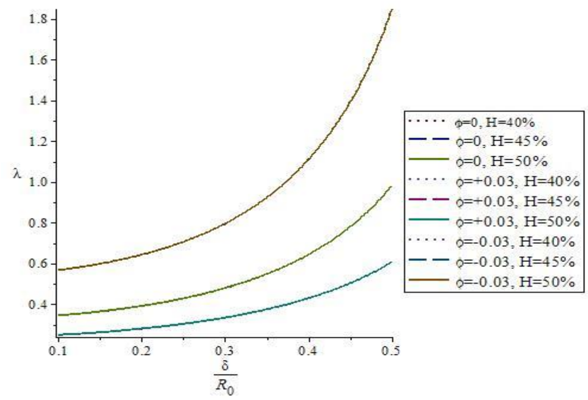

Figure 2. Variation of resistance to flow along stenosis height with artery shapes for different value of hematocrit level H.

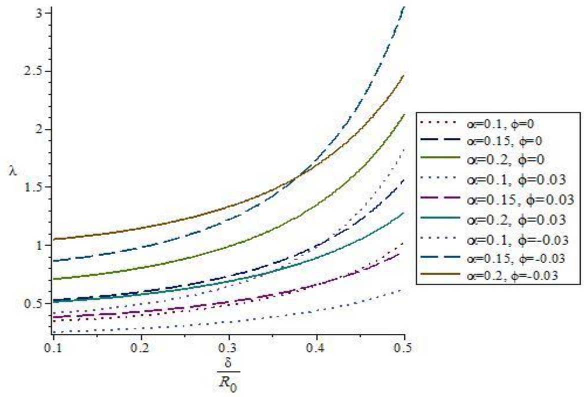

Figure 3. Variation of resistance to flow along stenosis height with artery shapes for different value of slip parameter α.

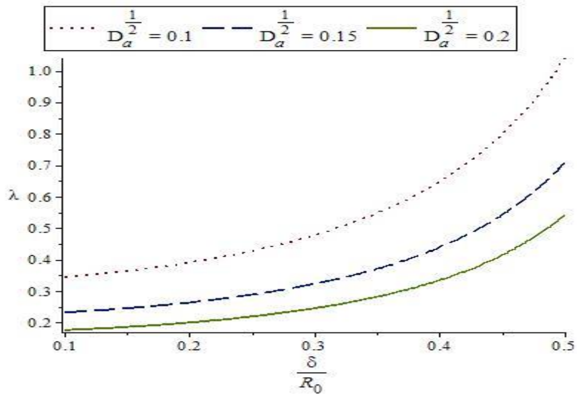

Figure 4. Variation of resistance to flow along stenosis height for different value of Darcy number D_a at angle φ=0.

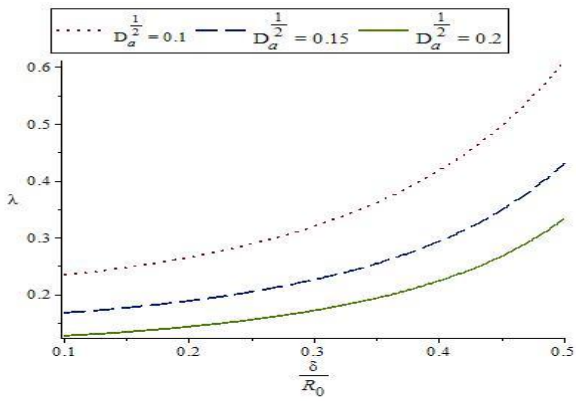

Figure 5. Variation of resistance to flow along stenosis height for different value of Darcy number D_a at angle φ=0.03.

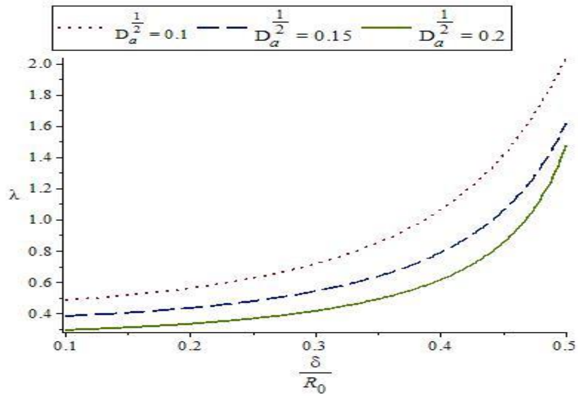

Figure 6. Variation of resistance to flow along stenosis height for different value of Darcy number D_a at angle φ=-0.03.

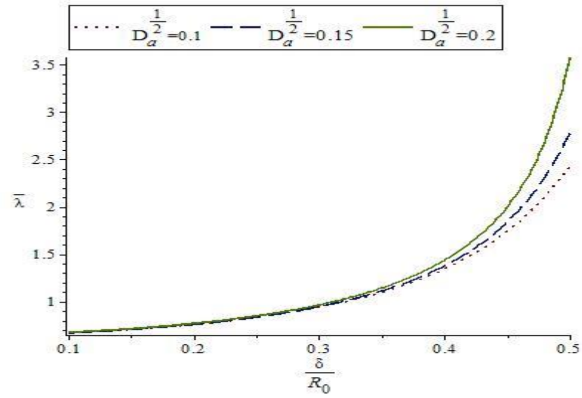

Figure 9. Variation of resistance in dimensionless form along the stenosis height for different values of Darcy number D_a at angle φ=-0.03.

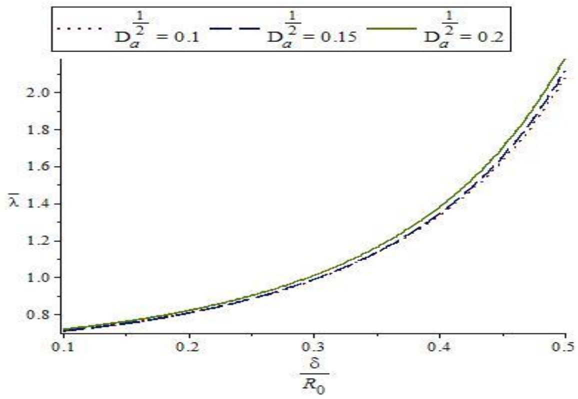

Figure 7. Variation of resistance in dimensionless form along the stenosis height for different value of Darcy number D_a at angle φ=0.

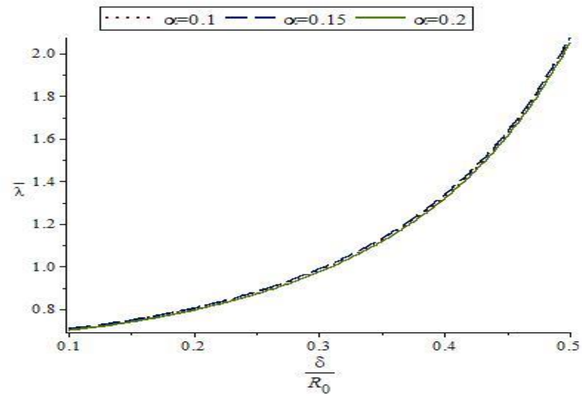

Figure 10. Variation of resistance in dimensionless form along the stenosis height for different values of slip parameter α at angle φ=0.

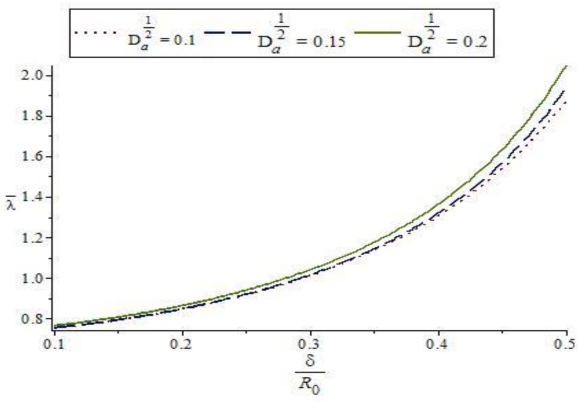

Figure 8. Variation of resistance in dimensionless form along the stenosis height for different value of Darcy number D_a at angle φ=0.03.

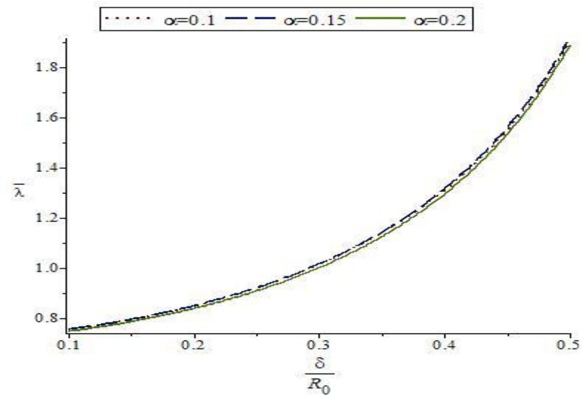

Figure 11. Variation of resistance in dimensionless form along the stenosis height for different values of slip parameter α at angle φ=0.03.

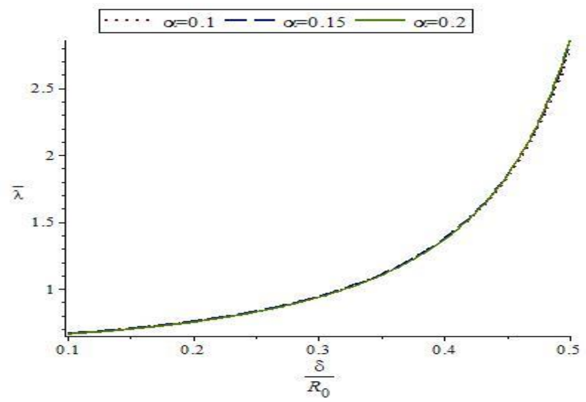

Figure 12. Variation of resistance in dimensionless form along the stenosis height for different values of slip parameter α at angle φ=-0.03.

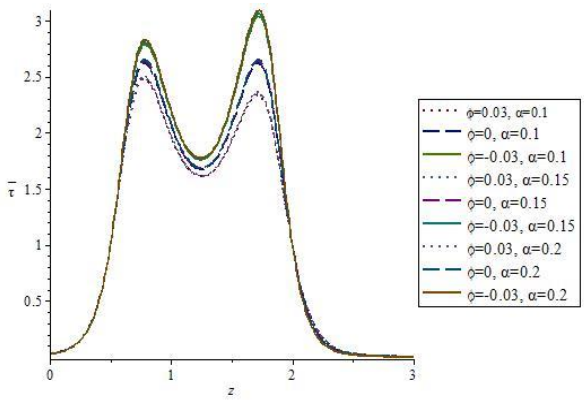

Figure 14. Variation of wall shear stress in dimensionless form along z axis with artery shapes for different value of slip parameter α.

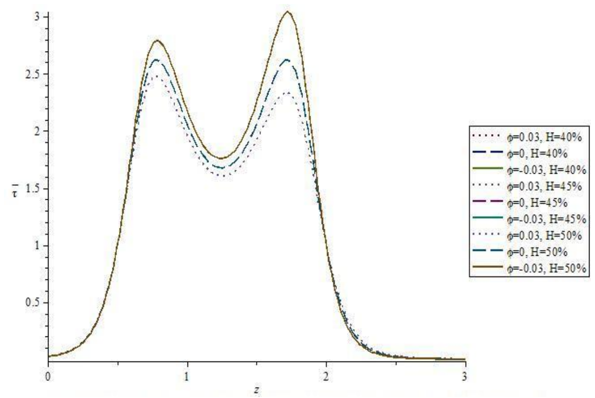

Figure 13. Variation of wall shear stress in dimensionless form along z axis with artery shapes for different value of hematocrit level H.

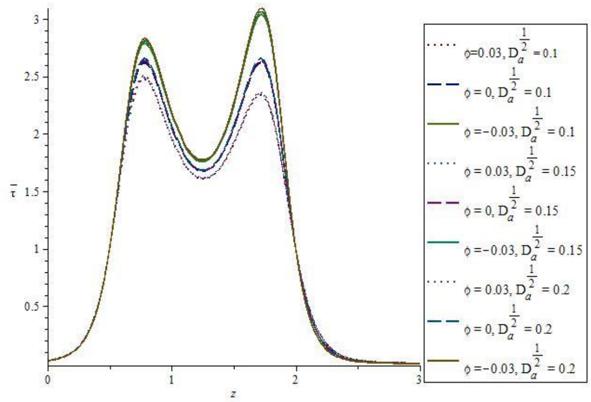

Figure 15. Variation of wall shear stress in dimensionless form along z axis with artery shapes for different values of Darcy number D_a

Table 1. Resistance to flow with variation of Hematocrit level H and stenosis height when φ=0.03.

Hematocrit Level (H)	$\frac{\delta}{R_0} = 0.0$	$\frac{\delta}{R_0} = 0.2$	$\frac{\delta}{R_0} = 0.4$
H=35%	0.8341597913	0.8462262895	1.307623927
H=40%	0.8341597403	0.8462262224	1.307623305
H=45%	0.8341589728	0.8462251538	1.307611986
H=50%	0.8341508549	0.8462137892	1.307490469
H=55%	0.8340934122	0.8461332322	1.306636108
H=60%	0.8338011120	0.8457252165	1.302279646

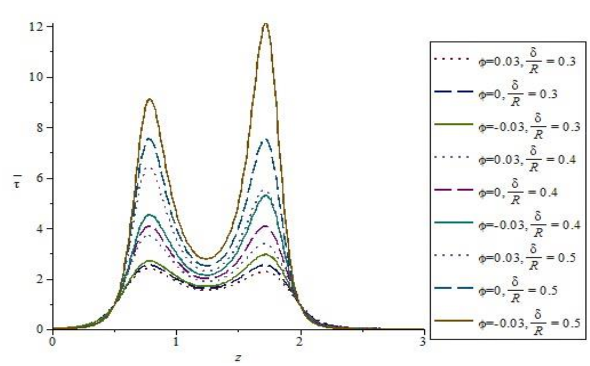

Figure 16. Variation of wall shear stress in dimensionless form along z axis with artery shapes for different values of stenosis height.

Conclusion

The effects of hematocrit level on resistance to flow through a tapered with overlapping stenosed artery and wall shear stress of permeable wall was determined in the present study. It was found that the resistance to flow increases with an increase in either stenosis height or artery shapes while it slightly decreases as hematocrit level increases. It is also observed that the resistances to flow increases with increasing slip parameter and decreases with increasing Darcy number due to porousity.

Moreover, for the wall shear stresses it was observed that where there is no stenosis no significant different in hematocrit level, slip parameter, Darcy number and stenosis height. But at the stenosis region, artery shapes (φ) decreases with increasing wall shear stress. In addition, wall shear stress increases with an increase in stenosis height at the middle.

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