An Electrical Model for Bronchitis and Emphysema of Human Respiratory System

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ABSTRACT: *In this paper, we have developed an electrical model which mimics two respiratory diseases. The electrical circuit is analogous to the actual anatomical structure of the breathing system and composed of the passive electrical components(R, Land C). The transfer function is derived from the electrical model. Different time-domain responses are observed from the transfer function to study the alveoli and respiratory tract conditions for qualitative assessment of bronchitis (due to narrowed bronchial tubes) and emphysema (due to air pollutants, smoking etc.) For each of the diseases we have considered its three different qualitative stages or levels e.g. moderate, good and poor for productive analysis.*

Keywords: *Bronchitis, Emphysema, Transfer function, Time-domain responses.*

I. INTRODUCTION:

The **respiratory system** (or **ventilatory system**) is the biological system of an organism that introduces respiratory gases to the interior and performs gas exchange. In humans and other mammals, the anatomical features of the respiratory system include airways, lungs, and the respiratory muscles. Molecules of oxygen and carbon dioxide are passively exchanged, by diffusion, between the gaseous external environment and the blood. This exchange process occurs in the alveolar region of the lungs. Other animals, such as insects, have respiratory systems with very simple anatomical features, and in amphibians even the skin plays a vital role in gas exchange. Plants also have respiratory systems but the directionality of gas exchange can be opposite to that in animals. [14]

The respiratory control system can also, under proper conditions, exhibit damped and sustained oscillation. Douglas and Haldane (1908) showed that after a period of voluntary hyperventilation several cycles of damped oscillation often occur [3], and in the clinical abnormality known as Cheyne-Stoke's respiration, the system continually overshoots and undershoots the regulated level and, thus, exhibits sustained oscillation. This study was designed to investigate the human respiratory control system. Its purpose has been, first, to derive the basic equations of the system and, secondly, to investigate the system as a biological regulator. This concept is not new; however the system has been analyzed mathematically only roughly. A simplified analysis was made by Grodins in 1954 in which CO2 was the only controller of ventilation considered; the tissue elements were lumped into a single reservoir, blood flow was held constant, and circulation times were considered to be infinitely short. Horgan and Lange (1963)[4] added circulation times and oxygen control to this basic model in order to study periodic breathing. Defares et al. (1960) extended Grodins' model by dividing the tissue reservoir into two distinct compartments, brain and body tissues and considering cerebral blood flow as a function of arterial Pco2. However, the effects of oxygen as a controller of ventilation and the effect of time delays in the transport of gases from the lungs to the two tissue reservoirs were not considered in this model because of their unimportance to the CO2 inhalation studies with which this model was concerned. These factors have all proved to be very important in describing the respiratory control system. They will be considered in detail in this analysis.[2][1]

II. RESPIRATORY PROBLEMS

In our present work we are concentrating on two major conditions i) breathing problems due to narrowed bronchial tubes ii) emphysema due to air pollutants etc.[15]Breathing problems occur when the bronchial tubes become constricted, or when the alveoli lose their elasticity and have difficulty forcing the carbon dioxide out.[8][12]

Acute bronchitis is an inflammation of the bronchial tubes of the lungs. Severe bronchitis (usually caused by a viral infection) narrows these passages and secretes mucus. As a result, the impedance (R_b and L_b) of the electrical circuit, equivalent to the bronchial airways, rise abnormally as shown in figure1.The increase in impedance causes a reduction in current flow through the circuit. [10]

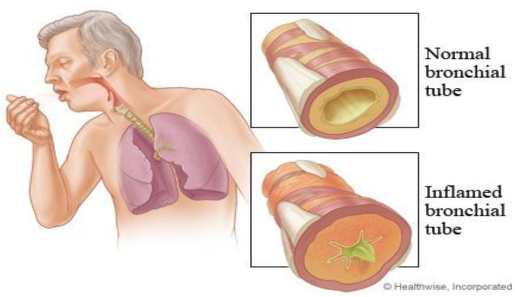


Fig.1: Normal and abnormal bronchial tubes [4]

We studied the status of alveoli due to extreme atmospheric pollution and human habits (like smoking etc.) Millions of tiny, flexible air sacs called alveoli connect to the bronchial tubes and blood vessels. This is where fresh air (oxygen) is exchanged with carbon dioxide from the blood. Air pollutants stimulate the production of elastase, which weakens the elasticity of the alveoli. When a substantial amount of elasticity is lost, the alveoli have difficulty pushing the carbon dioxide out, and one may have a dangerous condition called emphysema. The alveolar elasticity is described through its compliance (Fig.2) i.e. in the electrical circuit the capacitance (C_{bo}) decreases.[10][7]

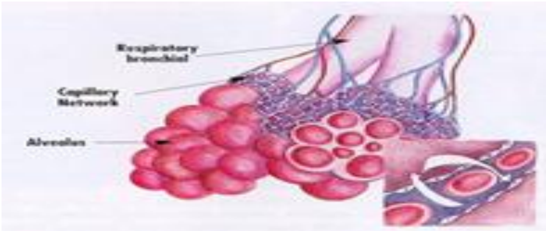


Fig.2: Status of alveoli

In first step, the equivalent electrical circuit of human respiratory system is designed considering the bronchial airways as the resistances and alveoli as the capacitors of the electrical circuit.
In second step, the transfer function of the equivalent electrical circuit is derived.
In third step, we studied the performance of the respiratory system through stability analysis.

III. THEORY

In the equivalent circuit, the electrical passive components represent different parts of lungs. Rt represents the trachea (an air way with largest cross-sectional area among the respiratory air ways). Rb1 and Rb2 are meant for the main bronchi (both left and right) (Bronchi are air paths with smaller cross-sectional areas relative to the trachea). [6][1]

The assembly, comprising of bronchiole and cluster of alveoli (Fig.2)is shown through Zbo in Fig.3. Zbo is a series combination of a resistor and an effective capacitor (So, alveolus, acting as an air sack, is supposed to carry the same quantity of air. The alveolus may be well thought-out an electrical analog of a capacitor.)

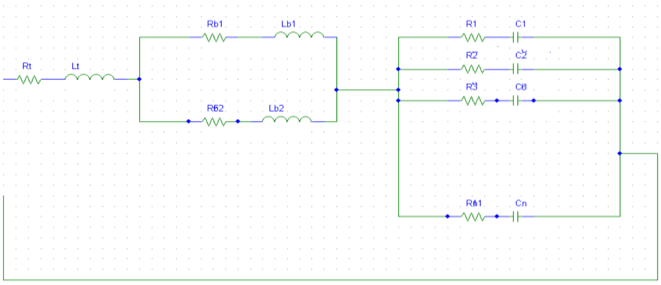


Fig.3: Electrical circuit of the respiratory system

IV. TRANSFER FUNCTION OF THE RESPIRATORY SYSTEM

We have derived the transfer function of the respiratory system based on the electrical circuit (Fig.2). It is known that alveolar number is closely related to the total lung volume. Hence one can say that larger the volume of lung more will be the alveoli. Here, we have considered the mean alveolar number as 480 million (range 274-790 million, coefficient of variation 37%). The mean volume of an alveolus is constant irrespective of the lung size [1, 2].[11]

$$z(s) = Rt + Lts + \frac{\{Rb1Rb2 + s(Lb1 + Lb2) + Lb1Lb2s^2\}}{\{Rb1 + Rb2 + s(Lb1 + Lb2)\}} + (sRCbo + 1)/nsCbo$$

$$\begin{aligned} z(s) = \{ & s^3(nCboLtLb1 + nCboLtLb2 + nCboLb1Lb2) \\ & + s^2(nCboLtRb1 + nCboLtRb2 + nCboRtLb1 + nCboRtLb2 + nCboLb2 + nCboLb1 + RCboLb1 \\ & + RCboLb2) + s(nCboRtRb1 + nCboRtRb2 + nCboRb1Rb2 + RCboRb1 + RCboRb2 + Lb1 + Lb2) \\ & + (Rb1 + Rb2)\}/\{nsCbo(Rb1 + Rb2 + s(Lb1 + Lb2))\} \end{aligned}$$

$$y(s) = \frac{1}{z(s)}$$

$$y(s) = \{nsCbo(Rb1 + Rb2 + s(Lb1 + Lb2))\} / \{s^3(nCboLtLb1 + nCboLtLb2 + nCboLb1Lb2) + s^2(nCboLtRb1 + nCboLtRb2 + nCboRtLb1 + nCboRtLb2 + nCboLb2 + nCboLb1 + RCboLb1 + RCboLb2) + s(nCboRtRb1 + nCboRtRb2 + nCboRb1Rb2 + RCboRb1 + RCboRb2 + Lb1 + Lb2) + (Rb1 + Rb2)\}$$

$$\text{The transfer function} = \frac{I(s)}{V(s)} = Y(s)$$

SIMULATION TOOLS:
The stability analysis of the equivalent electrical circuit is done in MatLab platform. Here, we used MatLab7.0 software: To study the response of emphysema and To study the response of bronchitis for step and ramp input.

PARAMETERS:
Impedance of trachea – Rt and Lt
Impedance of main bronchi (left) - Rb1 and Lb1
Impedance of main bronchi (right) -Rb2 and Lb2
Resistance of the bronchial airways –R
Compliance of the alveoli- Cbo

Rt (unit)	Rb1 (unit)	Rb2 (unit)	R (unit)	Lt (unit)	Lb1 (unit)	Lb2 (unit)	Cbo (unit)
4.5	9	9	0.5	0.043	0.17	0.17	0.01

V. RESULTS AND DISCUSSIONS

Condition 1: To study the response of emphysema

We have observed the responses of the respiratory system for emphysema with three different stages. i) average ii) good and iii) poor alveoli status. For average status we have assumed that the air ways impedances are constant and the electrical compliance is averaged with c=0.001 unit. Figs.4 (a) and (b) give the ramp and step responses. Output due to the ramp input quickly attains the steady state whereas the step sensation gives a damped sinusoid output resembling a second order underdamped system.

Stage1: We studied the performance of the respiratory system through stability analysis taking values of Rt= 4.5unit, Rb1=9 unit, Rb2=9 unit, R=0.5 unit, Lt=0.043 unit, Lb1=0.17 unit, Lb2=0.17 unit, Cbo= 0.001 unit in the electrical circuit [Fig 4] as standard and we got transfer function as

$$\frac{0.00034s^2 + 0.018s}{0.00004352s^3 + 0.002814s^2 + 0.511s + 18}$$

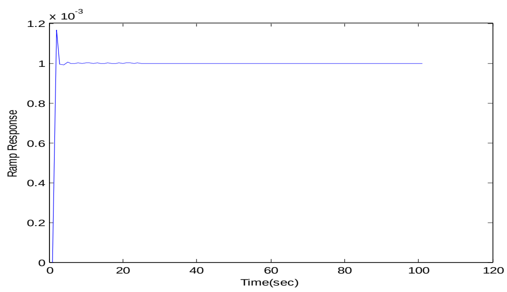


Fig.4 (a)

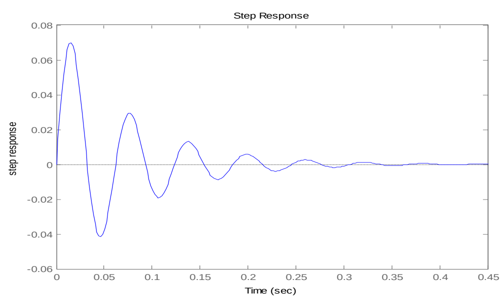


Fig. 4 (b)

Fig. 4 Avearge alveoli condition with compliance C=0.001 unit (a) Ramp response (b) Step response.

Stage2: Ramp and step responses are exact replica of each other when the patient's alveloi are at good condition as reflected in figs5 (a) and (b). Here keeping the air tract impedances unchanged we have altared the alveolar compliance to 0.01 unit. The transfer function was derived as

$$\frac{0.0034s^2+0.18s}{0.0004352s^3+0.02814s^2+2.05s+18}$$

taking Cbo=0.01 unit. The transients are dying out very quickly indicating a more stable alveolar state.

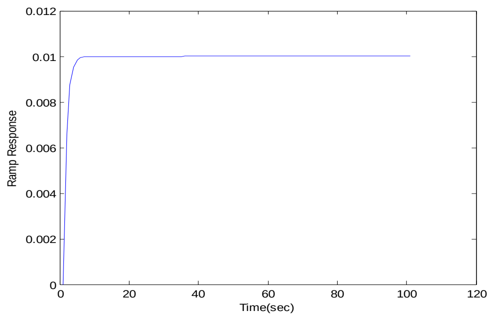


Fig.5 (a)

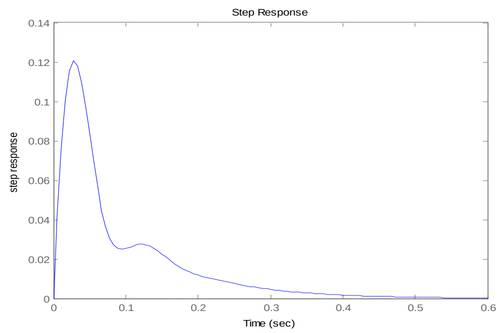


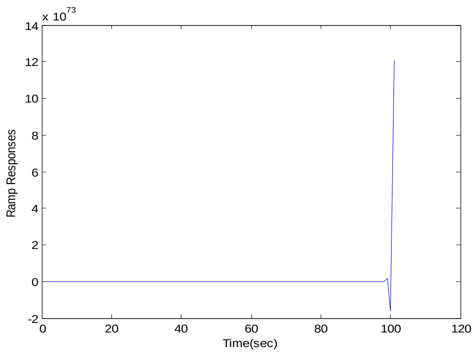
Fig. 5 (b)

Fig. 5 Avearge alveoli condition with compliance C=0.01 unit (a) Ramp response (b) Step response.

Stage3: Alveoli condition deteriots due to air polutants ,as a result the alveolar compliance decreases.We have followed the same analysis with ramp and step inputs choosing a value of C_{bo} =0.0001 unit.

Here we were taking Cbo=0.0001 in the transfer function (became $\frac{0.000034s^2+.0018s}{0.00004352s^3+0.0002814s^2+.3571s+18}$).

The ramp and step responses are shown in Fig. 6 (a) and (b).



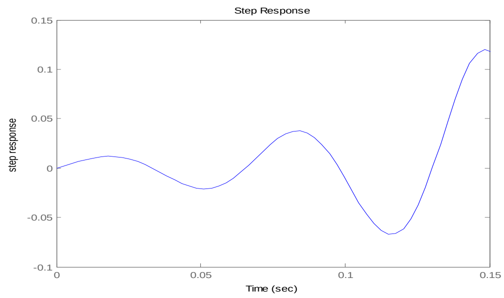


Fig. 6(a) & (b)

Fig.6 Depiction of poor alveoli condition with c= 0.0001 unit through (a) ramp response (b) step response

Condition 2: **To study the response of bronchitis**

To study the responses of bronchitis, we changed the values of R, Rt, Rb1, Rb2, Lt, Lb1, Lb2 to 1000 times to the standard values of each one respectively in the transfer fuction taking Cbo=0.001unit. The required tranfer function to plot step response [Fig 7] and ramp response[fig.8]becomes

$$\frac{0.34s^2 + 18s}{43.52s^3 + 2474.34s^2 + 171340s + 18000}$$

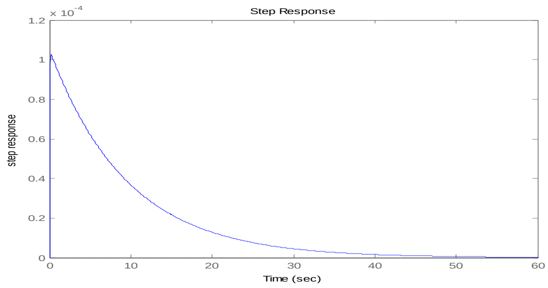


Fig. 7 Step responses with c = 0.001 unit

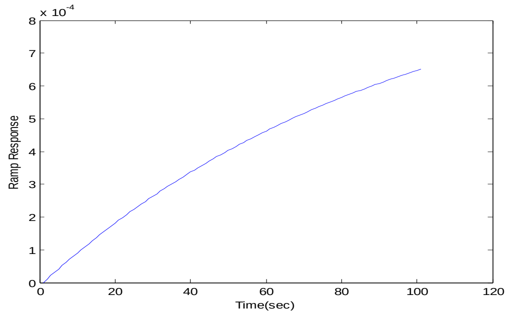


Fig 8: Ramp response taking all values of R and L 1000times to standard and Cbo=0.001 unit.

In the Fig. 8 the transients are decreasing towards time axis very slowly. It meets time axis arround 50 sec, which is very slow. The ramp response also deviating from the standard one. The impedance (R_b and L_b) of the electrical circuit, was changed, narrows the passages and secretes mucus of the lung.

VI. CONCLUSION

This paper discussed about the study of i) breathing problems due to narrowed bronchial tubes ii) emphysema due to air pollutants etc. With increasing the impedances the system attains the stability very slowly [Fig. 7 and 8]. It takes more time (approximate 49.55 seconds more) to stable. After discussing Fig. 4, 5 and 6 we can conclude that the alveolar compliance is directly proportional with the stability of the respiratory system. The tansfer function can be used to study the *chronic obstructive pulmonary disease (COPD)*, Pneumonia.

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