

# Modeling of Physiology Based Toxicokinetics and Toxicodynamic to Diagnose Acute Effects of Nicotine on Heart Rate

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**Abstract:** *In the modern world persons addicting to drugs are increasing gradually. Drugs are mostly in the form of cocaine, nicotine etc. which are harmful to our human body. The most commonly affected organs are lung, liver, kidney. In this paper we analyzed the effect of nicotine in lung, liver and kidney using Physiologically Based Toxicokinetics and Physiologically Based Toxicodynamics modeling. The effect of nicotine is more in lungs which also affect blood concentration and heart rate of the human. We also analyzed the efficiency of lung assist device by placing compliance chamber in between heart and lung. By using compliance chamber we can able to maintain the pulmonary artery pressure in the range of 8 to 25mm/Hg.*

**Keywords:** Physiologically Based Toxicokinetics (PBTk), Physiologically Based Toxicodynamics (PBD), artificial lungs, lung transplantation, compliance chamber (keywords)

## 1. Introduction

Tobacco which is particularly smoked product has been associated with great harm and growing public disapproval and can be expected to suffer in the market place. This situation has created opportunities for other less harmful nicotine containing products causes immediate effect on cardio vascular disorders and delayed effect on respiratory and cancer disorders [1]. The straw nicotine oral delivery system is a novel form of nicotine replacement therapy designed to provide not only nicotine but also oral and manual stimulation and ease of dosing. The straw is the single-use. Drinking straw containing loose nicotine bitartrate particles that are ingested with the first sip of beverage. Straw may be a useful new tool in supporting smoking cessation for several reasons [2]. The absorption of nicotine delivered by a transdermal delivery system (tedious) was investigated in two separate studies, single dose proportionality study and multiple dose study. The Area Under Curve (AUC) and Maximum Concentration (C<sub>max</sub>) values are proportional to the dose. Transdermal delivery provides continuous absorption of drug through stratum corneum even during sleep [3]. Sympathetic over activity is implicated in the increased cardiovascular risk of cigarette smokers.

Excitatory nicotine receptors are present on peripheral chemoreceptor. Chemoreceptors located in the carotid and aortic bodies increase Ventilation (V<sub>e</sub>), Blood Pressure (BP), Heart Rate (HR) and Sympathetic Nerve Activity to Muscle circulation (MSNA) in response to hypoxia. Nicotine Replacement Technique (NRT) increases myocardial oxygen consumption in periods of reduced oxygen availability [4]. The Pharmacokinetic and Hemodynamic effects of nicotine patch are significantly different between smokers and non-smokers. The Hemodynamic effects of the nicotine patch on blood pressure and heart rate were greater in nonsmokers than in smokers, and the parasympathetic effects such as nausea and vomiting occurs more frequently in non-smokers than in smokers [5].

The physiologically based Toxicokinetic model treats the time course of chemical distribution. It is illuminating to use fugacity to directly examine the relative equilibrium status of compartments and to provide the direct estimate of chemical activity thus with suitable parameterization it has potential for both bio-concentration and toxicity expressed as median lethal concentrations, critical body residues, and chemical activity as a function of time to death[6]. The Physiologically Based Toxicokinetics (PBTk) and Toxicodynamic modeling (PBD) was applied to provide concentration time profiles of nicotine. This model is used to estimate the heart rate in terms of maximum concentration based on inhalation, oral intake and absorption. The Toxicodynamic model is used to analysis the effect of nicotine in heart rate and the Toxicokinetic model is used to analyze the effect of nicotine in different organs of our body (kidney, liver, lung). Lungs are mainly affected during smoking [7].

**Table 1:** nicotine dosage

Types	Dosage level
Cigarettes(1.2mg)	
3 per day	3.6mg
8 per day	9.6mg
14 per day	16.8mg
21 per day	25.2mg
Dermal patches	7mg
	14mg
	21mg
Nicotine lozenges	
2mg for every 2 h	24mg
2mg for every 1h	48mg
4mg for every 1h	96mg

Artificial lungs may serve as transplant alternatives to patient with respiratory failure. To provide the pulmonary replacement, the device cannot significantly alter right ventricular after load. Addition of a compliance chamber reduces pulse wave reflection and normalizes ventricular function. The pulmonary replacement with the low-resistance artificial lung is tolerated by the right ventricular

in this short term model [8]. Matching the impedance of an artificial lung for pulmonary replacement to native pulmonary impedance is important in preventing right ventricular dysfunction. The lunged parameter model and the bench top simulation will aid in the design and testing of compliance chamber modification to improve its efficiency [9]. The contribution of this paper gives the detailed analysis of changes in blood concentration according to the nicotine dosages in liver and kidney using Physiologically Base Toxicokinetics (PBTk) modeling and heart rate changes based on using Physiologically Based Toxicokinetic modeling (PBTk) and cardiac output is determined. Based on this changes the lung is mainly affected which is demonstrated in relation between heart rate, cardiac output and blood flow. As a result of fixing artificial lungs that is, assisting device for lungs which is replaced instead of original lungs. Every device has certain original efficiency. In order to increase its efficiency, a compliance chamber is designed and fixed.

## 2. Nicotine Dosage Used

The dosages were selected for resting condition to show the difference in heart rate changes, blood concentration and cardiac output at identical concentration levels of nicotine. The selected dosing conditions for nicotine with web and literature references are mentioned in Table 1.

## 3. Physiological Modeling

### A) Physiologically Based Toxicokinetic modeling (PBTk)

In this model the drug concentration profile result from the uptake and elimination capacity of organ composing the body, the distribution of the drug to an organ depends on the blood flow to the organ, the organ weight and the partition coefficient of the drug between the blood and the organ, the major distribution takes place in liver, GI tract and kidney. The block representation of the PBTk model is represented in Figure 1.

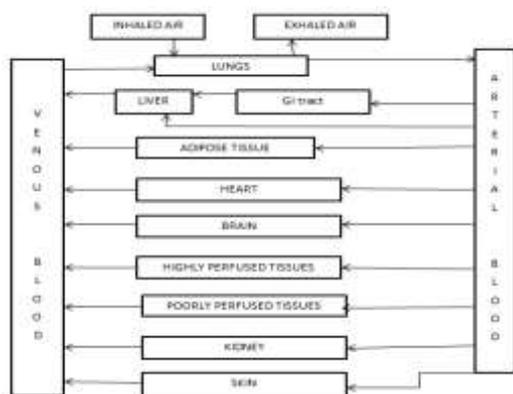


Figure 1: PBTk flow chart

#### Liver and GI tract:

The model equations for the liver and GI tract are given

#### liver:

$$\frac{dA_{liv}}{dt} = Fl_{git} + FOR_{Mliv} + Fl_{iv} \left( C_{art} - \frac{C_{liv}}{P_{Cliv}} \right) - MET_{liv} \quad (1)$$

$$C_{liv} = \frac{A_{liv}}{V_{liv}} \quad (2)$$

#### GI tract:

$$Fl_{git} = fra \cdot f_{git} \cdot \frac{C_{stm}}{P_{Cgit}} + frb \cdot f_{git} \cdot \frac{C_{si}}{P_{Cgit}} + frc \cdot f_{git} \cdot \frac{C_{li}}{P_{Cgit}} \quad (3)$$

$$C_{stm} = \frac{A_{stm}}{V_{stm}} ;$$

$$C_{si} = \frac{A_{si}}{\left(\frac{3}{4}\right) V_{int}} ;$$

$$C_{li} = \frac{A_{li}}{\left(\frac{1}{4}\right) V_{int}} \quad (4)$$

Where:

$A_{liv}$  = amount of nicotine present in liver.

$Fl_{iv}$  = fraction of liver.

$C_{art}$  = concentration present in arteries.

$P_{Cli}$  = partial coefficient of liver.

$MET_{liv}$  = metabolism of nicotine in liver.

$Fl_{git}$  = GI tract formation.

$Fra, frb, frc$  = absorbed fractions that reach liver from stomach, small intestine & large intestine.

$f_{git}$  = fraction of GI tract.

$P_{Cgit}$  = Partial Coefficient of GI tract.

$C_{stm}$  = Concentration of nicotine present in stomach.

$C_{si}$  = Concentration of nicotine present in small intestine.

$C_{li}$  = Concentration of nicotine present in large intestine.

$A_{stm}, A_{si}, A_{li}$  = amount of nicotine present in stomach, small intestine & large intestine.

$V_{stm}$  = volume of stomach.

$V_{int}$  = volume of intestine

Table 2: Parameters of TK model

Parameters	Values
Fliv	0.254
Fgit	0.025(man) 0.0265(woman)
Fra	0.2
Frb	0.6
Frc	0.2
PCgit	0.81
Cstm	Varies
Csi	Varies
Cli	Varies
Cart	0.8
FORMliv	0
Cliv	0.0061
PCLiv	0.81
METliv	0.1674

Table 3: weight of organs

Organs Name	% of Body Weight
Stomach	0.21
Small intestine	0.91
Large intestine	0.53
GI	1.71
Kidney	0.44
Heart	0.47
Lungs	0.76

These parameters values are mentioned in M.Gajewska et al.,[8] and Loizou et al.,[16] which are discussed in the

references. The volume of the organ is calculated with the information of organ's weight and its density is tabulated below. This is specified as the standard values for the average body weight of 70 kg. These data are taken from the paper (physiological parameter values for physiologically based pharmacokinetics models published by Brown et al.,)

**Kidney**

The equation for the kidney is given as

$$\frac{dA_{kid}}{dt} = F_{kid} \left( C_{art} - \frac{C_{kid}}{P_{C_{kid}}} \right) - CLR \left( \frac{C_{kid}}{P_{C_{kid}}} \right) \tag{5}$$

$$C_{kid} = \left( \frac{A_{kid}}{V_{kid}} \right)$$

Where:

- Akid= amount of nicotine present in kidney
- Fkid = blood flow rate through kidney
- Ckid = concentration of nicotine

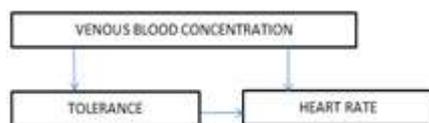
The standard values of kidney parameters are mentioned by M.Gajewska et al., in his paper[3]. Thus from the above information the modeling of kidney is done and the amount of changes in blood concentration for each organ is evaluated, based on the value of nicotine dosage given into our body, the amount of nicotine that can be distributed to the organ can be estimated.

**B) Physiologically Based Toxico-Dynamic modeling (PBTD):**

The PBTD model explanation is outlined in fattinger et al., [7]. Here venous blood concentration plays a vital role. Using PBTD the model for heart rate was developed. Here modification is necessary for the case of nicotine affected during exercise only. The block diagram for PBTD model is given in Figure 2.

**Table 4:** Parameters value for kidney

Parameters	Values
Fkid	0.19 (woman) 0.2 (man)
Akid	Varies
PCKid	1.34
Cart	0.8
CLR	0.036



**Figure 2:** PBTD model

The above block diagram gives the better fit and better description for the pharmacological response. Here for avoiding some issues one assumption is taken that the chemical concentration in blood(Cven) is always much less than the concentration needed to produce half of the maximal effect(Cven,50) (ie) Cven<<<<Cven,50. The antagonist formation and elimination rates are assumed to be constant and are dependent on venous blood concentration. The equation for the PBTD model is given as.

$$E = E_0 + \frac{\left( \frac{E_{max}}{C_{ven}} \right) \cdot C_{ven}}{\left( 1 + \frac{C_{ven}}{C_{ven,50}} \right) \left( 1 + \frac{C_{ven}}{C_{ven,50}} \right)} \tag{6}$$

$$E = E_0 + \frac{(s) \cdot C_{ven}}{\left( 1 + \frac{C_{ven}}{C_{ant,50}} \right)} \tag{7}$$

$$V_{ven} \cdot \left( \frac{dC_{ant}}{dt} \right) = K_{a,ant} \cdot (fu \cdot C_{ven}) - K_{el,ant} \cdot C_{ant} \tag{8}$$

Where:

- Ven = Venous blood
- Cant = Concentration of antagonist
- Ka,ant; Kel,ant = Formation and elimination rates of antagonist
- Fu = Free fraction of a stimulant
- E = Effect on heart rate
- E0 = Base line effect
- Emax = Maximal effect
- S = Ratio of Emax
- Cven = venous blood concentration

**Parameters Used:**

The parameter used are mentioned by porchet et al., in his paper[20]. Thus from the above information the modeling is done and the amount of changes in heart rate is determined, based on the value of nicotine dosage given into our body, the amount of nicotine that can be distributed also be found out.

These two modeling are used only for analyzing purposes. Thus the acute effect of nicotine in each organ and heart rate can be determined using this modeling.

**C) Relation Equation**

The heart rate and the blood flow both are indirectly related. During inspiration the lungs will expand and during expiration process the lungs will contract. Consequently in heart during inspiration there will be increase in heart rate and during expiration there will be decrease in heart rate. During intake of nicotine mostly the ventricle of the heart is affected. Hence ventricular assisting device (VAD) is used. The output from the VAD is given to the lungs and hence the input to the lungs depends on the output from the VAD (ie) ventricle of heart. The following equation gives the relation between heart rate and pressure.

$$P = SV \cdot HR \cdot TPR \tag{9}$$

$$BF = P/R \tag{10}$$

**Table 5:** Parameters of PBTD model

Parameters	Values
Cven	Varies
Eo	61.2,64(at rest) 145(during exercise)
S	1000
Ka,ant	3
Kel,ant	6
Cant,50	0.00772
Y	1(rest) 0.6 (during exercise)

Where

- P = Pressure
- SV = Stroke Volume
- HR = Heart Rate
- TP = Total Pressure Resistance
- R = Resistance
- BF = Blood Flow

The cardiac output (Q) is termed as the total volume of blood being pumped from heart ventricle in minute (ie)

blood leaves from the left ventricle every minute. At average resting time the cardiac output will be 5L/min and during exercise time it will be 4-7 times higher than rest.

$$CO=SV*HR \tag{11}$$

The stroke volume (SV) is defined as the volume of blood ejected from heart ventricle with each beat. at average resting time the stroke volume will be 60-70ml/beat. The heart rate (HR) determines the number of times heart pumps in 1 minute. At average resting time the heart rate will be 60-100 bpm (beats per minute).

#### 4. Design of Compliance Chamber

In general compliance means Ability of hollow organ to distend and increase volume with increasing trans-mural pressure to resist coil towards original dimensions on application of a distending or compressing force. It is also recognized as the tendency of arteries and veins to stretch in response to pressure has a large effect on perfusion and blood pressure. It is represented as  $C=\Delta V/\Delta P$ .

Where

C= compliance

$\Delta V$ = change in volume

$\Delta P$ = change in pressure

Here three element lumped parameter model is used to implement compliance chamber. The circuit consist of compliance element (C\*) and the resistive elements (R1\*, R2\*) before and after the C\*

The design of compliance chamber is outlined by the following equations

$$P^*=(R1^* + R2^*)Q_{ref} \tag{12}$$

$$Q^*=Q_{ref} Q \tag{13}$$

$$Ri^*=(R1^*+R2^*)Ri \tag{14}$$

$$T^*=T_{pulse}*t \tag{15}$$

Where:

P\*= pressure across the compliance element.

Tpulse= period of pulsatie flow.

T=ratio of the time scale of oscillatory flow.

R=total resistance in compliance chamber.

Qref=maximum value of periodic inlet flow

Q1= flow of blood in cardiac output.

Q2= flow of blood in pulmonary vein.

P1= pulmonary artery pressure.

P2= Left auricle pressure (10 mm/hg)

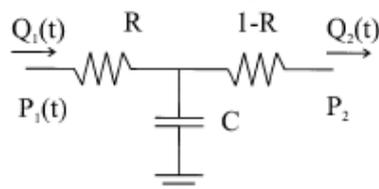


Figure 3: Compliance Chamber

From this the right ventricle pressure which is to be given for lungs as input is determined, which should have the range from 9mm/Hg to 21 mm/Hg.

#### 5. Heart-Lung Block

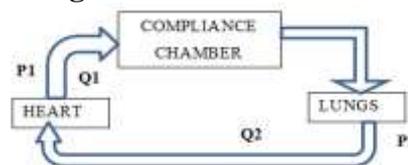


Figure 4: Heart-Lung model

The lung plays a major role in respiration; the purification of blood process is carried out in the lungs. The respiratory model for the human lungs is more complex. When there is the problem in lungs most of people undergoes, lung transplantation. But this process will get succeeded only when both the donor and receptor requirements matches. Hence the next developed system is fixing an artificial lung that is the assisting device which do all the work instead of lungs. The right side of a human heart play an important role, it's function is to collect a blood that contain oxygen and carbon dioxide from the body and transfer it to the lungs which collect all the oxygen and releases carbon dioxide. Now the left side of the heart collects bloods that contain a lot of oxygen from the lungs and then transfer it to the different part of the body.

The model for the combination of heart and lung is done in which the cardiac output is evaluated. The equation for all of the elements are then combined using continuity and the requirement that the total pressure drop along the circuit equal p1-p2. The non-dimensional governing equation of the system is given as

$$\frac{dP1(t)}{dt} = -T \frac{P1(t)}{1-R} + TQ1(t)(1 + \frac{R}{1-R} + R \frac{dQ1(t)}{dt}) \tag{16}$$

$$Q2 = Q1 - T \frac{dP1}{dt} + (\frac{R}{T}) \frac{dQ1}{dt} \tag{17}$$

where:

P1 = pulmonary artery pressure

Q1= flow of cardiac output

P2 =left atrial pressure ( 10mm/Hg)

Q2 = flow in pulmonary vein

T = time period

From this the pressure of heart P1 is determined for every change in the cardiac output. This is given as the input to the compliance chamber and the assisting device.

#### 6. Result and Discussion

##### Analysis

##### Analysis for liver and kidney using PBTK modeling:

Based on the PBTK modeling which is represented in the equations (1)(2)(3)(4) and Figure 1 the simulation is performed in MATLAB that is given in figure 8,9 the analysis is carried out. The analysis is done in order to find out the impact of nicotine in blood concentration of different organs (liver and kidney). The graphical representation of analysis shown in Figure 6, the X-axis represents the types of dosages and the y-axis represents the blood concentration values of both liver and kidney. It clearly conveys that while increasing the dosage level the blood concentration increases

and the impact of nicotine is more in kidney than in liver but while comparing with lungs the impact is greater in lungs.

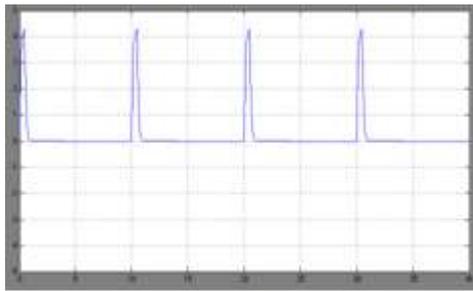


Figure 5: Right Ventricular Pressure (P1)

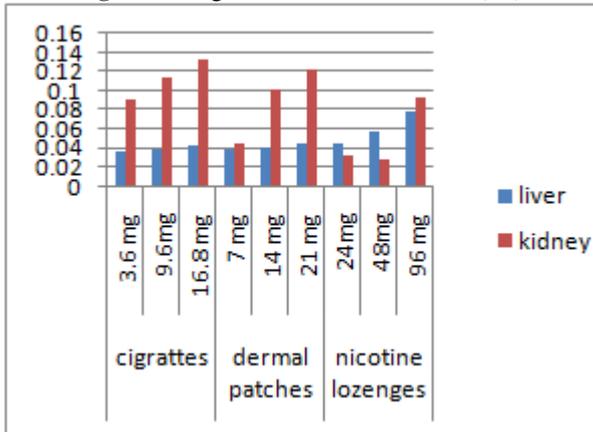


Figure 6: Blood concentration analyses

**Analysis of heart rate using PBD modeling**

Based on PBD modeling represented in the equations (6),(7),(8) and figure 2 the simulation is performed and given in figure10 and the analysis is done. This analysis is to identify the heart rate changes. The graphical representation of analysis is outlined in figure 7 where the x-axis represents the dosages and the y-axis represents the heart rate while increasing the dosage level the heart rate also increased.

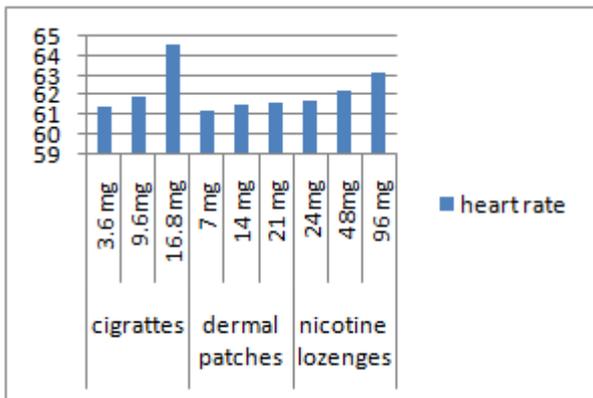


Figure 7: Heart Rate analyses

**Modeling**

**PBTK modeling:**

The Physiologically Based Toxicokinetic modeling is simulated for both liver and kidney using MATLAB/Simulink. The simulation is given in figure 8 for kidney and figure 9 for liver and their respective output is presented in the figure 8a) and 9a). The analysis is also determined for blood

concentration based on this that is explained in the analysis part of figure 6.

As a result from this modeling it is analyzed that the concentration of blood increases. In our human body, generally the concentration of blood should be minimum so that the blood can flow easily. Otherwise it will be very difficult for the blood to move freely. Because of this the organs are not supplied with rich oxygenated blood. Hence there may dis-function occurs. Thus the increased amount of nicotine intake affect the liver and kidney. They can't be able to do their proper function.

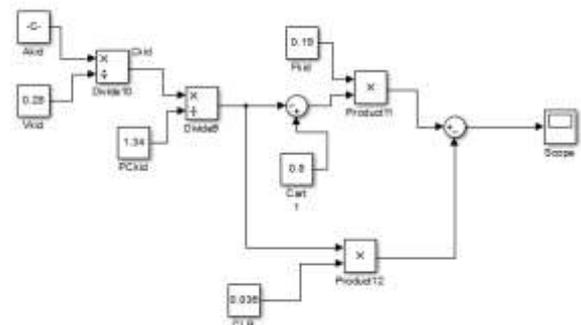


Figure 8: Modeling of kidney

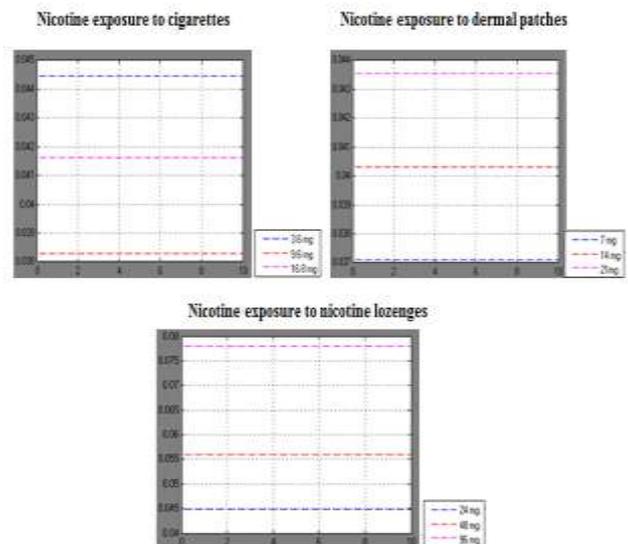


Figure 8 (a): simulation result for kidney at various nicotine dosages

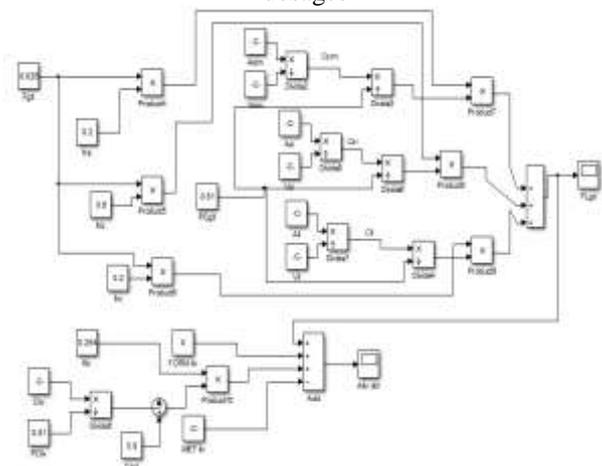


Figure 9: Modelling of Liver

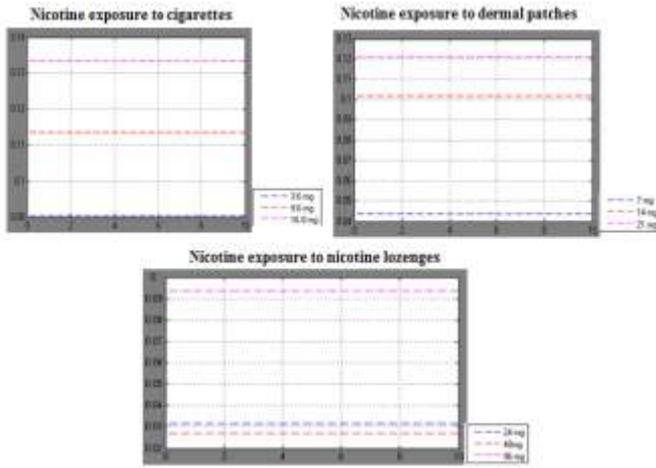


Figure 9 (a): simulation for liver at various dosages

**PBTD modeling:**

The Physiology Based Toxico-Dynamic modeling is simulated in MATLAB/Simulink. Here the simulation is done for occurring the heart rate which is represented in figure 10 and their respective simulation output is given in figure 10 a)

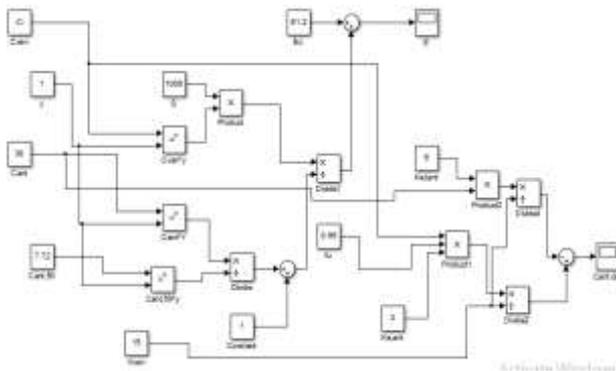


Figure 10: PBTD model

Table 6: PBTD & PBTK

	PBTK (Blood Concentration in Organs)		PBTD (parameters of heart)	
	Liver	Kidney	Heart Rate	Cardiac Output
Cigarettes(1.2mg)				
3.6mg	0.0355	0.09026	71.27	4.704
9.6mg	0.0383	0.1135	71.4	4.712
16.8mg	0.0416	0.1334	74.64	4.926
Dermal patches				
7mg	0.0371	0.04376	71.2	4.699
14mg	0.0403	0.1019	71.49	4.718
21mg	0.0435	0.1213	72.06	4.756
Nicotine lozenges				
24mg	0.045	0.03168	71.69	4.732
48mg	0.056	0.02716	72.18	4.764
96 mg	0.078	0.09358	73.16	4.829

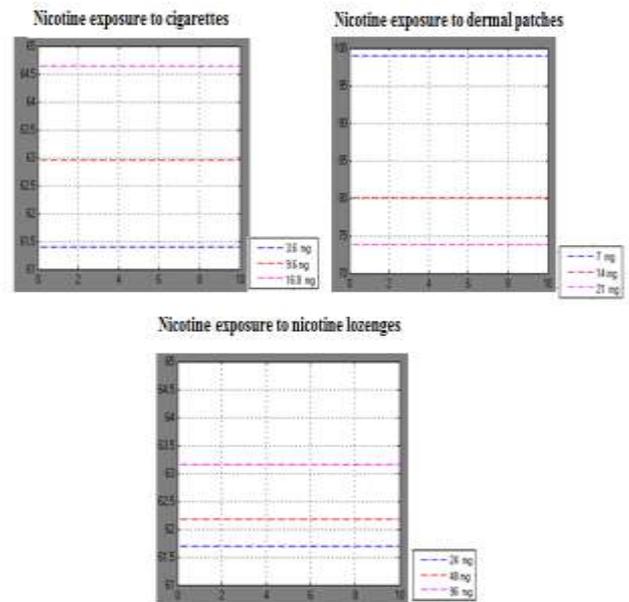


Figure 10: a) simulation result for PBTD modeling

As a result from this modeling it is analyzed that the rate of heart rate increases gradually based on the nicotine intake.

The table no:6 comprises of all information about the effect of blood concentration in liver, kidney and also the changes of heart rate and cardiac output based on nicotine intake which is analyzed in PBTD and PBTK modeling.

**Combined heart and lung model**

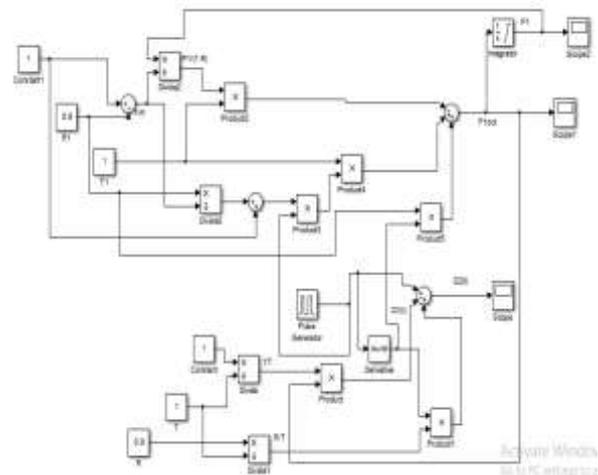


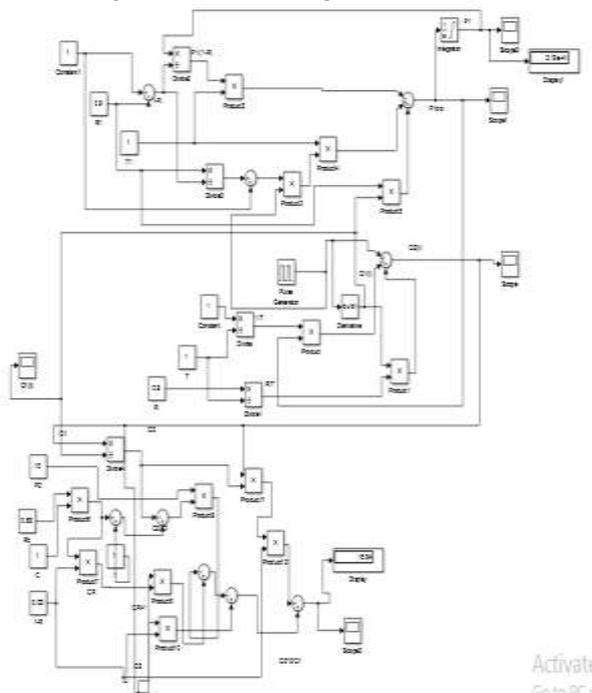
Figure 11: Model for combined heart and lungs.

By relating the heart and lungs, their modeling is done with the help of MATLAB/ Simulink. Here the pressure P1(pulmonary artery pressure) is determined which is given as input to the compliance chamber.

Thus the above modeling of heart- lung is simulated based on the equation 17 which is discussed in the paper by Jonathan et al.,. Before heart-lung model, the pulmonary artery pressure from right ventricle is determined which is given as input to the lung. Figure 7 shows the right ventricular pressure with respect to time (P1).

The compliance chamber designing is done in order to increase its efficiency based on the electrical network which

is mentioned in the figure 5. This compliance chamber is combined along with the heart-lung model .



**Figure 12:** Compliance chamber model along with heart lung

## Conclusion

As a result the acute effect of nicotine in human organs using Physiology Based Toxicokinetics (PBTk) and Physiology Based Toxicodynamics (PBD) modeling for various nicotine dosages and their effects on acute increase in blood concentration and heart rate is analyzed, however the effects of smoking on heart rate are definitely higher than any of the investigated methods for nicotine therapy. The apparent clearance of nicotine was slower in smokers than in non-smokers. The cardiac output for the analyzed heart rate is determined as well as the pressure and blood flow from the heart is given as input to the compliance chamber. The efficiency of the assisting device is increased by means of designing compliance-chamber.

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