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A Newtonian Model on the Two Phase Renal Blood Flow in Renal Capillaries with Special Reference to Kidney Infection (UTI)

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Abstract: *In the present paper we have formulated the renal blood flow along the capillaries in case of renal disease kidney infection (UTI) keeping in the view the nature of renal circulatory system in human body. Earlier researchers like Dr. V. Upadhyay and Dr. P.N.Pandey had assumed the blood flow has two phased, one of which is that of red blood cells and other is plasma. According to Fahreaus- Lindqvist affect the blood flow in two separated layers while passing through capillaries. The plasma layer which flows along the surface of the capillaries contains almost no blood cells. The second layer the core layer containing blood cells which float in plasma along the axis of capillary. We have collected a clinical data in case of kidney infection (UTI) for hematocrit v/s blood pressure. The graphical presentation for particular parametric value is much closer to the clinical observation. The overall presentation is in tensorial form and solution technique adapted is analytical as well as numerical. The role of hematocrit is explicit in the determination of blood pressure drop in case of renal disease kidney infection (UTI).*

Keywords- *Newtonian, Renal Blood Flow, UTI, Hematocrit*

I. Introduction

(Description Of Bio-Physical Problem)

The Kidneys are the primary organs for maintaining fluid, electrolyte and acid-base balance [1]. The kidney is the ultimate regulatory of blood pressure and therefore invariably implicated in its pathogenesis (Guyton et. Al. 1972) [2]. Each kidneys is about 11-12 cm. long and weighs about 150 gram. [3]. each person is normally born with two kidneys, which are located in the back of the body, on each side of the spine and positions under the rib cage [4]

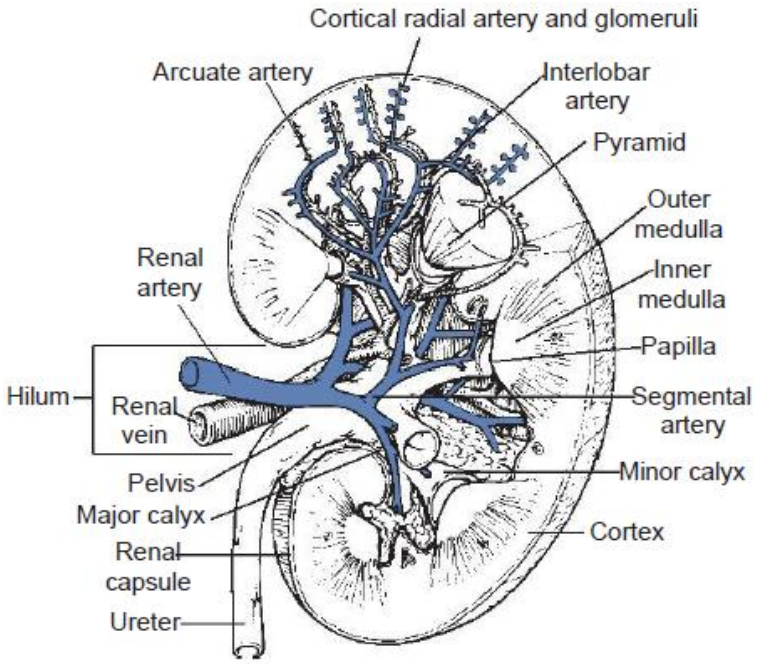


Fig 1: the human kidney, sectioned vertically. (Modified from Smith HW. Principles of Renal Physiology. New York: Oxford University Press, 1956.)

The kidney is a multifunctional organ, not only getting rid of metabolic waste, but also regulating the internal milieu (electrolytes and water balance), secreting hormones and eliminating toxins .[5] Filtration which takes place at the renal corpuscle, is the process by which cells and large proteins are filtered from the blood to make an ultra filtrate the eventually becomes urine. The kidney generates 180 liters of filtrate a day while reabsorbing a large percentage, allowing for the generation of only approximately 2 liters of urine. Secretion is the reverse process, in which molecules are transported in the opposite direction, from the blood into the urine [6]. Some other functions are- Excretion of waste, Acid balance, Sensing, Hormon Secretion. [6]

Duplex kidneys or double kidneys occur in approximately 1% of the population. This occurrence normally causes no complications, but can occasionally cause urine infections. [7][8] The kidneys receive blood from the renal arteries, left and right. Which branch directly from the abdominal aorta. Despite their small size, the kidneys receive approximately 20 % of the cardiac output. [9]

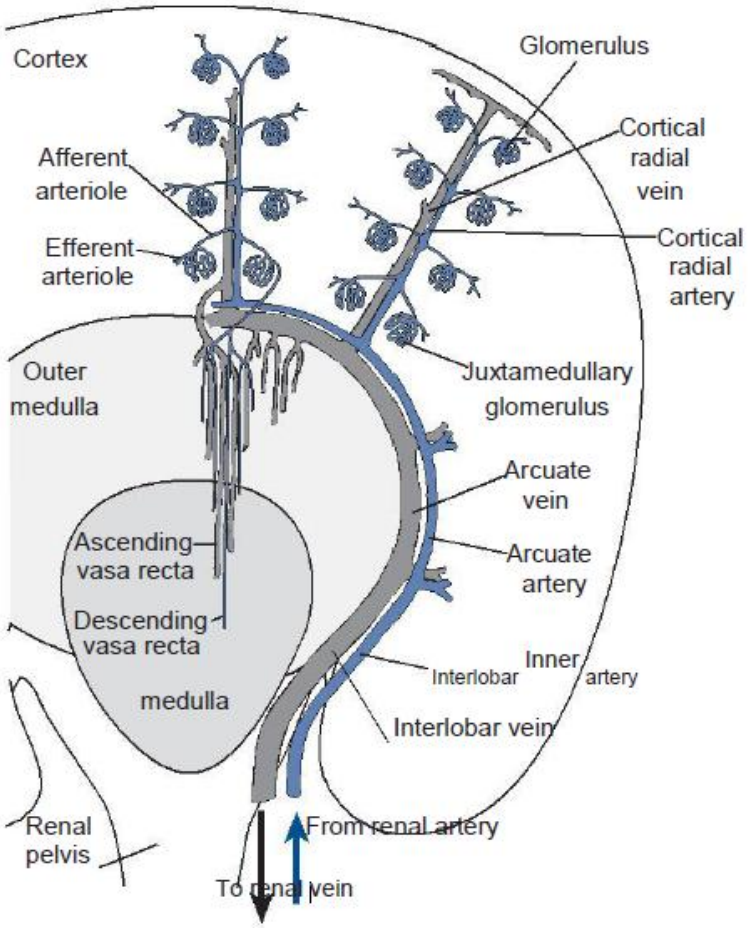


Fig 2: the blood vessels in the kidney. Peritubular capillaries are not shown. (Modified from Kriz W, Bankir L. A standard nomenclature for structures of the kidney. Am J Physiol 1988; 254:F1–F8.)

Renal circulation is unique in that it has two capillary beds, the glomerular and pertibular capillaries which are arranged in series and separated by the efferent arterioles that helps regulate the hydrostatic pressures in both sets of capillaries. High hydrostatic pressure in the glomerular capillaries (about 60 mm Hg) causes rapid fluid filtration, whereas a much lower hydrostic pressure in the pertibular capillary (about 13 mm Hg) permits rapid fluid reabsorption.

In summary:

Renal Artery-> Segmental Artery->Interlobar Artery->Arcuate Artery->Interlobar artery->Afferent Arterioles-> Glomerular Capillary -> Efferent Arterioles -> Vasarecta -> Pertibular Capillaries -> Small Veins -> Renal Veins [10] In a resting adult, the Kidneys receive 1.2 to 1.3 l. of blood per minute, or just under 25% of cardiac output .[11] Renal blood flow is determined by the pressure gradient across the renal vasculature divided by the total renal vascular resistance :

$$\text{Renal blood flow} = \frac{(\text{Renal artery pressure} - \text{Renal vein pressure})}{\text{Total renal vascular resistance}} \quad [12]$$

Blood is a complex fluid consisting of particulate corpuscles suspended in a non-Newtonian fluid. The particulate solids are red blood cells (RBCs), white blood cells (WBCs) and platelets. The fluid is plasma, which itself is a complex mixture of proteins and other intergradient in an aqueous base. By volume, the red blood cells constitute about 45% of the whole blood, the plasma about 54.3%and white cells about 0.7%. [13]

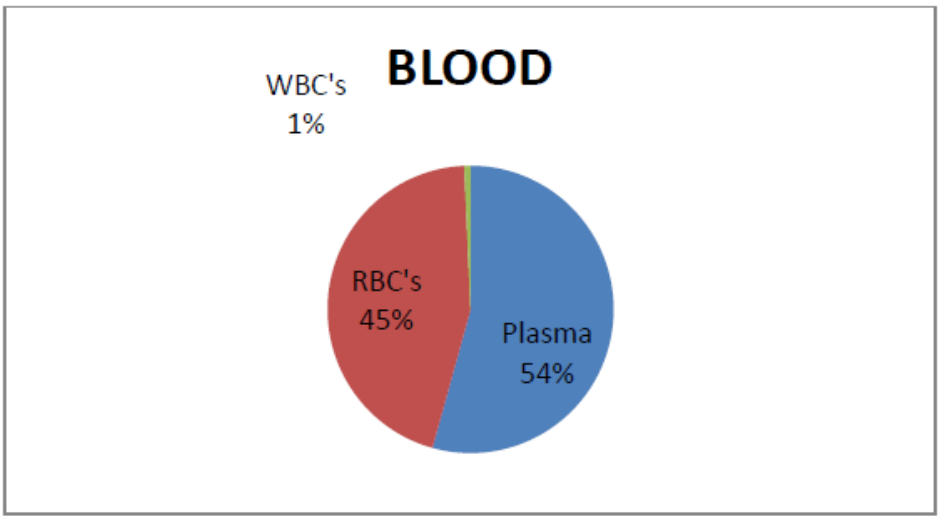


Fig 3

50% of the plasma and 45% of the blood cells in a whole blood and approximately 98% of RBCs in 45% of blood cells and there are a few parts (approximately 2%) of the other cells. Which are ignorable, so one phase of the blood is plasma and 2nd phase of the blood is RBCs. Two phase renal blood flow is a study of measuring the blood pressure if hemoglobin known. The percentage of volume covered by blood cells in the whole blood is called hematocrit.[13]

The glomerulus is a tuft of small blood vessels called capillaries located within Bowman's capsule within the kidney[14] Blood enters the capillaries of the glomerulus by a single arteriole called an afferent arteriole and leaves by an efferent arteriole[14] The human glomerulus is the primary filtration unit of the kidney, and contains the Glomerular Filtration Barrier (GFB). The GFB had been thought to comprise 3 layers – the endothelium, the basement membrane and the podocyte foot processes. [15] Filtration of fluid and solutes in the kidney occurs through The renal glomerulus, a structure in the renal cortex consisting of a knot of micro vessels sitting between afferent And efferent arterioles [15] The total length of the capillaries in a single glomerulus is 0.95cm, making a total of 19 km for all 2-million glomeruli. The total surface area of all glomerular capillaries is 6,000 cm2. The total filtration surface area is 516.1 cm2. [16] Each human kidney contains approximately one million nephrons. The glomerulus is the most proximal component of the nephron [17] the main function of the glomerulus is to filtrate plasma to produce glomerular filtrate, which will go down the length of the nephron tubule to form urine. The rate at which the glomerulus produces filtrate from plasma (the glomerular filtration rate) is much higher than in systemic capillaries because of the particular anatomical characteristics of the glomerulus. Unlike systemic capillaries, which receive blood from high-resistance arterioles and drain to low-resistance venules, glomerular capillaries are connected in both ends to high-resistance arterioles: the afferent arteriole, and the efferent arteriole. This arrangement of two arterioles in series determines the high hydrostatic pressure on glomerular capillaries, which is one of the forces that favour filtration to the Bowman's capsule [18]

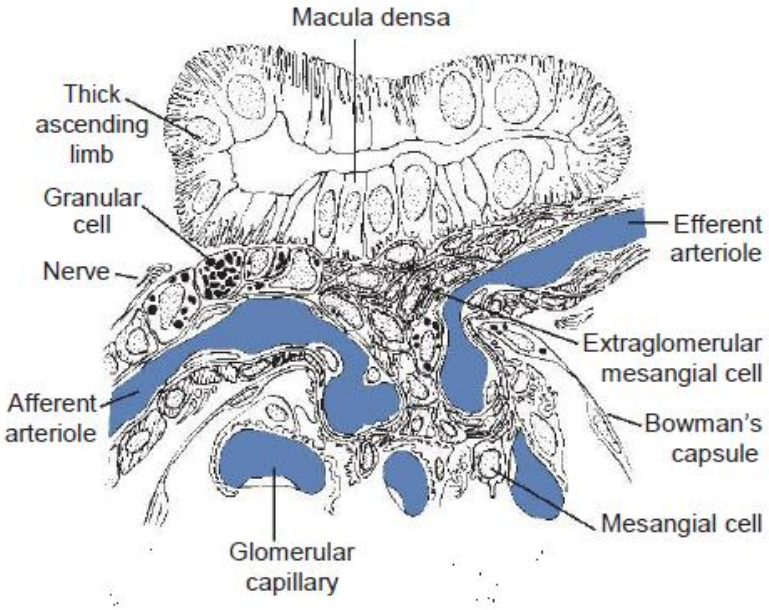


Fig 4: Histological appearances of the juxtaglomerular apparatus. A cross section through a thick ascending limb is on top, and part of a glomerulus is below. The juxtaglomerular apparatus consists of the macula densa, extraglomerular mesangial cells, and granular cells. (Modified from Taugner R, Hackenthal E. The Juxtaglomerular Apparatus: Structure and Function. Berlin: Springer, 1989.)

This work is important for human health. There are several researches, who examined the blood flow in the artery and veins. This work will focus on two phase renal blood flow in capillaries with special reference to kidney infection (UTI). A lot of work is available, but P.N.Pandey and V. Upadhyay (2001) [19] discussed a some phenomena in two phase blood flow gave an idea on the two phase renal blood flow in arterioles with a renal disease kidney infection (UTI). The work of P.N. Pandey and V.Upadhyay in whole circulatory system but this work will focus on renal circulatory system, and renal circulatory system is a sub system of whole circulatory system. In this work, applied the Power law Newtonian model.

We present an improvement on the previous work in the field and this is discussed separately below. The ultimate use of this model is to predict normal reference levels of two phase blood flow in capillaries for individual patients undergoing kidney infection (UTI) disease. According to Dan Med Bull kidney infection belongs to the family of infection of the Urinary system called Urinary tract infection (UTI's) (2011) [20]. A UTI is a serious health problem that affects millions of people each year. UTIs are the second most common type of infection in the body. Dan Med Bull studied on bacterial characteristics of importance for recurrent Urinary tract infection caused by Escherichia Coli (2011). [20]

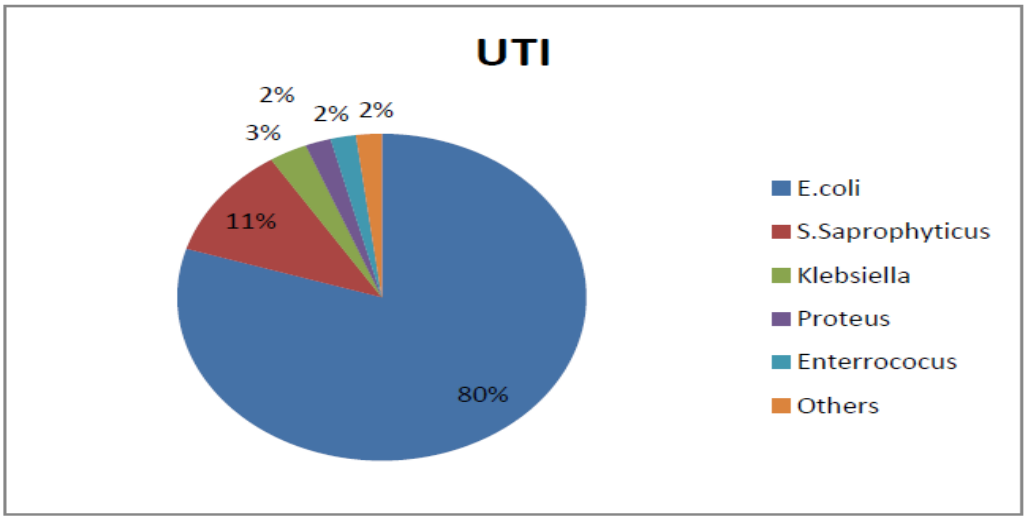


Fig 5: Diagram showing contribution of various microbes for causing the UTI: E.coli 79%, S.Saprophyticus 11%, Klebsiella 3%, Mixed 3%, Proteus 2%, Enterococcus 2%, other 2%. [21]

UTI is one of the most common infectious diseases in humans, with a prevalence strongly influenced by gender and age.[22]Kidney infection belong to the family of infections of the urinary system called urinary tract infections (UTIs).[23]UTIs have been well-studied in Sweden and other parts of Europe.[24] These studies have shown that one in 5 adult women experience a UTI at some point, confirming that it is an exceedingly common worldwide problem[24]. In 2007, approximately 3.9% of office visits in USA were related to symptoms involving the genitourinary tract. [25] 61% of all UTIs are managed in the primary care setting. [26] UTI may affect 10% of people during childhood [27]

II. Basic Bio-Fluid Equation For Two Phase Blood Flow

Let us the problem of blood flow in renal circulatory system is different from the problems in cylindrical tube and select generalized three dimensional orthogonal curvilinear coordinate system. Briefly described as E^3 called as Euclidean space. According to mishra the biophysical laws thus expressed fully hold good in any co-ordinate system which is a compulsion for the truthfulness of the laws (1990). [28]

According to Sherman I.W. and Sherman V.G. Blood is mixed fluid [29]. Mainly there are two phases in blood. The first phase is plasma, while the other phase is that of blood cells are enclosed with semi-permeable membranes whose density is greater than that of plasma. These blood cells are uniformly distributed in plasma. Thus, blood can be considered as a homogeneous mixture of two phases (1989). [29]

(2.1) Equation of Continuity for two phase blood flow-

According to Singh P. and Upadhyay K.S. The flow of blood is affected by the presence of blood cells. This effect is directly proportional to the volume occupied by blood cells [30]. Let the volume portion covered by blood cells in unit volume be X , this X is replaced by H/100, where H is the Hematocrit the volume percentage of blood cells .Then the volume portion covered by the plasma will be 1-X . If the mass ratio of blood cells to plasma is r then clearly

$$r = \frac{X\rho_c}{(1-X)\rho_p} \tag{2.1}$$

where ρ_c and ρ_p are densities of blood cells and blood plasma respectively .Usually this mass ratio is not a constant , even then this may be supposed to constant in present context (1986) [30]

The both phase of blood, I. e. blood cells and plasma move with the common velocity .Campbell and Pitcher has presented a model for two phase of blood separately (1958) [32]. Hence equation of continuity for two phases according to the principle of conservation of mass defined by J.N and Gupta R.C. [31] as follow

$$\frac{\partial(X\rho_c)}{\partial t} + (X\rho_c v^i)_{,i} = 0 \tag{2.2}$$

And

$$\frac{\partial(1-X)\rho_p}{\partial z} + ((1-X)\rho_p v^i)_{,i} = 0 \tag{2.3}$$

Where, v is the common velocity of two phase blood cells and plasma.

If we define the uniform density of the blood ρ_m as follow

$$\frac{1+r}{\rho_m} = \frac{r}{\rho_c} + \frac{1}{\rho_p} \quad [31] \tag{2.4}$$

Then equation (2.2) and (2.3) can be combined together as follow,

$$\frac{\partial\rho_m}{\partial t} + (\rho_m v^i)_{,i} = 0 \tag{2.5}$$

(2.2) Equation of Motion for two phase blood flow-

According to Ruch, T.C. and H.D. The hydro dynamical pressure p between the two phases of blood can be supposed to be uniform because the both phases i.e. blood cells and plasma are always in equilibrium state in blood (1973) [33]. Taking viscosity coefficient of blood cells to be η_c and applying the principle of conservation of momentum, we get the equation of motion for the phase of blood cells as follows:

$$X\rho_c \frac{\partial v^i}{\partial t} + (X\rho_c v^j)v^i_{,j} = -Xp_{,j}g^{ij} + X\eta_c(g^{jk}v^i_{,k})_{,j} \tag{2.6}$$

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

$$(1-X)\rho_p \frac{\partial v^i}{\partial t} + \{(1-X)\rho_p v^i\} v^i_{,j} = -(1-X)p_{,j} g^{ij} + (1-X)\eta_c \left(g^{jk} v^i_{,k}\right)_{,j} \quad (2.7)$$

Now adding equation (2.6) and (2.7) and using relation (2.4), the equation of motion for blood flow with the both phases will be as follows:

$$\rho_m \frac{\partial v^i}{\partial t} + \left(\rho_m v^j\right) v^i_{,j} = -p_{,j} + \eta_m \left(g^{jk} v^i_{,k}\right)_{,j} \quad (2.8)$$

Where $\eta_m = X\eta_c + (1-X)\eta_p$ is the viscosity coefficient of blood as a mixture of two phases.

III. Mathematical Modeling

Description of the problem-

How the blood flow in capillaries is possible as we know that these vessels are far enough from the heart as well as thin. It's a natural question because the blood flows very slowly in arterioles where there is high viscosity. The satisfactory answer of this problem is given by Fahreaus-Lindqvist effect. According to this effect the blood flows in two separated layers while passing through capillaries. The plasma layer containing almost no blood cells. The second layer is that of blood cells. The second layer is that of blood cells which float in plasma on the axis of the capillary. In this process the effective blood viscosity depends upon radius of the capillary. That's why the effective viscosity decreases, as the radius and thus the blood flow becomes possible.

Mathematical Modeling-

We consider the two layer blood flow to be Newtonian. The first layer is that of plasma while second one is core layer. Let the viscosity of plasma layer be η_p and that of core layer η_m where $\eta_m = X\eta_c + (1-X)\eta_p$ where η_c is viscosity of blood cells and X is portion of blood cells in unit volume .

Now the basic equations can be written in a similar way as before.

Now we describe the basic equations for Power law blood flow as follows:

Equation of Continuity in tensorial form as follows:

$$\frac{1}{\sqrt{g}}\left(\sqrt{g}v^i\right)_{,i} = 0 \quad \text{……………………………………………………………………. (3.1)}$$

Equation of motion:

$$\rho_m \frac{\partial v^i}{\partial t} + \rho_m v^j v^i_{,j} = -\rho_{,j} g^{ij} + \eta_m \left(g^{jk} v^i_{,k}\right)_{,j} \quad \text{……………………………………. (3.2)}$$

Where,

η_p = Viscosity of Plasma layer

η_m = Viscosity of core layer

η_c = Viscosity of blood cells

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

X = portion of blood cells in unit volume

X = H/100

ρ_m = density of mixture blood

ρ_p = density of plasma

ρ_c = density of blood cells

$\rho_m = X\rho_c + (1-X)\rho_p$

We have transformed in cylindrical form eq. (3.1) & (3.2)

The blood flow in capillary is symmetric w. r. t. axis.

Hence,

$v_\theta = 0, v_z , v_r$ and p do not depend upon θ.

Since only one Component of velocity which is along axis is effective.

We have,

$v_r = 0, v_\theta = 0, v_z = V$

Since, flow is steady,

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

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

$$v_z = V(r)$$

r-component

$$\rho_m(0) = -\frac{\partial p}{\partial r} + \eta_m(0)$$

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

P = p (z)

θ - Component

$$\rho_m(0) = 0 + \eta_m(0)$$

0 = 0

Z-component

$$\rho_m v_z \frac{\partial v_z}{\partial t} = -\frac{\partial p}{\partial z} + \eta_m \left[\frac{1}{r} \frac{\partial}{\partial r} \left\{ r \frac{\partial v_z}{\partial r} \right\} + \frac{\partial^2 v_z}{\partial z^2} \right]$$

$$\rho_m V_r \frac{\partial V(r)}{\partial t} = -\frac{\partial p}{\partial z} + \eta_m \left[\frac{1}{r} \frac{\partial}{\partial r} \left\{ r \frac{\partial V(r)}{\partial r} \right\} + \frac{\partial^2 V(r)}{\partial Z^2} \right]$$

And pressure p depends on Z.

i.e. $p = -\frac{\partial p}{\partial z}$

By using first & second boundary condition, we get

$$V = \frac{P}{4\eta_m}\left(R^2 - r^2\right)$$

The velocity of plasma layer is obtained by replacing η_m by η_p in formula …… of Newtonian model, which is as follows:

$$v_p = \frac{P}{4\eta_p}\left(R^2 - r^2\right); \quad R - \delta \le r \le R$$

The velocity of core layer can also be obtained in a similar way as follows:

$$v_m = \frac{P}{4\eta_m}\left(R^2 - r^2\right) + \frac{P}{4\eta_m}\left[R^2 - \left(R - \delta\right)^2\right]\left(\frac{\eta_m}{\eta_p} - 1\right); \; 0 \le r \le R - \delta$$

Where R is the radius of the capillary and δ is the thickness of the plasma layer. δ Is supposed to be independent of R.[34] It is remarkable that velocity of plasma layer is taken as if whole capillary is filled with plasma. Again the velocity of core layer is taken as if the core layer blood is filled in whole capillary. The relative velocity of the both layers is also added to it.

IV. Real Model

Blood is a Complex fluid consisting of Particulate curpusclees suspended in a non-Newtonian fluid. The particulate solids are red blood cells (RBCs), white blood cells (WBCs) and platelets. 50% of the plasma and 45% of the blood cells in a whole blood and approximately 98% of RBCs in 45% of blood cells and there are a few parts (approximately 2%) of the other cells. Which are ignorable, so one phase of the blood s plasma and 2nd phase of blood is RBCs.

Boundary Conditions are as follows:

1. The velocity of blood flow on the axis of capillaries at r=0 will be maximum and finite , say V_0

   Maximum velocity = V_0
2. The velocity of blood flow on the wall of blood vessels at r=R, Where, R is the radius of capillary, will be zero.

This condition is well known as no-slip condition.
The Newtonian power law Equation-

$\tau = \eta e$

Where, η is the Viscosity coefficient. [35]
This is found to hold good in the broad blood vessels where there is low hematocrit.

Pressure difference is a difference of pressure of two end points of the vessels. Let us consider in any blood vessels of renal circulatory system. Let p_i represents the pressure at the origin of the vessels, at the other end point pressure is p_f . Then the pressure difference is represented by $p_i - p_f$ blood pressure of first end point is greater than the blood pressure of other end point, that is

$$p_i > p_f$$

$$\Delta p = -\left(p_f - p_i\right)$$

V. Result (Bio-Physical Interpretation)

Patient Name – Mr. S.C. Chaudhary
Diagnosis – UTI/PFR

Date	HB	Blood Pressure	Hematocrit	Blood Pressure
2/06/2012	9.6	150/90	28.8	19998.3/11998.98
4/06/2012	9.9	130/50	29.7	17331.86/6666.1
5/06/2012	9.4	100/60	28.2	13332.2/7999.32
6/06/2012	9.3	110/80	27.9	14665.42/10665.76
7/06/2012	9.5	110/70	28.5	14665.42/9332.54

According to Berkow, Robert The hematocrit (expressed as percentage points) is normally about three times the hemoglobin concentration (reported as grams per deciliter). [36]
The Flow flux of blood in Capillary is:

$$Q = \int_0^{R-\delta} V_m 2\pi r\, dr + \int_{R-\delta}^{R} V_p 2\pi r\, dr$$

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

If the whole capillary is supposed to be filled with only one Newtonian blood whose affectivity viscosity is η .
Then flow flux of Blood is

$$Q = \frac{\pi P R^4}{8\eta} \quad \text{..... (5.1)}$$

And effective viscosity is

$$\eta = \eta_p\left[1-\left(1-\frac{\delta}{R}\right)^4\left(1-\frac{\eta_p}{\eta_m}\right)\right]^{-1}$$

This depends upon the radius R of the capillary. $\frac{\delta}{R} \square\ 1$ Can be expended in higher power of $\frac{\delta}{R}$ and it is observed that the effectively decreases with the decrease of radius of capillary R. Thus Fahreaus – Lindiqvist effect is explained mathematically.
From eq. (5.1)

$$Q = \frac{\pi R^4}{8\eta} P$$

Where,

$P = -\frac{dp}{dz}$ (Pressure Gradient)

$$Q = \frac{\pi R^4}{8\eta}\left(-\frac{dp}{dz}\right)$$

$$-dp = \frac{8\eta}{\pi R^4} Q\, dz$$

Integrating both side

$$-\int_{p_i}^{p_f} dp \;=\; \int_{z_i}^{z_f} \frac{8\eta}{\pi R^4} Q\, dz$$

$$\left(p_i - p_f\right) = \frac{8\eta}{\pi R^4} Q\left(z_f - z_i\right)$$

Where,

$(z_f - z_i)$ = Length of Capillary

Average (H) = 28.62

Average (BP) = 15998.64/9332.54

Bp in Capillary = 7332.71 $\left(p_i\right)$

$\left(p_f\right)$ BP in venules = 4888.47

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

$$\eta_m = \eta_c\left(\frac{H}{100}\right) + (1 - \frac{H}{100})(0.0012)$$

$$\eta_c = 0.0105 pa.s$$

$$\eta_c = 0.011 pa.s$$

$$\eta = \frac{\eta_p}{\left[1 - \left(1 - \frac{\delta}{R}\right)^4 \left(1 - \frac{\eta_p}{\eta_m}\right)\right]}$$

$$\eta_m = 0.0012 + 0.000098H$$

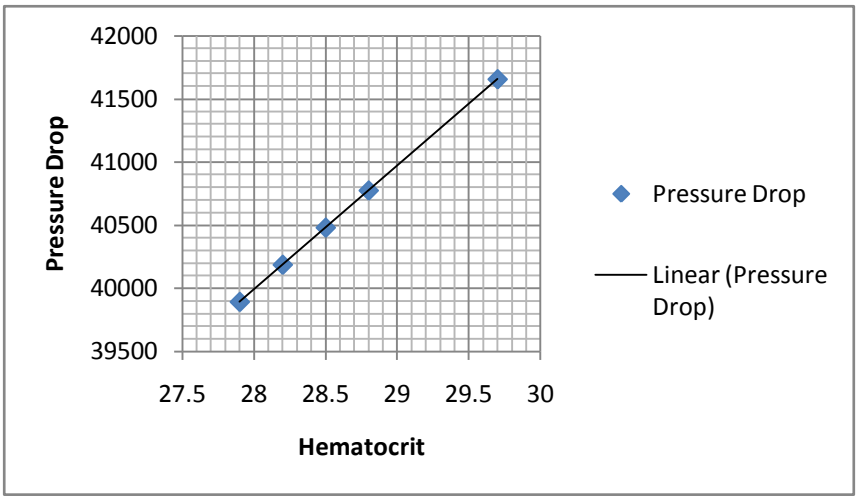
$$\eta = \left[\frac{1.44\times10^{-6} + 1.176\times10^{-7} H}{0.0012 + 3.92\times10^{-7} H}\right]$$

$$(p_i - p_f) = \frac{8\times0.01833\times19000}{3.14\times(0.0965)^4}\eta$$

$$(p_i - p_f) = 10232325.83\left[\frac{1.44\times10^{-6} + 1.176\times10^{-7} H}{0.0012 + 3.92\times10^{-7} H}\right]$$ [37-42]

We get,

H	Pressure Drop
28.8	40774.89
29.7	41656.84
28.2	40186.5
27.9	39892.3
28.5	40480.7



Graph 1

VI. Conclusion

A simple survey of the graph (1) between blood pressure drop and hematocrit in Urinary Tract Infection patient shows that when hematocrit increased then Blood pressure also increased. That is Hematocrit proportional to blood pressure drop in renal capillaries.

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Remark

If this would have been possible to get blood Pressure on the particular tissue (Kidney) then the relation between blood pressure and hemoglobin has been measured more accurately.

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