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Mathematical Model of Two Layered Non-Newtonian Blood Flow through Artery in Presence of Stenosis during Liver Cancer

Ram Naresh Yadav[1], V. Upadhyay[2]

[1]Assistant Professor, Govt, P. G. College Karwi Chitrakoot (U.P.) India
[2]Associate Professor, Dept. of Physical sciences, M.G.C.G. Vishwavidyalay Chitrakoot, Satna (M.P.) India

Abstract:
The aim of the present study is to examine a mathematical model of two phased blood flow in human pulmonary artery in the presence of stenosis, keeping in view the nature of pulmonary blood circulation during liver Cancer. Some of the previous researchers have already considered the blood flow to be of two phase. We have applied power law model (based on non-Newtonian flow) in biofluid mechanical set up. For the purpose, blood has been assumed to be constituted of plasma and blood cells which is realistic so far. The pressure drop along the length of stenosis has been calculated. In present study overall presentation is in tensorial form and the solution technique adopted is analytical as well as numerical. The role of Hematocrit is explicit in determination of blood pressure drop.

Keywords: Mathematical modeling, non-Newtonian blood flow, human pulmonary artery, stenosis, Hematocrit.

INTRODUCTION

Stenosis

Stenosis means that an artery is getting narrower because of the buildup of arteriosclerotic plaques or other unusual tissue growth. The presence of stenosis in an artery can have catastrophic repercussions and disturb the regular functioning of the circulatory system. When blood flow is restricted, nutrients and oxygen cannot reach the tissues that require them. Sinha et al. [11] proposed that the presence of stenosis can cause serious circulatory blood flow in porous vessels with double stenosis in the presence of an external magnetic field, whereas Shit and Roy [9] analysed a mathematical model for unsteady flow of blood through arteries with stenosis, in which blood was treated as a Newtonian viscous incompressible fluid, and also investigated that the wall shear stress decreases as the stenosis shape parameter increases. Bali and Awasthi [7] investigated the influence of external magnetic fields on blood flow in a stenotic artery.

Blood

Blood is made up of two components: a yellow fluid called plasma and cells suspended in it. Plasma is a subset of extracellular fluid found only in blood vessels. Plasma, which makes up 55% of blood fluid, is 92% water by volume [8]. Blood accounts for about 7% of the human body's weight [9] by volume; red blood cells make up around 45% of whole blood, plasma about 54.3%, and white cells about 0.7% [10].

Whole blood (plasma and cells) exhibits non-Newtonian fluid dynamics. Red blood cells contain blood haemoglobin and transport oxygen [11]. Because blood is a complicated non-Newtonian flow, there are several signs of non-Newtonian rheology, including shear thinning [35], yield stress [36], and viscoelasticity [37]. The blood also exhibits unusual thixotropic behaviour [38], as evidenced by the presence of hysteresis loops during shearing cycles [39]. These non-Newtonian features affect not only the flow patterns inside the flow channels and fluid transportation but also the mechanical stress on the blood artery walls and surrounding tissues [40], particularly in cases of uneven lumen geometry, such as stenosed arteries [41].

Description of disease

HCC is the most frequent type of liver cancer, which is a severe cancer that begins in the liver. People who already have liver illnesses, such as cirrhosis, hepatitis B and C infections, or non-alcoholic fatty liver disease (NAFLD), are more prone to develop it. The disease's high fatality rate makes early detection more challenging, as does the possibility that symptoms will not appear until the disease has advanced.

Liver cancer, particularly hepatocellular carcinoma (HCC), has a significant impact on the body's haematological system, affecting haemoglobin levels and red blood cell (RBC) counts specifically. Because these effects can create significant problems and impact therapeutic decisions, it is critical to understand them when treating patients with liver cancer.

The protein haemoglobin in red blood cells is responsible for transporting oxygen throughout the body. Red blood cells are responsible for removing carbon dioxide from the body and transporting oxygen to tissues and organs. Haemoglobin levels normally range between 13.5 and 17.5 grammes per decilitre in men and 12.0 and 15.5 grammes per decilitre in women, though this varies with age and gender. Anaemia, caused by a decrease in haemoglobin or red blood cell count, can affect organ function, causing weakness and tiredness.

REAL MODEL

Selection of Parameter and Frame of Reference

For mathematical modelling of hepatic blood flow, we use a generalised three-dimensional orthogonal curvilinear coordinate system, sometimes known as a three-dimensional Euclidean space. The biophysical rules thus described are totally consistent in any coordinate system, which is required for the law's validity (1990) [13]. Now let the coordinate axes be OX^i, where O is the origin and superscript i = 1, 2, 3. Let X^i be the coordinate of any point P in space. The mathematical description of the state of flowing blood is altered by means of functions that give the distribution of blood velocity $v^i = v^k(X^i,t)$, k = 1, 2, 3 and of any two thermodynamic quantities pertaining to the blood for the pressure $p = p(X^i, t)$ and the density $\rho = \rho(X^i, T)$. Blood is a heterogeneous fluid separated into two phases: plasma and blood cells. The blood cells are surrounded by a semi-permeable membrane with a density larger than that of plasma; these blood cells are evenly dispersed in plasma. Thus, blood can be viewed as a homogeneous mixture of two phases.

Mathematical Formulation

V. Upadhyay and P.N. Pandey claim that the blood flow in the hepatic arteries that are far from the heart is non-Newtonian and that the strain rate determines the effective viscosity of the blood flowing in these arteries [16]. Here, the power law law $T' = \eta_m e^n$, where $0.68 \leq n \leq 0.80$ holds true for blood flow,

causes the blood flow to become non Newtonian for strain rates between 5 and 200 per second. The following equation is used to determine the surface of the axially symmetric stenosis.

$$\frac{R(z)}{R_0} = 1 - \frac{\delta}{2R_0}\left(1 + \frac{cos\pi z}{z_0}\right), \quad -z_0 \le z \le z_0 \qquad (1)$$

We shall assume that $\frac{\delta}{R_0} <<< 1$ and $R_e \frac{\delta}{R_0} <<< 1$, where R_0 the Reynolds number of fluid flows.

The equation of continuity for power law flow will be as follows:

$$\frac{1}{\sqrt{g}}(\sqrt{g}v^i)_{,i} = 0 \quad (2)$$

again the equation in tensorial form is as follows:

$$\rho_m \frac{\partial v^i}{\partial t} + (\rho_m v^j)v^i{}_{,j} = T^{ij}{}_{,j} \quad (3)$$

The constitutive equations for the power law non-Newtonian blood flow is as follows:

$$T^{ij} = -pg^{ij} + \eta_m(e^{ij}) + T'^{ij}$$

According to Singh P. and Upadhyay K.S., the presence of blood cells influences blood flow, and this effect is proportional to the volume occupied by blood cells [15]. Let X be the volume part covered by blood cells in unit volume; this X is replaced by H/100, where H represents the haematocrit. The volume part covered by the plasma will be 1-X.

Where $\rho_m = X\rho_C + (1-X)\rho_P$ and $\eta_m = X\eta_C + (1-X)\eta_P$

Since the blood vessels are cylindrical, the above governing equations have to transform into cylindrical co-ordinates.

Let $x^1 = r$, $x^2 = \theta$, $x^3 = z$

Matrix of corresponding metric tensor in cylindrical form is as follow:

$$[g_{ij}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & r^2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

So Matrix of conjugate metric tensor is

$$[g^{ij}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{r^2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Whereas Christoffel's symbols of 2nd kind are as follows:

$\left\{ {1 \atop 2\ 2} \right\} = -r$, $\left\{ {2 \atop 2\ 1} \right\} = \left\{ {2 \atop 1\ 2} \right\} = \frac{1}{r}$ exsscept of these all are zero.

Contravarient and physical components of velocity of blood flow will be related as

$$\sqrt{g_{11}}v^1 = v_r \Rightarrow v_r = v^1, \sqrt{g_{22}}v^2 = v_\theta \Rightarrow v_\theta = rv^2, \sqrt{g_{22}}v^3 = v_z \Rightarrow v_z = v^3$$

Further the physical component of $-p_{,j}\, g^{ij} are -\sqrt{g_{ii}}p_{,j}\, g^{ij}$

The matrix of physical component of shearing stress – tensor

$T^{,ij} = \eta_m(e^{ij})^n = \eta_m(g^{ik}v^i_{,k} + g^{jk}v^j_{,k})^n$ will be as follows :

$$\begin{bmatrix} 0 & 0 & \eta_m\left(dv/dr\right)^n \\ 0 & 0 & 0 \\ \eta_m\left(dv/dr\right)^n & 0 & 0 \end{bmatrix}$$

The covariant derivative of $T^{,ij}$ is

$$T^{,ij}_{,j} = \frac{1}{\sqrt{g}}\frac{\partial}{\partial x^j}\left(\sqrt{g}T^{,ij}\right) + \left\{ \begin{matrix} i \\ j \end{matrix} \begin{matrix} \\ k \end{matrix} \right\} T^{,kj}$$

Given the preceding facts, the governing tensorial equations can be converted into cylindrical forms as follows:

The equation of continuity –

$\frac{\partial v}{\partial z} = 0$ (4)

The equation of motion along r,θ , z direction become

$$-\frac{\partial p}{\partial r} = 0, \qquad 0 = 0, \qquad 0 = -\frac{\partial p}{\partial r} + \frac{\eta_m}{r}\frac{\partial}{\partial r}\left(r\left(\frac{dv}{dr}\right)^n\right) \qquad (5)$$

Here this fact has been taken in view that in axial flow is symmetric in artery so that $v_\theta = 0$ *and* v_r, v_z*and* p do not depend upon. Also the blood flows steadily, i.e.

$$\frac{\partial p}{\partial t} = \frac{\partial v_r}{\partial t} = \frac{\partial v_\theta}{\partial t} = \frac{\partial v_z}{\partial t} = 0$$

On integrating equation (4), we get $v_z = v(r)$since v does not depend upon θ

(6)

The integrating first equation of (5), we get $p = p(z)$ (7) since p does not depend upon θ

Now, with the help of equation (6) and (7), the third equation of motion of (5) converts in the following form:

$$0 = -\frac{dp}{dz} + \frac{\eta_m}{r}\frac{d}{dr}\left(r\left(\frac{dv}{dr}\right)^n\right) \qquad (8)$$

Analysis and solution

The pressure gradient $-\frac{dp}{dz} = P$ of blood flow in the arteries remote from liver can be supposed to be constant and hence the equation (8) becomes:

$\frac{d}{dr}\left(r\left(\frac{dv}{dr}\right)^n\right) = -\frac{P(z)r}{\eta_m}$ (9)

Integrating equation (9) we get

$r\left(\frac{dv}{dr}\right)^n = -\frac{P(z)r^2}{2\eta_m} + A(z)$ (10)

At r = 0, $v = v_0$(constant), we apply this condition on equation (10) A (z) = 0. Hence the equation (10) becomes:

$r\left(\frac{dv}{dr}\right)^n = -\frac{P(z)r^2}{2\eta_m} \Rightarrow -\frac{dv}{dr} = \left(\frac{P(z)r}{2\eta_m}\right)^{1/n}$(11)

Again integrating equation (11), we get

$v = -\left(\frac{P(z)}{2\eta_m}\right)^{1/n}\frac{r^{\frac{1}{n+1}}}{(n+1)/n} + B(z)$ (12)

Now for the value of B (z) we apply the no-slip condition on the stenosis surface given by

$$v = 0 \; at \; r = R(z), -z_0 \le z \le z_0$$

$v = 0 \;\; at \; r = R_0, \quad -z_0 \le z \le z_0,$ we obtain

$$B(z) = \left(\frac{P(z)}{2\eta_m}\right)^{1/n}\frac{nR(z)^{1/n+1}}{n+1}$$

Hence the equation (12) takes the following form:

$v = \left(\frac{P(z)}{2\eta_m}\right)^{\frac{1}{n}}\frac{n}{n+1}\left[R(z)^{\frac{1}{n+1}} - r^{\frac{1}{n+1}}\right]$ (13)

This is velocity of blood flow passing through stenosis.

Result and discussion (Bio- Interpretation)

The total flow- flux of blood through the transverse section of the arteries is [17].

$$Q = \int_0^{R(z)} v.2\pi r dr = \int_0^{R(z)} \left(\frac{P(z)}{2\eta_m}\right)^{1/n} . \frac{1}{n+1}\left(R(z)^{1/n+1} - r^{1/n+1}\right) 2\pi r dr$$

$$= \left(\frac{P(z)}{2\eta_m}\right)^{1/n} . \frac{2\pi n}{n+1}\left(\frac{R(z)^{1/n+1} r^2}{2} - \frac{n.r^{1/n+1}}{3n+1}\right)_0^{R(z)}$$

$$= \left(\frac{P(z)}{2\eta_m}\right)^{\frac{1}{n}} . \frac{2\pi n}{n+1} . \frac{(n+1)R(z)^{1/n+3}}{2(3n+1)}$$

$$Q = \left(\frac{P(z)}{2\eta_m}\right)^{\frac{1}{n}} . \frac{\pi n (R(z))^{\frac{1}{n}+3}}{(3n+1)} \quad , \quad where P(z) = -\frac{dp}{dz}$$

$$Q = \left[\frac{P_i - P_f}{2\eta_m(z_i - z_f}\right]^{\frac{1}{n}} . \frac{\pi n (R(z))^{\frac{1}{n}+3}}{(3n+1)} \qquad (14)$$

OBSERVATIONS:

Hemoglobin Vs Blood pressure is taken from Medical College Banda (U.P.)

Patient Name: A, **Age / Sex:** 64 Years / Male, Annual No. 224/2025

Clin: Dr. Karan Rajpoot

Table 1: Clinical blood pressure Vs hemoglobin

S.No.	Date	B.P. (In mm hg)	Hemoglobin (gm/dl)	Hematocrit (H)	B.P. (In Pascal)	Cli. BPD
1	16/01/2025	160/108	11.9	35.7	21331.2/14398.56	-3466.32
2	10/02/2025	155/102	10.6	31.8	20664.6/13598.64	-3532.98
3	15/03/2025	145/98	9.8	29.4	19331.4/13065.36	-3332.6
4	22/05/2025	147/94	9.2	27.6	19598.04/12532.08	-3532.98

Average Systolic Pressure = 20231.31 Pa

Average Diastolic Pressure = 13398.66 Pa

H= Average hematocrit = 31.125

Pi= Pressure in Artery = Average Systolic Pressure = 20231.31Pa

Pf= Pressure in Arterioles $=\frac{S+D}{2}$ = 16814.985 Pa

According to Glenn Elert (2010)

η_m = Viscosity of mixture = 0.035p.s

According to Gustafson, Daniel R. (1980)

η_p = Viscosity of plasma =0.0013 p.s [18]

Length of common hepatic artery = 0.0341 m

Length of common hepatic artery = 0.0025 m

Since $\eta_m = \eta_c X + \eta_p(1 - X)$

or, $\eta_m = \eta_c \frac{H}{100} + \eta_p \left(1 - \frac{H}{100}\right)$ where$X = \frac{H}{100} 0.035 = \eta_c \frac{31.125}{100} + 0.0013 \left(1 - \frac{31.125}{100}\right)$

$\eta_c = 0.109573092$ P.S =Viscosity of cells

Now putting the value of $\eta_c$in η_m , we have

$$\eta_m = 0.109573092 \frac{H}{100} + 0.0013 \left(1 - \frac{H}{100}\right)$$

$$\eta_m = 108.273092 \times 10^{-5} H + 0.0013$$

If the 50% stenosed, **δ**=50% 0f radius of hepatic artery =$0.0025 \times 0.5 = 0.00125$ m

$R(z) = R_0 - \delta = 0.0025 - 0.00125 = 0.00125$ m

Now from equation (14), Flow flux is given as

$$Q = \left[\frac{P_i - P_f}{2\eta_m (Z_i - Z_f)}\right]^{1/n} \cdot \frac{\pi n \, R(z)^{\frac{1}{n}+3}}{(3n+1)}$$

$$\text{where } Q = 1000 \text{ml/min} = 0.0167 \text{lit/sec} = 1.67 \times 10^{-5} \text{m}^3/\text{sec}$$

$$1.67 \times 10^{-5} = \left[\frac{20231.31 - 16814.985}{2 \times 0.035 \times 0.0341}\right]^{\frac{1}{n}} \cdot \frac{3.14 \times n \times (0.00125)^{\frac{1}{n}+3}}{(3n+1)}$$

$$2723.05733 = (1789.0265)^{\frac{1}{n}} \left(\frac{n}{3n+1}\right)$$

$$n log \frac{n}{3n+1} - 3.43505678 \, n + 3.25261677 = 0$$

Let, $f(n) = n log \frac{n}{3n+1} - 3.43505678 \, n + 3.25261677$

or, $f(x) = x log \frac{x}{3x+1} - 3.43505678 \; x + 3.25261677$ (15)

$df(x) = log \frac{x}{3x+1} + \frac{1}{3x+1} - 3.43505678$ (16)

Solve above equation by Newton- Raphson method

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

We get $n = 0.800495$

Now again from equation (4.1), we will find pressure drop

$$\triangle P = \left[\frac{(3n+1)Q}{\pi n R(z)^3}\right]^n \left[\frac{2\eta_m \Delta Z}{R(z)}\right]$$

Substituting values in above equation, we have

$$\Delta P = \left[\frac{(3 \times 0.800495 + 1)(1.67 \times 10^{-5})}{3.14(0.800495)(0.00125)^3}\right]^{0.800495} \cdot \left[\frac{2\eta_m (0.0341)}{0.00125}\right]$$

Or, $\Delta P = (97629.0592)\eta_m$

Or, $\Delta P = (97629.0592)(108.273092 \times 10^{-5} H + 0.0013)$

$\Delta P = 105.706 \, H + 126.917777$ (17)

Putting values of H in above equation (17) .We get the following table of blood pressure drop

Table 2 : Hematocrit Vs Blood pressure drop

Date	16/01/2025	10/02/2025	15/03/2025	22/05/2025
Hematocrit (H)	35.7	31.8	29.4	27.6
Blood pressure drop (ΔP)	3900.62	3488.37	3234.67	3044.40

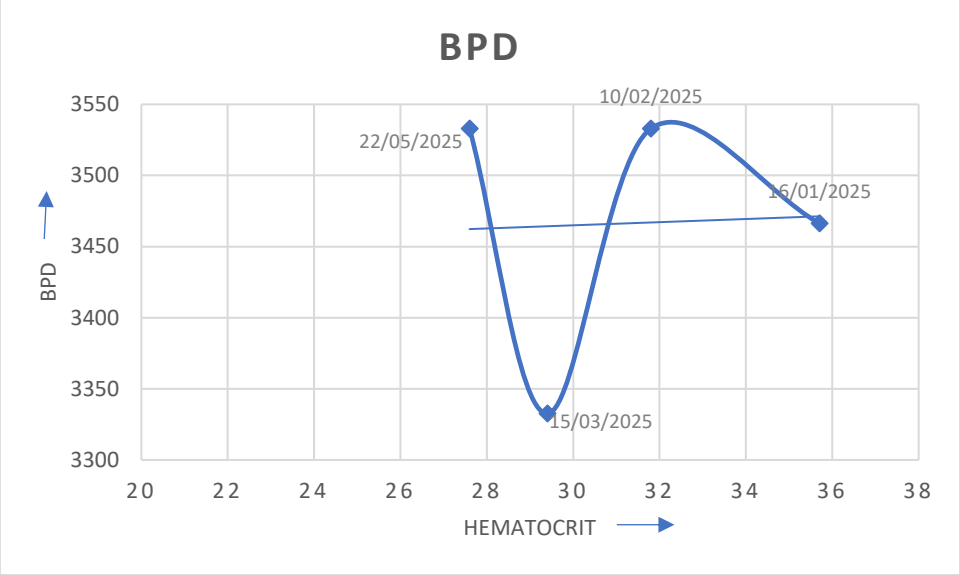

Figure 1: Graph of hematocrit vs Clinical blood pressure drop

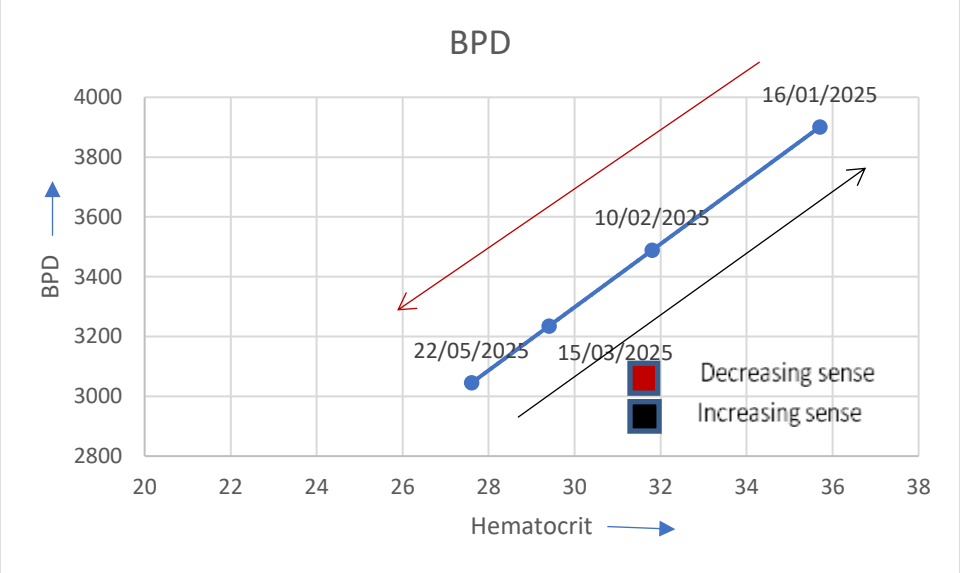

Figure 2: Graph of hematocrit vs Modulated blood pressure drop

Observation of graph

Figure 2 shows a graph of blood pressure drop and haematocrit for malaria patients with 50% hepatic artery stenosis. We observed a minimum blood pressure drop of 3044.40 on May 22, 2025, and a maximum blood pressure decrease of 3900.62 on January 16, 2025. At haematocrit values ranging from 35.7 to 27.6 via 31.8 and 29.4, blood pressure drops steadily from 16/01/2025 to 22/05/2025 to 10/02/2025 and 15/03/2025.

CONCLUSION:

If the slope of a straight line is absolute, then blood pressure drop is proportional to haematocrit; as haematocrit increases, blood pressure drop increases, and as haematocrit drops, blood pressure drop reduces. When we see a straight line trend in a declining direction, we might conclude that the medicine dose should be gradually increased.

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