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Two phase modelling for hepatic capillary blood flow in dengue disease by power law model

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Abstract
In this paper, blood flow in capillary analysis has been done by power law model, where one phase is core layer (cell phase) and another is plasma layer. Plasma, core layer have been taken Newtonian and non -Newtonian. Power index (n) calculated by newton Raphson python coding. Finally a linear relationship has been found between modulated blood pressure drop and hematocrit. Both MBPd AND Real clinical blood pressure drop have been compared using graphical approach. Almost both graph has given same trend with respect to hematocrit.

Keywords: Hematocrit, palsma, Newtonian power index, two phase, MBPD, RCBPD

Introduction

Shear Thinning: As the shear rate rises, blood viscosity falls. Red blood cells (RBCs) have a tendency to cluster (form rouleaux) at low shear rates (slow flow), which raises viscosity. These clumps disintegrate and RBC deformability rises with increasing flow, which results in decreased viscosity [1]. The flexible membrane and cytoskeleton of red blood cells are primarily responsible for the blood's elastic and viscous characteristics. Microcirculatory flow dynamics and oxygen transport are impacted as a result of the cells' ability to deform and regain their shape [2, 3]. RBC aggregation causes a detectable yield stress in blood in extremely tiny channels or at low flow. In contrast to Newtonian fluids, which flow at all stress levels, this is the lowest stress required to initiate blood circulation [4, 6]. When blood is sheared or flows, its viscosity can alter; it stays low until the blood is allowed to rest and the aggregates re-form.

Dependency on RBC and plasma composition: The rheological behaviour of blood in capillaries is dominated by RBC aggregation and deformability. Microvascular resistance and tissue perfusion are changed by conditions that impact these characteristics, such as illness, dehydration, or hereditary diseases. Despite small capillary widths, blood's non-Newtonian characteristics allow for efficient perfusion and oxygen transport in capillaries. In order to maintain proper tissue perfusion, shear thinning makes sure that blood may flow with less resistance as velocity increases. Reduced capillary flow and illness states such sickle cell disease or inflammation can be caused by impaired RBC deformability, increased aggregation, or enhanced viscosity.

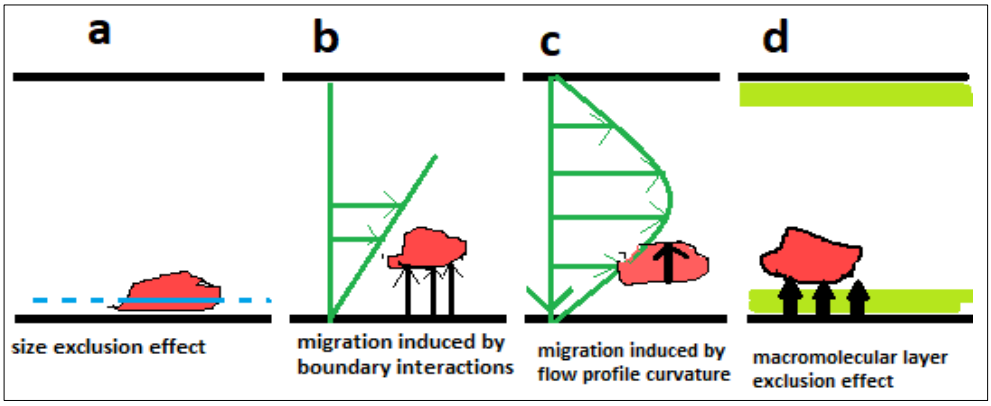
The physical and kinetic characteristics of RBCs and plasma components cause the non-Newtonian behaviour of blood in capillaries, namely shear thinning and viscoelasticity, which directly affects tissue oxygenation and microvascular flow resistance [5].

Clinical features suggesting dengue related hepatic involvement are the presence of liver enlargement and elevated transaminases [7]. Among the clinical features of hepatic involvement, patients have abdominal pain (18%-63%), nausea/ vomiting (49%-58%) and anorexia [8, 9]. Symptoms such as abdominal pain and anorexia have been found to be significantly more common in DF than DHF [10]. Hepatomegaly is present in both DF and DHF but more common in DF [10]. The frequency of hepatomegaly in the adult dengue patients ranges from 4%-52% [9-11]. Clinical jaundice has been detected in 1.7%-17% in various series [6, 9, 10] and hyperbilirubinemia has been found to be as high as 48% [9].

A complex network of branching tubes, the circulatory system spans a broad range of flow velocities and geometrical sizes. Thus, a broad variety of fluid mechanical events are included in the mechanics of blood flow in the circulation. Inertial effects play a significant role in big blood arteries with dimensions between millimetres and centimetres. These vessels may also exhibit secondary flows, boundary layers, flow separation, instability, and occasionally

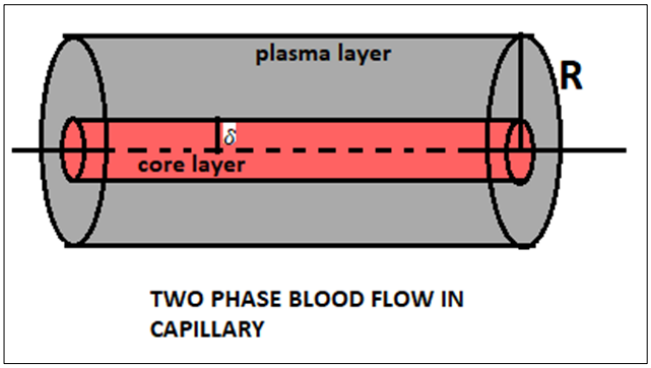
turbulence. Nonetheless, a simplifying characteristic of blood is that it functions essentially as a homogenous Newtonian fluid in vast blood arteries. In the microcirculation, things are the opposite. Inertial effects are insignificant since blood flow Reynolds numbers (Re) are usually significantly less than 1. For instance, based on a density of roughly 1 g/cm3 and a viscosity of roughly 0.03 dyn s/cm2, Re is around 1.7 × 10−3 in a capillary with a diameter of 5 µm and a flow velocity of 1 mm/s. In an arteriole with a diameter of 100 µm and a flow rate of 2 cm/s, Re is around 0.7 in the upper range of microvessel sizes. Consequently, the Stokes equations for an incompressible fluid provide a decent estimate of the fluid flow [23].

One significant simplifying characteristic of these equations is their linearity. However, due to the large number of suspended cells—primarily highly deformable red blood cells, or erythrocytes-whose sizes are not much lower than the blood channel diameters, blood flowing in microvessels cannot be regarded as a homogenous fluid. Noncontinuum effects become quite important and need to be taken into account. Examining the mobility of a concentrated suspension of highly deformable particles in a geometrically intricate branching network of extremely tiny tubes is a major focus of the research of fluid mechanics of the microcirculation.



The primary cause of the unique flow characteristics of blood in microvessels is the development of a cell-free or cell-depleted layer close to the vessel walls. This behaviour is influenced by a number of physical events (Figure 3). For instance, the radial distribution of cell centres is constrained by the RBC's limited size (Figure a). The centre of mass of an RBC in a disk-like form cannot physically approach within 1 µm of the wall since the minimum dimension is at least 2 µm. RBCs have a propensity to move away from a solid barrier when positioned in a shear flow next to it (Figure b). The Poiseuille velocity profile's curvature in tube flow creates a propensity for migration towards the flow's centerline regardless of wall influences (Figure c). An extra effect that does not exist in glass tubes occurs in microvessels in vivo. An exclusion zone for RBC movement is produced by the glycocalyx, also known as the ESL, which is made up of a matrix of macromolecules (Figure d). The numerous particle-particle interactions in a concentrated suspension's shear flow cause a net migration towards the walls along the concentration gradient (Figure e). The processes that push migration away from the wall are counteracted by this impact [23].

Here it is clear that flowing of blood is in two phase according to above discussion and figure is given below Since plasma layer has no cells inside so here we assume that it is Newtonian and another core layer is non-Newtonian



Real Model

When blood flows via a larger artery, Newtonian blood behaviour is reasonable to anticipate. It is not acceptable if the blood vessel is small (radius less than 1 mm). From the standpoint of biofluid mechanics, blood would not be expected to obey Newton's incredibly simple, one parameter, linearised law of viscosity. The non-Newtonian characteristics of blood can only be accurately represented by higher order constitutive equations, such as the power-law paradigm (Enderle *et al.*).

Parametrization

The blood's velocity$v^k = v^k(X^i, t) k = 1, 2, 3$ and any two thermodynamic quantities related to it, such as pressure, $P = P(X^i, t)$ and density, $\rho = \rho(X^i, t)$, were distributed according to functions that affected the mathematical description of the state of a moving blood. All thermodynamic quantities, together with the equation of state, are determined by the values of any two of them, as is often known. Thus, we may fully ascertain the condition of flowing blood if we have five variables: the density ρ, the pressure P, and the three components of velocity v^k.

The coordinates $X^i, i = 1, 2, 3$, and the time t are functions of all these values. It stressed that the blood's velocity at a given position X^i in space and at a given time t was represented by the expression $v^k(X^i, t)$.
Let one unit volume of whole blood and
$X =$ volume fraction of plasma
$Y = 1 - X =$ volume fraction of RBC
the mass ratio of RBC to plasma is m

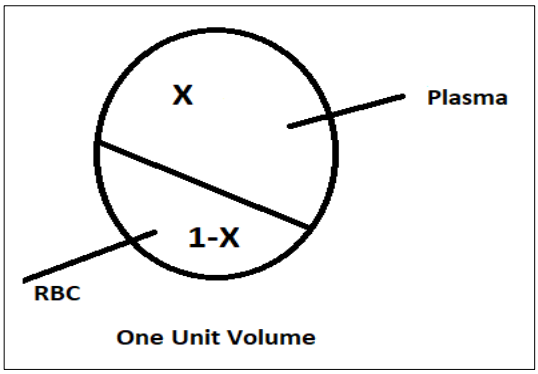
$$m = \frac{Y\rho_C}{X\rho_P}$$

where ρ_C, ρ_P, ρ_W are the densities of RBC, plasma, WBC.
we define density of blood mixture ρ_m as follows

$$\frac{1+m}{\rho_m} = \frac{m}{\rho_c} + \frac{1}{\rho_P}$$

And viscosity of blood mixture η_m as follows

$$\eta_m = Y\eta_c + X\eta_P$$



Boundary conditions.
1. The velocity of blood flow on the axis of blood vessels at r = 0 will be maximum and finite, say $v_0 =$ maximum velocity.
2. The velocity of blood flow on the wall of blood vessels at $r = R$, where, R is the radius of blood vessels, will be zero. This condition is well known as no slip condition.

Equation of Continuity
continuity equation for three phases

$$\frac{\partial((1-X)\rho_c)}{\partial t} + ((1-X)\rho_c v^i)_{,i} = 0 \quad [1]$$

$$\frac{\partial(X\rho_P)}{\partial t} + (X\rho_P v^i)_{,i} = 0 \quad [2]$$

Where, v^i is the common velocity of two phase blood cells and plasma. Again $(X\rho_c v^i)_{,i}$ is co-variant derivative of $(X\rho_c v^i)$ with respect to X^i.
Equation of motion for blood flow with the three phases using the principle of force conservation (or momentum conservation) in hepatic arteries and assuming that the consistency coefficient (or viscosity coefficient) of RBC cells is η_c.

$$(1-X)\rho_c \frac{\partial v^i}{\partial t} + \left((1-X)\rho_c v^i\right) v^i_{,j} - (1-X)P_{,j}g^{ij} + (1-X)\eta_c\left(g^{jk}v^i{}_{,k}\right)_{,j}$$

Similarly, taking the viscosity coefficient of plasma to be the equation of motion for plasma will be as follows-

$$X\rho_P \frac{\partial v^i}{\partial t} + (X\rho_P v^i)v^i_{,j} - XP_{,j}g^{ij} + X\eta_P\left(g^{jk}v^i{}_{,k}\right)_{,j}$$

then equation of motion for blood flow with the all Two phases will be as follows-

$$\rho_m \frac{\partial v^i}{\partial t} + (\rho_m v^j)v^i{}_{,j} = -P_{,j}g^{ij} + \eta_m\left(g^{jk}v^i{}_{,k}\right)_{,j} \quad [3]$$

Whenever percentage of blood is reduces the blood has been supposed Newtonian but in case of increasing the hematocrit, the

effective viscosity of blood flowing through arteries remote from the heart depends on the strain rate.
For this reason, the blood will flow as non Newtonian fluid. When strain rate is in between 5 to 200 per second, the power law

$$\tau' = \eta_m e^n$$

where $0.68 \leq n \leq 0.80$ Describes the flow of blood very well. The constitutive equation of blood is as follow
Blood's constitutive equation is as follows:

$$\tau^{ij} = -pg^{ij} + \eta_m (e^{ij})^n = -pg^{ij} + \tau'^{ij} \quad [4]$$

Where τ^{ij} is stress tensor and τ'^{ij} is shearing stress tensor.

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

$$\frac{1}{\sqrt{g}}(\sqrt{g}v^i)_{,i} = 0 \quad [5]$$

Again the equation in tensorial form is as follows:

$$\rho_m \frac{\partial v^i}{\partial t} + \rho_m v^j v^i{}_{,j} = \tau^{ij}{}_{,j} \quad [6]$$

Since the blood vessels are cylindrical, the above governing equation have to transformed 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

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

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

$$\begin{Bmatrix} 1 \\ 2 \quad 2 \end{Bmatrix} = -r, \begin{Bmatrix} 2 \\ 2 \quad 1 \end{Bmatrix} = \begin{Bmatrix} 2 \\ 1 \quad 2 \end{Bmatrix} = \frac{1}{r}$$

except 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

$$\tau'^{ij} = \eta_m (e^{ij})^n = \eta_m (g^{ik} v^i_{,k} + g^{jk} v^j_{,k})^n \quad [7]$$

Will be as follows:

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

The covariant derivative of $\tau^{,ij}$ is

$$\tau^{,ij}_{,j} = \frac{1}{\sqrt{g}}\frac{\partial}{\partial x^j}\left(\sqrt{g}\tau^{,ij}\right) + \left\{ {i \atop j\ k} \right\}\tau^{,kj} \quad [8]$$

Keeping in view the above facts the governing tensorial equation can be transformed into cylindrical form which are as follows

The Equation of continuity

$$\frac{\partial v}{\partial z} = 0$$

The Equation of motion

r-Component

$$-\frac{\partial p}{\partial r} = 0$$

θ-Component

$$0 = 0$$

Z-Component

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

These are the r, θ, z components respectively
Further the fact has been considered that axial flow in artery is symmetric, so that $v_\theta = 0\ and\ v_r, v_z\ and\ p$ do not depend upon θ. 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, we get $v_z = v(r)$ because v does not depend upon θ
The integration of equation of motion, we get $p = p(z)$ since p does not depend upon θ
Now, with the help of equation, the equation of motion converts in the following form:

$$0 = -\frac{dp}{dz} + \frac{\eta_m}{r}\frac{d}{dr}\left(r\left(\frac{dv}{dr}\right)^n\right) \quad [9]$$

The pressure gradient $-\left({}^{dp}/_{dz}\right) = P$ of blood flow in the arteries remote from liver can be supposed to be constant and hence the equation takes the following form:

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

On integrating equation (9), we get

$$r\left(\frac{dv}{dr}\right)^n = -\frac{Pr^2}{2\eta_m} + A \quad [10]$$

We know that the velocity of blood flow on the axis of the cylindrical arteries is maximum and constant. So that the apply the boundary condition at r=0, v = V_0(contant), on equation (10) to get the arbitrary constant A = 0. Hence the equation (11) takes the following form:

$$r\left(\frac{dv}{dr}\right)^n = -\frac{Pr^2}{2\eta_m}$$

$$-\frac{dv}{dr} = \left(\frac{Pr}{2\eta_m}\right)^{1/n} \quad [11]$$

Integrating equation (11) once again, we get

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

To determine the arbitrary constant B, we apply the no –slip condition n the inner wall of the arteries: at $r = R, V = 0$, where $R =$ radius of vessel, on equation (12) so as to get

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

Hence the equation takes the following form:

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

Which determines the velocity of blood flow in the arteries remote from the liver where P is gradient of blood pressure and η_m is the viscosity of blood mixture.
Shear stress

$$\tau = \left(\frac{Q(1+3n)}{\pi n}\right)^n \frac{r\eta_m}{R^{3n+1}}$$

Strain rate $\frac{dv}{dr} = \left(\frac{\Delta P r}{2\Delta z\, \eta_m}\right)^{1/n}$

Analysis for hepatic capillary where one layer is Newtonian and other is non-Newtonian
The basic equation can be written as before
This is the velocity for non- Newtonian power law model

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

Let $n = 1$ (Newtonianflow)

$$v_p = \frac{P}{4\eta_m}\left[R^2 - r^2\right]; R - \delta \le r \le R \quad [14]$$

Where δ is the radius of core layer.

$$v_c = \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - (R-\delta)^{\frac{1}{n}+1}\right] \quad [15]$$

.
Relative velocity of plasma layer with respect to core layer is $v_p - v_c$.

The velocity of core layer is obtained as the formula of power law model as follows

$$v_m = \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right] + \left[\frac{P}{4\eta_p}\left[R^2 - (R-\delta)^2\right] - \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - (R-\delta)^{\frac{1}{n}+1}\right]\right] \quad [16]$$

$0 \le r \le R - \delta$

The total flow- flux of blood through the transverse section of the arteries is

$$Q = \int_0^{R-\delta}\left[\left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}}\left(\frac{n}{n+1}\right)\left(R^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right) + \left\{\frac{P}{4\eta_p}(R^2 - (R-\delta)^2) - \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}}\left(\frac{n}{n+1}\right)\left(R^{\frac{1}{n}+1} - (R-\delta)^{\frac{1}{n}+1}\right)\right\}\right] 2\pi r dr + \int_{R-\delta}^{R} \frac{P}{4\eta_p}(R^2 - r^2) 2\pi r dr$$

$$Q = \frac{\pi n}{1+3n}\left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} (R-\delta)^{\frac{1}{n}+3} + \frac{\pi P}{8\eta_p}\left[R^4 - (R-\delta)^4\right] \quad [17]$$

Observations
According to Glenn Elert (2010)
η_m = viscosity of mixture = 0.0045 pascal sec
According to Gustafson, Daniel R. (1980)
η_p = Viscosity of plasma =0.0015 pascal sec

Table 1: Data of Dengue Patient

S.N	DATE	B.P (mmHg)	HB	HCT
1	09/12/2024	110.4/72.4	13.77	41.31
2	10/12/2024	111.3/72.8	13.99	41.97
3	13/12/2024	112.6/72.2	14.15	42.45
4	14/12/2024	115.4/77.0	13.98	41.94
5	15/12/2024	113.1/74.6	14.01	42.03

Average Systolic Pressure =112.56 mm Hg
Average Diastolic Pressure = 73.8 mm Hg
Pressure drop =2473.79 pascal
Average hematocrit =41.934

Length of hepatic capillary =275 micrometer [24]

Radius of capillary = R=6 micrometer [24]

$$R - \delta = \frac{2}{3}R = 4\ micrometer$$

$$\eta_m = Y\eta_c + X\eta_P$$

$$\eta_c = 0.008654099\ pascal\ sec$$

$$\eta_m = 0.0000715H + 0.0015$$

FLOW FLUX $Q = 660\frac{ml}{min} = 0.000011\ cubic\frac{meter}{sec}$

By equation

[17]

$$0.000011 = (3998.04)^{\frac{1}{n}}\ \frac{n}{(3n+1)}(200.96 \times 10^{-18})$$

find value of n by newton Raphson method using python coding

```
fx = (3.6018475/x) + log(x/(3*x + 1)) - 10.73725306

fx_prime = (1/x) - (3/(1+ 3*x)) - (3.6018475/x**2)

delta = fx/fx_prime

x_new = x - delta

return x_new, delta

def get_optimized_value(x_init, n_iteration, eps):

for i in range(n_iteration):

try:

x_new, delta = get_newton_raphson(x_init)

print(x_new)

temp = x_new

If abs(delta)<=eps:
n_iteration = i+1

break

x_init = x_new
```

Except:

```
x_new = x_init

n_interation = i

abs_per_error = abs((x_new-x_init)/x_new)

return x_new, n_iteration, abs_per_error

if __name__=="__main__":

x_init = 1

n_interation = 2000

eps = 0.00000000001

x, n, abs_per_error = get_optimized_value(x_init=x_init, n_iteration=n_interation, eps=eps)

print(f"x: {x}, n: {n}, abs_per_error: {abs_per_error}")
```

0.2309713775586229
0.29704416158965563
0.3196993159967061
0.32094151063369564
0.320912900602739
0.32091367276624067
0.3209136519962187
0.3209136525549516
0.32091365253992116
0.32091365254032544

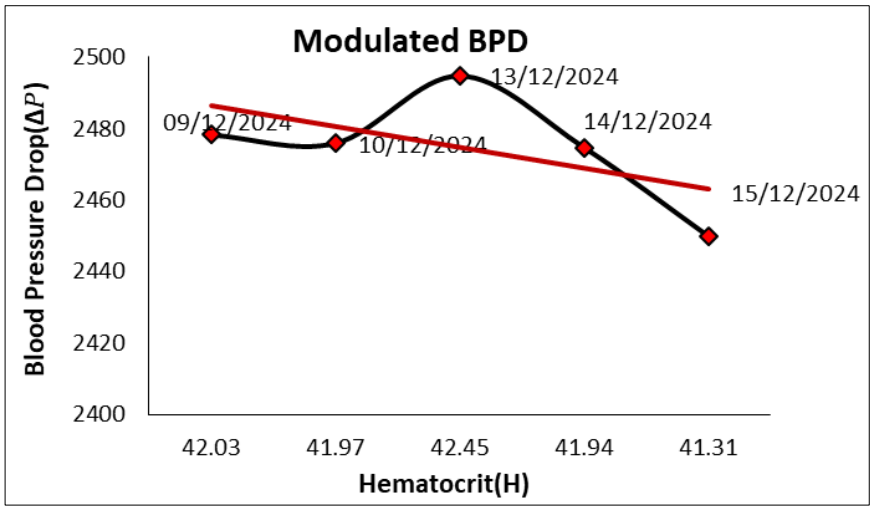
Initial Guess taken: 0.15

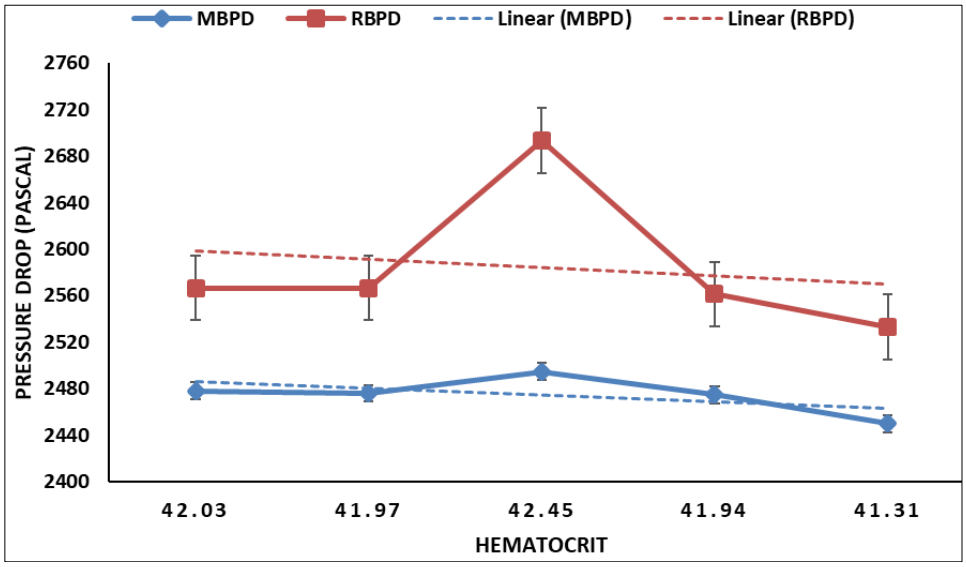
Final result
x: 0.32091365254032544, n: 10, abs_per_error: 1.2598021655262818e-10
Finally here we put the all respective value in equation [17]
We got the relation between blood pressure drop and hematocrit

$$\Delta P = 39.33H + 825.20$$

Table 2: MBPD AND RCBPD V/S hematocrit (H)

S. No.	Date	Hematocrit (H)	MBPD (ΔP_{modu}) in Pascal	RCBPD (ΔP_{clin}) in Pascal	WSS in pascal
1	09/12/2024	42.03	2478.23	2566.60	18.02
2	10/12/2024	41.97	2475.88	2566.60	18.00
3	13/12/2024	42.45	2494.75	2693.26	18.14
4	14/12/2024	41.94	2474.70	2561.26	17.99
5	15/12/2024	41.31	2449.92	2533.27	17.81





Conclusion

Blood pressure drop decrease and hematocrit were shown to be linearly related $\Delta P = 39.33H + 825.20$ and $\Delta P_{min} = 2449.92$ pascal, $\Delta P_{max} = 2494.75$. The trend line displays a low-steep downhill trend. Thus, we can up the medication dosage in this case to help the dengue patient recover quickly. We shall gradually reduce the medicine dosage if the trend line shows an upward tendency day by day. In this article, the doctor is advised to administer the medication dosage to the dengue patient during the case.

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