

# Physical and Mathematical Model of Heart and Cardiovascular System

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## Abstract

The cardiovascular system is modelled as a fluid flow system consisting of networks of pumps and piping systems. A mathematical model relating different cardiovascular parameters was developed. The change in cardiovascular parameters with individuals' physical activity level, habits and environmental factors was established. The models used to predict how an individual can control the cardiovascular parameters to be healthy and diagnosing problems in the system.

**Keywords:** Blood Pressure; Circulatory system modelling; Heart Rate.

## Introduction

The cardiovascular system is considered as a set of pumps connected with combination of series and parallel resistances and capacitances or compliances (consisting of blood vessels) [1, 2]. It is analogous to fluid flow system with variable viscous forces and connected with storage tanks (capacitance or compliances). Corresponding to every fluid flow circuit, there exists an equivalent electrical circuit having source of energy like battery or electrical generator, resistances and capacitances. So laws applicable to equivalent electrical circuit are applicable to cardiovascular system. Using those laws, the relationship between parameters of cardiovascular system was established.

Heart is agglomerate of two separate pumps; right heart that pumps blood through the respiratory organ, and left heart that pumps blood through the peripheral organs. Each of these pumps is a pulsatile two-chamber pump composed of an atrium and a ventricle. Each atrium is a weak primer pump for the ventricle, helping to move blood into the ventricle. Ventricles in a following rhythm supply the main pumping force that propels the blood either (1) through the pulmonary circulation by the right ventricle or (2) through the peripheral circulation by the left ventricle. The specialized excitatory and conductive fibres, exhibit either automatic rhythmical electrical discharge in the form of action potentials or conduction of the action potentials through the heart, providing an excitatory system that controls the rhythmical beating of the heart [2].

The heart beats, stroke volume, flow delivered and blood pressure of the circulatory system and the effect of different parameters on them were widely studied.

The stroke length and hence stroke volume of heart depends on venous return. The increase in venous return stretches the heart muscle more and exerts more pressure and stroke volume increases [2].

The effect of non-pharmacological interventions like salt restriction, weight change, physical and mental stress control, alcohol consumption, food habit on blood pressure was examined and correlated [3-9]. Sedentary behaviors and its impact on health were studied by Matthews et al [10]. For all age-groups and in both sexes, a direct and strong relationship between weight and blood pressure was established [11].

Potassium in the extracellular fluids causes the heart to become dilated and flaccid and also decreases the heart rate. Excess of calcium ions promotes spastic contraction. Cardiac muscle has three types of membrane ion channels that play important roles in causing the voltage changes of the action potential. They are (1) fast sodium channels, (2) slow sodium-calcium channels, and (3) potassium channels [1, 2].

Increased body temperature increases heart rate and decrease in body temperature decreases it [1]. Heart Rate depends both on non-modifiable factors (age, gender and ethnicity) and modifiable factors (Physiological and Pathological factors, Lifestyle factors, Neuropsychological factors, and Environmental factors [12].

The factors that determine the resistance (R) of a blood vessel to blood flow are expressed by the Poiseuille equation:

$$R = 8 * h (\text{viscosity of blood}) * l (\text{length of blood vessel}) / \{ \text{radius of blood vessel } (r) \}^4 [1].$$

Kotchen et al [13] found Blood pressure at one age is predictive of blood pressure at a later age. Bowman et al [14] found that systolic Blood Pressure is a strong, consistent, and independent predictor of Cardio Vascular Disease death for men aged 39 to 84 years old. Rockwood and Howlett [15] found that blood pressure changed little in relation to age in all groups, except in individuals with untreated hypertension. Penuela and Penuela [16] concluded "age shows a positive but divergence relationship with standard deviation for day and night with diastolic and systolic blood pressure. Blood pressure variation both systolic and diastolic at day and night were found higher in female".

Effect of gene on hypertension has been established. It

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involves multiple genes with only mild effects on phenotype, gene–gene interactions (epistasis), and genes that manifest as multiple traits [17-20].

Integrative model of cardiovascular system with arterial network and flow of blood through different organ was established.

The peripheral circulation is divided into the upper body, renal, splanchnic, and lower extremity sections; the intra-thoracic superior, inferior vena cava, and extra-thoracic vena cava are identified separately. The model thus consists of compartments, each of which is represented by resistance (R) and compliance or capacitance (C) [1, 21]. Compliance or capacitance here is the volume of blood the vessel can hold per unit pressure.

Cardiac output is distributed among various organs: approximately 15% of the cardiac output is delivered to the brain via the cerebral arteries, 5% is delivered to the heart via the coronary arteries, 25% is delivered to the kidneys via the renal arteries. The percentage distribution of cardiac output among the various organ systems is not fixed [1].

**Research Gap:** The physical model or mathematical model of circulatory system as a whole is unavailable.

**Objectives:**

- I. To Build up a physical model of Cardiovascular system
- II. To Build up mathematical models relating cardiovascular parameters
- III. Establishing relationship of blood pressure with level of exercise
- IV. Applying models for clinical purposes

**Materials and Methods**

The research has been carried out in two stages. From review of literature about the blood circulation loops and its analogy with similar electrical (heart as variable voltage source and blood vessels as resistors in parallel with capacitors) and mechanical system (heart as peristaltic pump and blood vessels as resistive frictions in parallel with a storage tank), model for circulatory system was prepared. First secondary data has been collected from published data sources and from available laws and relationships between parameters, the variables used in models were computed. In the second state primary data was collected. The large sample (400) was taken [22] by stratified random sampling. From the collected primary data model has been validated.

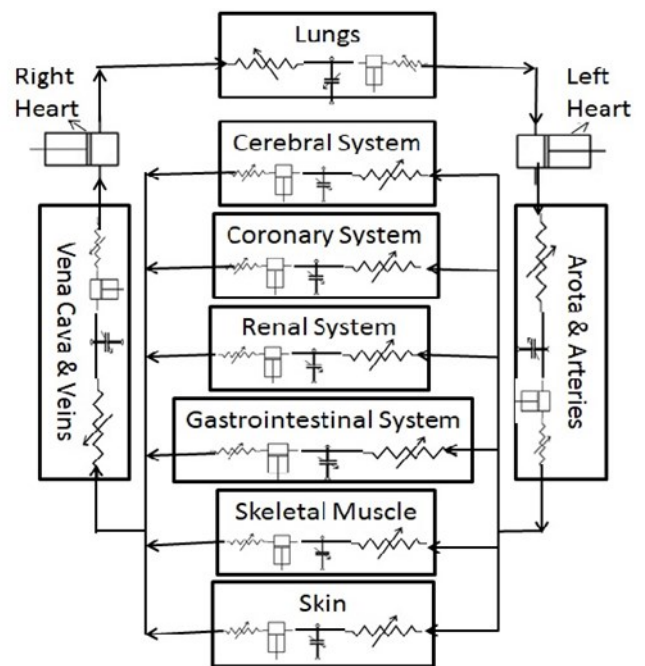
**Developing Models:**

*Physical Models:*

Literature indicates heart can be considered as variable speed, variable output pump of reciprocating type or it can be compared with a controllable variable voltage battery. The circulatory system can be considered as a system consisting of series and parallel resistances (that causes hindrance to blood circulation like friction and drops blood pressure) and connected with compliances/capacitance (that acts like electrical capacitor or a storage tank connected with system, if pressure of the system increases blood will flow to the storage tank which has low pressure or head so that flow through system not increases due to increase in system pressure similarly if pressure decreases blood comes from storage tank to

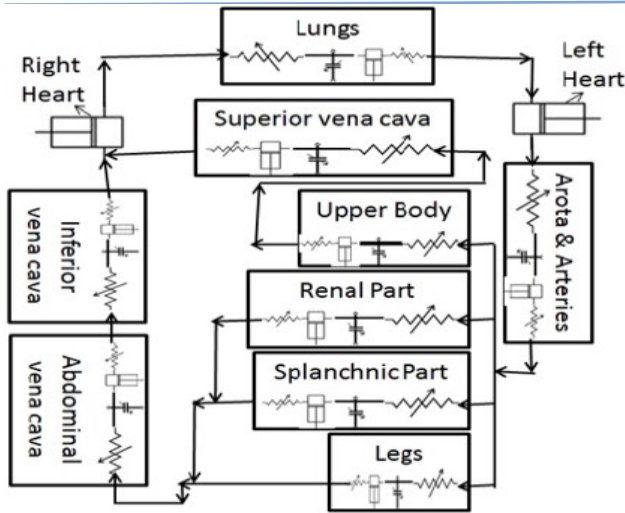
system, hence it tries to maintain flow or opposes change in flow). When pressure of the circuit increases it will exert more force on the wall of organs of circulatory system and holds more volume so that flow through the system not changes much with changing pressure, opposite is the case in-case pressure decreases. Resistances and Compliances are of adjustable types that is can be changed based on requirement of blood in their respective organs. The discharge of reciprocating pump per second (Q) = Discharge in one revolution \* number of revolution per second [23]. The pressure developed by the piston of pump = Constant \* frequency<sup>2</sup> \* Cos (2π\*frequency\*time) [23]. Accordingly for Heart the flow of blood (Q) = Ventricular Stroke Volume (SV) \* Heart Rate (n in beats/second). SV = End Diastolic volume – End Systolic volume. The Pulse Pressure of Heart (PP) = Constant (A) \* Square of Heart Rate (n<sup>2</sup>) \* Cos (2π\*n\*t + α) where t is time and α is the phase angle at time zero or the time at which heart muscle starts constructing. The value of α will be 180° or π as diastolic pressure is minimum. The pulse pressure due to stroke of heart exists only in aorta, all arteries and arterioles and not exists in capillaries and veins as their compliances absorbs the pulse like capacitor in electricity. Pulse Pressure in different circulatory part is governed by the same equation as in heart only the value of constant is different.

The exchanges of gases in capillaries take place at very low velocity. The movement muscles of the organs should also provide energy to the blood to reach it to heart despite low velocity at capillaries. So it can be considered as variable output pumps. In view of the above and the information of Constanzo [1] and other literature review, Circulatory system can be represented as in figure 1. Similarly as per the information of Kim et al [21] and other literature review, Circulatory system can be represented as in figure 2. The symbols used are as follows:

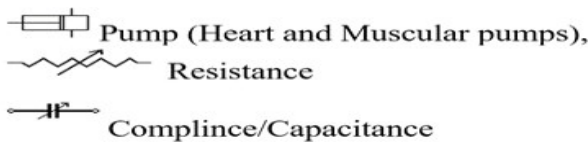


**Fig 1: Blood Flow through Different Systems**

Heart and other muscular pumps, Resistances, capacitances/compliances.



**Fig 2. Blood Flow through Body Parts**



The resistance of a circuit consisting of series of resistances is the sum of individual resistances, whereas in case of parallel resistances; the inverse of system resistance is the sum of inverse of individual resistances. The compliance of a system (C in ml/mm Hg) is the ratio of change in volume of the system (DV) and change in Pressure of the system (DP) or ratio of volume (V) and pressure (P) ( $C = DV/DP$ ) or  $V/P$ ) [1].

The Resistance offered by Capacitor (X) having capacitance (C) operating in electrical circuit with frequency (f) is given by:  $X = 1/(2\pi * f * C)$  [24]. Accordingly the Resistance (X in mm Hg/ml) offered by Compliance in circulatory system is given by:  $X = 1/(2\pi * n * C)$  where n is heart rate. The total resistance of a circuit (Z) consisting of Resistance R and Resistance X due to capacitance C is given by:  $Z = \text{square root}(R^2 + X^2)$  [24]. Accordingly total resistance (Z in mm Hg/ml) of the part with Resistance offered by Resistances (R in mm Hg/ml) and Resistance offered by Compliance (X) in circulatory system is given by:  $Z = \text{square root}(R^2 + X^2)$ . Voltage Drop (V) in portion of electrical circuit is given by Ohms law:  $V = \text{Current through the Circuit}(I) * \text{Resistance of the portion of electrical circuit}(R)$  [24]. Similarly Pressure Drop (DP in mm Hg) across a part of circulatory system with total resistance (Z) and blood flow through it (Q in ml/sec) is given by:  $DP = Z * Q$ . The Pressure at the outlet of a subsystem in circulatory system is given by:  $(Po) = \text{Pressure at the inlet of the system}(Pi) - \text{Pressure drop by total resistance} + \text{Pressure developed by muscular pump in the system}$ .

Resistances and Compliances of a few parts of the circulatory system are available in the paper published by Kim et al [21]. Volume of Blood stored in different parts of circulatory system and pressure at different points of circulatory systems are collected from Literature [1]. Total blood flow and blood flow through different body parts were calculated from data available in literature [1], [2, 25]. From the collected and calculated data and applying Kirchoffs voltage law and Kirchoffs current law in fluid flow system, drawing analogy to electrical

system, and the relationship between different parameters, the value of different parameters has been computed according to models in Figure 1 and in Figure 2 and are given in Table 1 and Table 2 respectively.

**Mathematical Models:**

The Stroke Volume (SV) is a function of venous return ( $V_r$ ) and the Heart Rate (n) depends on non-modifiable factors {age (Ag), gender (Ge) and ethnicity (Et)} and modifiable factors {Physiological and Pathological factors (Pf), Lifestyle factors (Lf), Neuropsychological factors (Nf), and Environmental factors (Ef). The blood flow discharged by heart (Q) is a function of all these factors.

$$Q(V_r, Ag, Ge, Et, Pf, Lf, Nf, Ef) = SV(V_r) * n(Ag, Ge, Et, Pf, Lf, Nf, Ef) \dots \dots \dots (1)$$

Mean Blood Pressure (BMP) developed by Heart depends on Q and Resistance of the system (R). R depends on viscosity of blood (h), effective length (l) and effective radius (r) of blood vessel. Viscosity of blood depends on composition and hence can be written as function of blood composition also.

$$BMP(V_r, Ag, Ge, Et, Pf, Lf, Nf, Ef, h, r, l) = Q(V_r, Ag, Ge, Et, Pf, Lf, Nf, Ef) * R(h, r, l) - \text{pressure developed by muscular pump}(M_p) \dots \dots \dots (2)$$

Blood Pressure (BP) is the sum of BMP and Pulse Pressure (PP).

$$PP(n, t) = A * n^2 * \text{Cos}(2\pi * n * t + \pi) \dots \dots \dots (3), \text{ time } (t) = 0 \text{ means diastolic pressure.}$$

$$BP(V_r, Ag, Ge, Et, Pf, Lf, Nf, Ef, h, r, l, t) = BMP(V_r, Ag, Ge, Et, Pf, Lf, Nf, Ef, h, r, l) + A * n^2 * \text{Cos}(2\pi * n * t + \pi) \dots \dots \dots (4)$$

When the value of  $\text{Cos}(2\pi * n * t + \pi)$  is +1, the Blood Pressure is systolic pressure and when the value of  $\text{Cos}(2\pi * n * t + \pi)$  is (-)1, the Blood Pressure is diastolic pressure.

$$\text{Blood Pressure at Periphery}(B_{pp}) = BP - \text{Resistance from heart to Peripheral Part}(R_p) * \text{Blood Flow through that peripheral Part}(Q_p) + \text{Pressure developed by muscular pump}(M_p) \dots \dots \dots (5)$$

**Data Collection:** Primary data was collected from people of different part of India by stratified random sampling basis. The data was taken randomly from the persons came in different health centres for health check-up. The values of blood pressures, heart rates at different levels of work, provided by health centres to them were taken as primary data. The data was taken only from them who were willing to provide the same knowing the purpose of the data collection. The age group of the persons was 18-40 years. All of the persons were free from any disease.

**Secondary Data Analysis:** Cardiac output is 5300 ml/minute when a person is at rest and linearly it increases with exercise [2]. From the data the equation of cardiac output (Q in ml/minute) that is discharge of heart for different level of exercise (W in watt) is derived as follows:  $Q = 5300 + 96.36 * W$  ml/minute or

$$Q = 88.333 + 1.606 * W \text{ ml/second} \dots \dots \dots (6)$$



**Results**

Analysis of Primary data indicates correlation exists between exercise level and heart rate as follows:

$$n = (72 + 0.52 * W) \dots \dots \dots (7),$$

heart rate in beats per minute and work (W) in watt.

The peripheral system can change the resistance to fulfil its blood flow requirement. So the pressure drop across the system remains constant and from the Table 1, it is found to be 70 mm of Hg. The pressure dropped in entire system is 100 mm Hg.

Pressure developed by heart at starting of aorta is given by:

BP heart = 70 + Q \* (Resistance of Aorta + Resistance of Arteries + Resistance of Veins + Resistance of Vena Cava) - Pressure developed by Muscular pumps + A \* n<sup>2</sup> \* Cos (2π\*n\*t + π). Substituting values of cardiovascular parameters from Table 1, value of Q in equation (6), relationship between parameters obtained from primary data analysis and computed value of A, we have:

$$BP \text{ heart} = 71.0 + 0.402597 * n + (0.00008 * n^2 + 0.34 * n - 5) * \text{Cos} (2\pi * n * t + \pi) \dots \dots (8)$$

Substituting the value of heart rate (n) from equation (7) to equation (8) we have

$$BP \text{ heart} = 100 + 0.209 * W + (20 + 0.185 * W + 0.000022 * W^2) * \text{Cos} \{2\pi * (1.2 + 0.00867 * W) * t + \pi\} \dots \dots (9),$$

at rest W = 0.

Substituting value of Cosine function with (-)1 and +1, in equation (9) we have:

$$\text{Diastolic Pressure} = 100 + 0.209 * W - (20 + 0.185 * W + 0.000022 * W^2),$$

$$\text{Systolic Pressure} = 100 + 0.209 * W + (20 + 0.185 * W + 0.000022 * W^2)$$

Pressure at aorta and large arteries is same as BPheart. At small arteries pressure is given by:

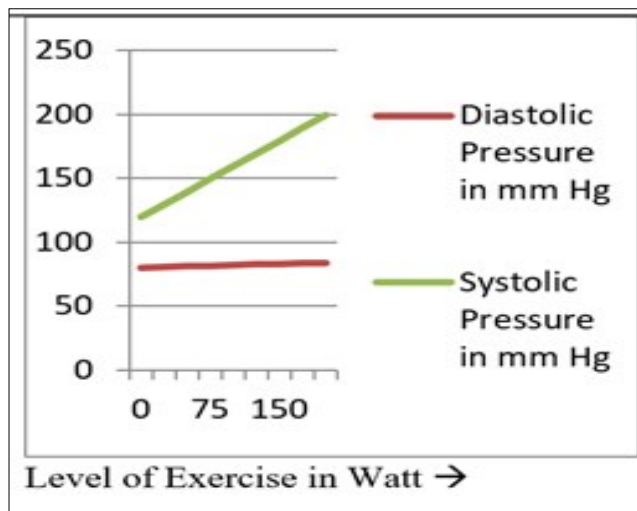
$$BP_{sa} = 90 + 0.1306 * W + (12.5 + 0.1156 * W + 0.00001375 * W^2) * \text{Cos} (2\pi * (1.2 + 0.00867 * W) * t + \pi) \dots \dots (10)$$

Pressure at any part of cardiovascular system can be obtained from equation (5) as derived in developing mathematical models. For capillaries and veins coefficient of Cos function is zero as large capacitance associated with this part absorbs time varying component.

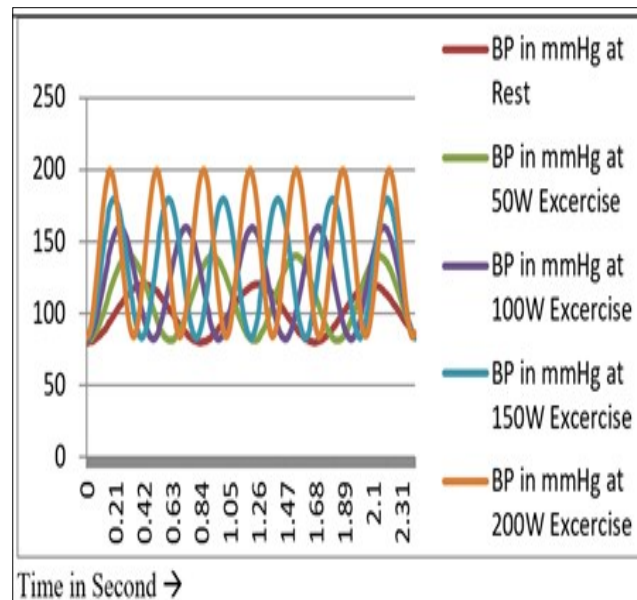
The systolic and diastolic blood pressure as calculated from equation (9) with value of Cosine function as + 1 and (-) 1 respectively, for rest and different level of exercise is shown in Figure 3. Similarly the blood pressure at rest and different level of exercise as a function of time as obtained from equation (9) is shown in Figure 4.

The average error of model as calculated in terms of percentage deviation of predicted value of model from primary data are 0.91%, 0.99% and 0.49% for heart rate, systolic blood pressure and diastolic pressure respectively. The modulus of individual error that is converting negative error to positive is taken for finding

an average error. The error was taken for the level of exercise for which primary data could be collected. The primary data is also validated from t-test with p value less than 0.01.



**Fig 3: Variation of Systolic and Diastolic Pressure with exercise**



**Fig 4: Variation of Blood Pressure (BP) at different level of Exercise with time**

**Validation of Model:**

Level of Exercise	Calculated from Equation (9)			Primary Data		
	HR	SBP	Dias-tolic BP	Hear Rate	Systolic BP	Diastolic BP
Watt	beats/min	mmHg	mmHg	beats/min	mmHg	mmHg
				Mean±SD	Mean ±SD	Mean±SD
0	72	120	80	72 ± 7	120 ± 7	80 ± 6
25	85	129.9	80.6	84 ± 9	126 ± 8	80.2 ± 6
50	98	139.8	81.1	96 ± 8	138 ± 9	80.6 ± 7
75	111	149.7	81.7	110 ± 10	148 ± 10	81.1 ± 8
100	124	159.6	82.2	123 ± 9	159 ± 12	82 ± 10
125	137	169.6	82.7	138 ± 11	170 ± 12	82 ± 10
150	150	179.6	83.1	151 ± 13	181 ± 14	83 ± 12
175	163	189.6	83.5			
200	176	199.7	83.9	Data could not be collected		

**Table 1. Cardiovascular parameters as per model in figure 1**

Circulatory System	Inlet Resistance	Outlet Resistance	Compliance	Resistance of Compliance	Total Resistance	Flow	Pressure drop	Pressure Developed by pump
	mm Hg/ml	mm Hg/ml	ml/mm Hg	mm Hg/ml	mm Hg/ml	ml/min	mm Hg	mm Hg
Lungs	0.1	0.04	0.1	0.02	0.142	5300	13	3
Cerebral System	6.56	0.48	0.010	0.22	7.043	710	83	13
Coronary System	19.68	1.44	0.003	0.66	21.130	233	82	12
Renal System	4.1	0.3	0.016	0.14	4.402	1135	83	13
Gastrointestinal System	3.2	0.21	0.020	0.11	3.412	1420	81	11
Skeletal Muscle	3.35	0.27	0.020	0.11	3.622	1420	86	16
Skin	12.5	0.9	0.005	0.41	13.406	382	85	15
Aorta & arteries	0.08	0.02	0.03	0.07	0.124	5300	11	1
Vena Cava & veins	0.2	0.08	0.39	0.01	0.280	5300	25	6

**Table 2: Cardiovascular parameters as per model in figure 2**

Circulatory System	Inlet Resistance	Outlet Resistance	Compliance	Resistance of Compliance	Total Resistance	Flow	Pressure drop	Pressure Developed by pump
	mm Hg/ml	mm Hg/ml	ml/mm Hg	mm Hg/ml	mm Hg/ml	ml/min	mm Hg	mm Hg
Lungs	0.1	0.04	0.1	0.02	0.142	5300	13	3
Cerebral System	6.56	0.48	0.010	0.22	7.043	710	83	13
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Skin	12.5	0.9	0.005	0.41	13.406	382	85	15
Aorta & arteries	0.08	0.02	0.03	0.07	0.124	5300	11	1
Vena Cava & veins	0.2	0.08	0.39	0.01	0.280	5300	25	6

**Research Findings:**

- ⇒ Blood Pressure at any Part of human body depends on heart rate (n) and is given by  $BP = A + B*n + (C*n^2 + D*n + E) * \cos(2\pi*n*t + \pi)$ , where A, B, C, D and E constant for a particular point in the cardiac system, time (t) is measured from diastolic pressure. The value of cosine function is -1 for diastolic pressure and +1 for systolic pressure.
- ⇒  $BP = P + Q*W + (R*W^2 + S*W + T) * \cos(2\pi*(1.2 + 0.00867 * W)*t + \pi)$ , where P, Q, R, S and T constant for a particular point in the cardiac system and W is the work level of the person which is zero at rest and negative if the energy requirement of the body goes down below the level of normal energy requirement of the body, time (t) is measured from diastolic pressure. The value of cosine function is -1 for diastolic pressure and +1 for systolic pressure.
- ⇒ Value of Pulse Pressure (cosine part) is negligible in vena cava, veins, venules and capillaries as high capacitance/compliance (C) associated with them absorb the pulsating component similar to electrical capacitors.
- ⇒ The pressures produced by muscles (muscular

- pumps), resistances and compliances of different parts in circulatory system were computed and were shown in Table 1 and 2.
- ⇒ Heart Rate increases linearly with energy requirement of body

**Discussion**

Research findings indicates that laws of physics holds good for circulatory system. The heart is like a variable speed variable stroke length reciprocatory pump. The pressure developed by pump can be calculated as a function of time and systolic and diastolic pressure can be obtained. When body needs more energy more blood is required and this is achieved by increasing heart rate like speed of a pump. The constant terms of the blood pressure equations

Are constant for a normal healthy person. The deviation of this constants for a person during rest or exercise indicates some problem in either blood constituent or circulatory system or in the control system governing heart rate and stroke length.

Equation (2) relates blood pressure with blood flow and system resistance each of which is function of different cardiovascular system parameters. Hence the reason for changing normal blood pressure can be attributed to those

parameters and further investigation about those parameters shall help to identify the exact reason of the problem.

**Application of Model:** The model can be used to know the variation of blood pressure with time for rest as well as any level of exercise. It can be used to predict blood pressure at any component in the circulatory system.

From the model Resistance in any part of the system is known and by measuring pressure drop of any person actual Resistance can be calculated. If the resistance is more it indicates radius of the blood vessel has reduced (Resistance is inversely proportional to the 4<sup>th</sup> power of radius). So by measuring blood pressure, the blockage of blood vessel can be identified.

Establishing relation between resistance of blood vessels with composition of blood (Sodium, Potassium etc), the blood composition can be changed to normal level.

The comparison of systolic and diastolic pressure variation of a person with the modelled data shall predict if person is suffering any cardiovascular disease.

### Conclusion

The cardiovascular system can be modelled as equivalent electrical system or fluid flow system. Relation can be established among different cardiovascular parameters and the cardiovascular system can be modelled mathematically which shall provide necessary information with more than 99% accuracy. The system changes the parameters like resistances, compliances, heart rate as per the requirements. The energy requirement of the body has strong relationship with cardiovascular system parameters and the same can be predicted with more than 99% accuracy.

**Direction for future research:** Effect of all variables on different cardiovascular parameters as developed in developing mathematical model section needs further research. This will open a lot of windows in clinical research.

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**Conflict of Interest:** Nil

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