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A Non-Newtonian mathematical Model on the two phase renal mean blood flow in renal arterioles with special reference to Kidney Infection (UTI)

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ABSTRACT - In this paper, we have presented a model of two phased blood flow in renal arterioles remote from the heart and proximate to the Kidney keeping in view the nature of renal blood circulation in human body. If blood flows arterioles to capillaries then blood pressure drop arises in human body the viscosity increases in the arterioles due to formation of roulex along axis by red blood cells, as we know the arterioles are remote from heart and proximate to the kidney. P.N. Pandey and V. Upadhyay have considered the blood flow has two phased , one of which is that of red blood cells and other is Plasma .They have also applied the Herschel Bulkley non –Newtonian Model in bio-fluid mechanical set-up . We have applied the Campbell-Pitcher two phase model in biofluid mechanical setup which is realistic in so for as the blood flow is considered to be two phased homogenous mixture of blood cells and plasma .We have collected a clinical data in case of Kidney Infection (UTI) for Hematocrit v/s Blood Pressure drop. 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 in case of renal disease – Kidney Infection (UTI).The graphical presentation for particular parametric value is much closer to the clinical observation.

***Key words:-*UTI- Urinary Tract infection, E. Coli- Escherichia Coli, rouleaux-structure formed by RBC in tough situation, non Newtonian-fluid, renal, pressure drop.**

I. INTRODUCTION (DISCRIPTION OF BIO-PHYSICAL PROBLEM)

The kidney is multifunctional organ , not only getting rid of metabolic waste, but also regulating the internal milieu (electrolytes and water balance), secreting hormones and eliminating toxins [1][2]. The kidneys are bean-shaped structures and weigh about 150 g in the male and about 135 g in the female. They are typically 10-12 cm in length, 5-7 cm in width, and 2-3 cm in thickness. [3] According to Brubacker (1922), the kidney is surrounded by a thin smooth membrane composed of white fibrous and yellow elastic tissue. Acc. To Walter (2004) each adult kidney weighs between 125 and 170 grams in males and between 115 and 155 grams in females [4]. There are two, one on each side of the spine. In humans the kidneys are located in the abdominal cavity [5]. Acc. To glodny B Unterholzner V, Tafemer B (2009), the left kidney is typically slightly larger than the right.

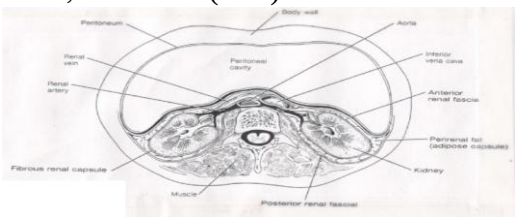

Fig 1 : Cross-Sectional View of Kidneys in Body ; A. P. Spence and E. B. Mason 'Human Anatomy and Physiology', The Benjamin/Cummings Publishing Company, Inc.: Menlo Park, CA 1979, p.708. [48]

It is only when you examine kidneys under the microscope that you find that their structure is not simple at all. The cortex and medulla are seen to be composed of masses of tiny tubes. These are called kidney tubules or nephrons.

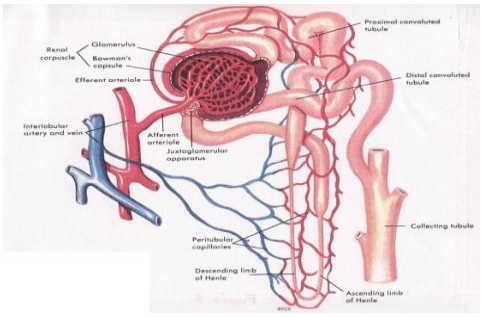

Fig 2 : Diagram of Vasculature Going Into and Out of Glamorous C.P. Anthony and G.A. Thibodeau "Textbook of Anatomy and Physiology", Tenth Ed., The C. V. Mosby Company: St. Louis: 1979, p. 541. 15[47]

In humans, a normal kidney contains 800,000 to 1.5 million nephrons. [39] At one end of each nephron in the cortex of the kidney, is a cup shaped structure called the (Bowman's or renal) capsule. It surrounds a tuft of capillaries called the glamorous that carries high pressure blood [7].

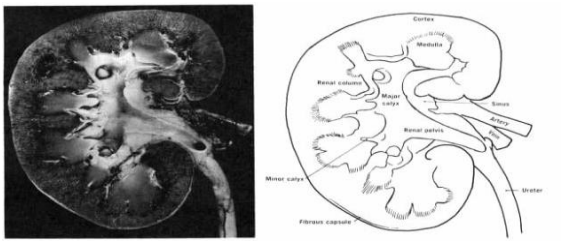

Fig 3. Coronal section of a kidney. (From Yokochi, C, Photographic Anatomy of the Human Body, Igaku Shoin, Ltd., Tokyo, 1971.) [38]

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The kidneys serve important functions, including filtration and excretion of metabolic waste products (urea and ammonium); regulation of necessary electrolytes, fluid, and acid-base balance; and stimulation of red blood cell production. They also serve to regulate blood pressure via the renin-angiotensin-aldosterone system, controlling reabsorption of water and maintaining intravascular volume. The kidneys also reabsorb glucose and amino acids and have hormonal functions via erythropoietin, calcitriol, and vitamin D activation. [40]

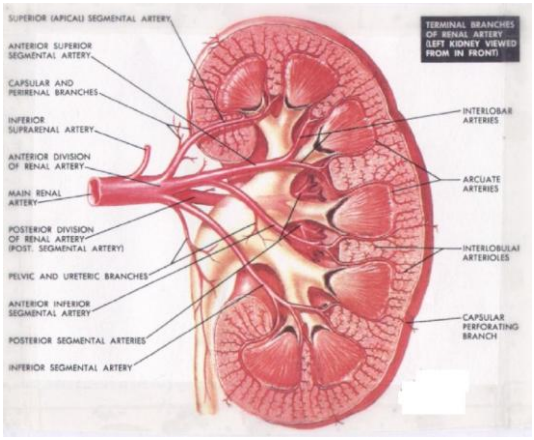

Fig 4 : F H Netter , "The Ciba collection of Medical Illustrations" , Volume 6 , "Kidney , Ureters , and Urinary Bladder " CIBA pharmaceutical Company : Summit , NJ , 1973 , P, 16, [49]

Blood is a specialized bodily fluid in human that delivers necessary substances such as nutrients and oxygen to the cells and transports metabolic waste products away from those cells. It is composed of blood cells suspended in a liquid called blood plasma. Plasma which constitutes 55% of blood fluid is mostly water (92% by volume) [11]. And contains dissipated proteins, glucose, minerals ions, hormones, carbon dioxide (plasma being the main medium for excretory products transportation) and blood cells themselves. Blood accounts for 7% of the human body weight [12][13]. By volume, the red blood cells constitute about 45% of whole blood, the plasma about 54.3% and white cells about 0.7%. [14] Whole blood (plasma and cells) exhibits non- Newtonian fluid dynamics. Red blood cells contain the blood's hemoglobin and distribute oxygen [15]. White blood cells are part of the body's immune system. They destroy and remove old or aberrant cells and cellular debris as well as attack infectious agents. [16] Thrombocytes also called platelets; thrombocytes are responsible for blood clotting [16] about 55% of blood is blood plasma, a fluid that is the blood's liquid medium, which by itself is straw- yellow in color.

An **arteriole** is a small diameter blood vessel in the microcirculation that extends and branches out from an artery and leads to capillaries. [41]

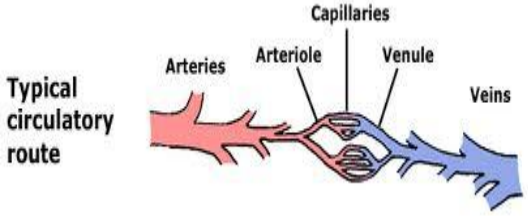

Fig 5

ARTERIOLES are very small arteries that deliver blood to capillaries. As arterioles branch off an artery, they have smooth muscle and a few elastic fibers in the tunica media. These gradually taper away as the arteriole becomes smaller, leaving mostly the endothelium and a few smooth muscle fibers by the time the arteriole connects to the capillaries Arterioles play a key role in regulating blood flow into capillaries. Vasoconstriction of arterioles decreases blood flow into capillaries; vasodilatation increases flow. A change in the diameter of a large number of arterioles at once will also affect blood pressure. 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 arterioles with special reference to kidney infection (UTI). The mean arterial pressure (MAP) is a term used in medicine to describe an average blood pressure in an individual. [42] At normal resting heart rates MAP can be approximated using the more easily measured systolic and diastolic pressures, SP and DP:[43]

$$MAP \simeq DP + \frac{1}{3}(SP - DP)$$

or equivalently

$$MAP \simeq \frac{2}{3}(DP) + \frac{1}{3}(SP)$$

or equivalently

$$MAP \simeq \frac{(2 \times DP) + SP}{3}$$

At high heart rates MAP is more closely approximated by the arithmetic mean of systolic and diastolic pressures because of the change in shape of the arterial pressure pulse. A lot of work is available, but P. N. Pandey and V. Upadhyay (2001) 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 Herschel Bulkley non-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 arterioles for individual patients undergoing kidney infection (UTI) disease. A

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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, UTI are more common in women than men.[17] According to Dan Med Bull kidney infection belongs to the family of infection of the Urinary system called Urinary tract infection (UTI's) (2011). A urinary tract infection is a bacterial infection that affects part of the Urinary tract. When it affects the lower urinary it is known as simple cystitis (a bladder infection) and when it affects the upper urinary tract it is known as pyelonephritis (a kidney infection). Lower urinary tract infection is also referred to as a bladder infection. UTI symptoms are frequently lacking in the elderly. [18] UTI has been described since ancient times with the first documented description in the Ebers Papyrus dated to C. 1550 BC. [19] It was described by the Egyption as "sending forth heat from the bladder" [20] UTI may affect 10% of the people during childhood [21]. Among children UTI are the most common in uncircumcised males less than three months of the age followed by females less than one year [22]. UTI are the most frequent bacterial infection in women [23]. UTI occurs four times more frequently in females than males [21]. They occur most frequently between the ages of 16 and 35 years, with 10% of women getting an infection yearly and 60% having an infection at some point in their lives [24][21]. E. coli is the cause of 80-85% of urinary tract infections, with staphylococcus saprophytic us being the cause in 5-10% [24]. Urinary tract infections have been described since ancient times with the first documented description in the Ebers Papyrus dated to c. 1550 BC.[44] It was described by the Egyptians as "sending forth heat from the bladder".[45]

II. REAL MODEL

We have to select a frame of reference for mathematical modeling of the state of a moving blood· keeping in view the difficulty and generality of the problem of blood flow, we select generalized three-dimensional orthogonal curvilinear co-ordinate system, briefly prescribed as E^3 , called as 3-dim Euclidean space, We interpret the quantities related to blood flow in tensorial form which is comparatively more realistic, The biophysical laws thus expressed fully hold good in any co-ordinate system , which is compulsion for the truthfulness of the law (1990) [25] Now , let the co-ordinate axes be OX^i where O is origin and superscript i= 1,2,3 let X^i be the co-ordinates of any point P in space, The mathematical description of the state if a moving blood is affected by means of functions which give the distribution of the blood velocity $v^k = v^k(X^i , t)$, k= 1,2,3 and of any two thermodynamic quantities pertaining to the blood, for instance the pressure $p = p (X^i , t)$ and the density $\rho = \rho (X^i , t)$, As is well known, all the thermodynamic quantities are determined by the values of any two of them, together with the equate of state, Hence, if we are given five quantities, namely the three components of velocity v^k, the pressure p and the density ρ , the state of moving blood is completely determined· All these quantities are , in general , functions of the co-ordinates X^i , i=1,2,3 and of the time t, We emphasize that $V^k (X^i , t)$ is the velocity of the blood at a given point X^i in space and at a given t, ie it refers to fixed points in space and not to fixed particles of the blood; in the course of time , the latter move about in space , The same remarks apply to p and ρ Blood is a mixed fluid, Mainly there are two-phases in blood, The first phase is plasma, while the other phase is plasma, while the other phase is that of blood cells· The blood cells are enclosed with a semi-permeable membrane 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·[26]

A. *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 [27]. 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) [28] 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). Hence equation of continuity for two phases according to the principle of conservation of mass defined by J.N and Gupta R.C. 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.

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If we define the uniform density of the blood ρ_m as follow $\frac{1+r}{\rho_m}=\frac{r}{\rho_c}+\frac{1}{\rho_p}$ [29]

(2.4)

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

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

(2.5)

B. 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) [30]. 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:

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

(2.6)

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

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

(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:

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

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

As the velocity of Blood flow decreases, the viscosity of blood increases. The velocity of blood decreases successively. The Herschel Bulkley law holds good on the two phase blood flow through veins arterioles, veinules and whose constitutive equation is as follows:

$T'=\eta_m e^n+T_p\,(T'\geq T_p)$ and $e=0\,(T'<T_p)$ where, T_p is the yield stress.

When strain rate $e=0(T'<T_p)$ a core region is formed which flows just like a plug. Let the radius of the plug be r_p. The stress acting on the surface of plug will be T_p. Equating the forces acting on the plug, we get,

$$P\pi r_p^2=T_p 2\pi r_p$$

$$\Rightarrow r_p=2\frac{T_p}{P}$$

(3.1)

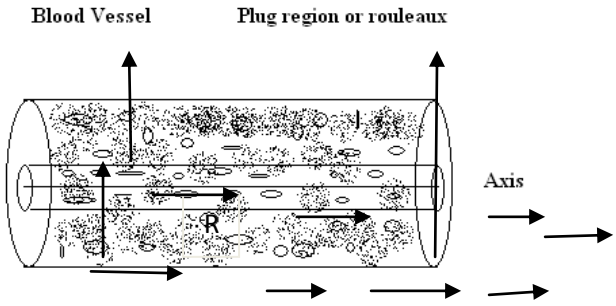

Fig 6: Herschel Bulkley blood flow

The Constitutive equation for test part of the blood vessel is

$T'=\eta_m e^n+T_p$ or $T'-T_p=\eta_m e^n=T_e$ Where, T_e = effective stress, whose generalized form will be as follows

$T^{ij}=-Pg^{ij}+T_e^{ij}$ Where, (2.8) $T_e^{ij}=\eta_m\left(e^{ij}\right)^n$ While $e^{ij}=g^{jk}V^i_k$

Where, the symbols have their usual meanings.

Now we describe the basic equations for Herschel Bulkley blood flow as follows:

A. Equation of Continuity

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

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B. Equation of Motion

$$\rho_m \frac{\partial v^i}{\partial t} + \rho_m V^j V^i_{,j} = -T^{ij}_{e,j}$$

(3.2)

Where all the symbols have their usual meanings, since, the blood vessels are cylindrical; the above governing equations have to be transformed into cylindrical co-ordinates. As we know earlier: $X^1 = r, X^2 = \theta, X^3 = Z$ Matrix of metric tensor in cylindrical co-ordinates is $\left[g_{ij}\right]$ and matrix of conjugate metric tensor is $\left[g^{ij}\right]$ whereas the chritoffel's symbols of 2nd kind are as follows:

$$\begin{Bmatrix} 1 \\ 2\ 2 \end{Bmatrix} = -r, \begin{Bmatrix} 1 \\ 2\ 2 \end{Bmatrix} = \begin{Bmatrix} 1 \\ 2\ 2 \end{Bmatrix} = \frac{1}{r}$$ Remaining others are zero.

The governing tensorial equations can be transformed into cylindrical forms which are follows: the equation of Continuity-: $\frac{\partial v}{\partial z} = 0$

The equation of Motion-

R-component: $-\frac{\partial p}{\partial z} = 0, \theta - \text{component} : 0 = 0$

Z-component: $0 = -\frac{\partial p}{\partial z} + \frac{\eta_m}{r}\left[r\left(\frac{\partial v_z}{\partial r}\right)^n\right]$

Here, this fact has been taken in view that the blood flow is axially symmetric in arteries concerned, i.e. $v_\theta = 0$ and v_r and v_z and p do not depend upon θ.

We get $v_z = v(r)$ and $dp = p(z)$ and

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

(3.3)

Since, pressure gradient $-\frac{dp}{dz} = P$

$r\left(\frac{dv}{dz}\right)^n = -\frac{pr^2}{2\eta_m} + A$, we apply boundary condition: at r=0. $V = V_0$ then $\Rightarrow -\frac{dv}{dr} = \left(\frac{pr}{2\eta_m}\right)^{\frac{1}{n}}$ Replace r from $r - r_p$

$$-\frac{dv}{dr} = \left(\frac{\frac{1}{2}pr - \frac{1}{2}pr_p}{\eta_m}\right)^{\frac{1}{n}}$$

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

(3.4)

Integrating above equation (12) under the no slip boundary condition: v=0 at r = R so as to get:

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

(3.5)

This is the formula for velocity of blood flow in arterioles, veinules and veins.

Putting $r = r_p$ to get the velocity V_p of plug flow as follows:

$$V_p = \frac{n}{n+1}\left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}}(R - r_p)^{\frac{1}{n}+1}$$

(3.6)

Where the value of r_p is taken from (2.7)

IV. ANALYSIS (SOLUTION)

Observations: Hematocrit Vs Blood pressure from an authorized Jabalpur Hospital & Research Centre by Dr. Anil Jain

Patient Name: - Mr. Narendra Dwivedi **Diagnosis: -** UTI/Sepsis

Date	HB(Hemoglobin)	B.P.(in mmhg)	Hematocrit = $3\times HB$	BP (pascal)
1/06/12	11·2	130/80	33·6	17331·6/10665·6
2/06/12	11·9	120/80	35·7	15998·4/10665·6
4/06/12	12·4	120/90	37·2	15998·4/11998·8
5/06/12	13·0	110/80	39·0	14665·2/10665·6
6/06/12	13·5	120/80	40·5	15998·4/10665·6
7/06/12	12·2	120/60	36·6	15998·4/7999·2

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According to Berkow, Robert The hematocrit (expressed as percentage points) is normally about three times the hemoglobin concentration (reported as grams per deciliter). [31]. The flow flux of two phased blood flow in arterioles, veinules and veins is

$$Q = \int_0^{r_p} 2\pi r V_p dr + \int_{r_p}^{R} 2\pi r V dr$$

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

Using (12) and (14)

$$= \frac{\pi n}{(n+1)}\left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} R^{\frac{1}{n}+3} \left[\frac{r_p^2}{R^2}\left(1-\frac{r_p^2}{R}\right)^{\frac{1}{n}+1} + \left(1+\frac{r_p}{R}\right)\left(1-\frac{r_p}{R}\right)^{\frac{1}{n}+2} - \frac{2\left(1-\frac{r_p}{R}\right)^{\frac{1}{n}+2}}{\left(\frac{1}{n}+2\right)} + \frac{2\left(1-\frac{r_p}{R}\right)^{\frac{1}{n}+3}}{\left(\frac{1}{n}+2\right)\left(\frac{1}{n}+3\right)}\right]$$

(4.1)

Q=900 ml. /min R =1, $r_p = \frac{1}{3}$ [32] According to Gustafson, Daniel R. (1980)

η_p = 0.0015 (Pascal-sec.) [33] According to Glenn Elert (2010)

η_m = 0.035 (Pascal-sec.) H = 37·1

Length of renal arterioles = 454+_ 30 micrometer [46]

i.e, 424 – 484 micrometer

$Z_f - Z_i$ = 0.000454 meter

By using relation $\eta_m = \eta_c X + \eta_p (1-X)$ where, $X = \frac{H}{100}$ We get,

η_c = 0.091796 and again using same above relation we get, η_m = 0.00090296H+0.0015

Substituting the values of, r_p and R in equation (4.1), we get

$$Q = \pi\left(\frac{2P}{6\eta_m}\right)^{\frac{1}{n}}\left(\frac{2}{27}\right)\left[\frac{26n^3+33n^2+9n}{6n^3+11n^2+6n+1}\right]$$

$$\frac{Q\times 27}{2\pi} = \left(\frac{P}{3\eta_m}\right)^{\frac{1}{n}}\left[\frac{26n^3+33n^2+9n}{6n^3+11n^2+6n+1}\right]$$

(4.2)

$$\text{Let } A = \frac{26n^3+33n^2+9n}{6n^3+11n^2+6n+1}$$

$$\frac{P}{3\eta_m} = \left(\frac{27Q}{2\pi A}\right)^n \quad \Rightarrow P = \left(\frac{27Q}{2\pi A}\right)^n \times 3\eta_m$$

$$P = -\frac{dp}{dz}$$

-dp = Pdz

$$\int_{p_f}^{p_i} dp = -\int_{Z_i}^{Z_f} \left(\frac{27Q}{2\pi A}\right)^n \times 3\eta_m \, dZ$$

Where,

Pressure drop = $p_f - p_i$

Length of renal arterioles= $Z_f - Z_i$

$$\Rightarrow P_i - P_f = \left(\frac{27Q}{2\pi A}\right)^n \times 3\eta_m (Z_f - Z_i)$$

Substituting the values of Q, pi, pf , η_m in equation (4.2), and solve by Numerical method we get, **n = -4.526** again from equation (4.2)

$$\Rightarrow 3\eta_m = \left(\frac{2\pi A}{27Q}\right)^n \frac{(p_i - p_f)}{(Z_f - Z_i)}$$ and substitute the value of η_m , η_c ,X and n we get

$p_i - p_f$ = 426.8921 H+ 709.1544

V. RESULT & DISCUSSION (BIO-PHYSICAL INTERPRETATION)

We get, values of Blood Pressure drop if hematocrit known by using above equation (relation between Blood Pressure and hematocrit)

H (Hema tocrit)	33·6	35·7	37·2	39·0	40·5	36·6
P (Blood Pressure drop)	1505 2.73	1594 9.20	165 89.54	1735 7.94	179 98.29	163 33.41

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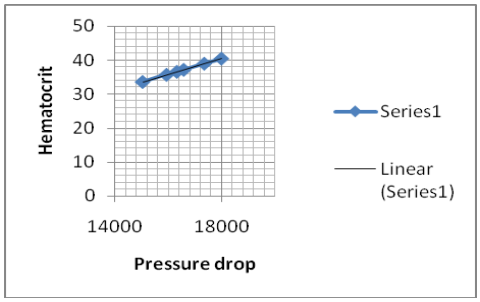

Graph: (1)

VI. CONCLUSION

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

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VIII. 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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