MATLAB/Simulink Mathematical Model for Lung and Ventilator

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Abstract*— Patients diagnosed with positive coronavirus results suffer from difficulties in breathing and major drop in blood oxygen saturation. This could lead unfortunately to a possible death if not treated well. Thus, this has increased the demand for the medical mechanical ventilators worldwide. The idea behind this work is development of a computational model for the study of the impact of different ventilation modes on patient's respiratory system generally, and lungs more specifically. This model has been created using Matlab/Simulink platform. The studied ventilation mode is the Pressure Controlled Ventilator (PCV) signal combined to single and two compartmental models in series and in parallel mathematical models configuration of the lungs that represent the respiratory system parameters for testing. The ventilator's setup includes the following parameters: positive end-expiratory pressure (PEEP), pressure wave, respiratory rate (RR), tidal volume, and others. By changing one of these parameters, we can monitor how this will affect the lungs by checking the volume, flow and PV loop for each lung mode. Simulation results have been recorded and are promising because this allows to study any type of ventilation modes conventional or novel ones virtually without the need to jeopardize the life of human subjects during clinical trials.

Keywords—PEEP, Mathematical model, Lung model, Pressure controlled ventilator, Mechanical ventilator, PV-loop, MATLAB/Simulink and Simscape.

I – INTRODUCTION

Mathematical model (MM) is a presentation of a system using a mathematical concept. The process of developing these type of systems is termed as mathematical modeling. The availability of amazing computational software with useful and powerful tools, such as Matlab, Labview and other platforms, has facilitated the creation of computational models for studying these MMs, and performing simulations under different conditions and senarios.

The development of computational MM of the respiratory system with a ventilator plays an important role in testing novel modes of ventilation as well as upgrading conventional ones, such as volume-controlled ventilation (VCM), and assist control ventilation in normal and abnormal tests [1]. The Pressure Controlled Ventilator (PCV) is one of the many modes of ventilation used to support the lungs facing breathing problems.

PCV mode has been used in oour work because it is one of the most common modes used for adults, pediatrics, and neonates ventilation [2]. Furthermore, the parameters used in PCV mode setup are: positive end-expiratory pressure (PEEP), tidal-volume, inspiratory to expiratory (I:E) ratio …etc.

Recently, the lungs are represented as a series or parallel one or two-compartmental electrical circuits, and converted to a mathematical model by their transfer functions [3]. These electrical circuits represented as the resistance and compliance of the lungs by resistors and capacitors respectively.

In this paper, modeling and simulation of the PCV signal are demonstrated. This PCV signal represents the breathing activities (inspiration and expiration cycles) with an important controlled parameter during the mechanical ventilation process, which is the Positive End-Expiratory Pressure (PEEP). This PCV mathematical model is applied using periodic functions with inequalities representing the beginning and the end of the inspiration and expiration activity cycles [4].

To have complete model representing the system, the mathematical model of the PCV signal is combined with one of the several mathematical models of the lungs (single or multi-compartmental models) [3]. Changes are applied to the input variables of the PCV signal, such as inspiratory pressure (*IP*), inspiratory duration (T_{in}), and PEEP. This has been applied to the mathematical model of the lungs to check the result, and monitor the effectiveness of the suggested method.

The system is modeled by the Matlab/Simulink package in the Matlab platform. It represents the pressure wave of PCV signal applied to the lungs model. The outputs will include the patient lungs' volume and airways flow, which are monitored as continuous waveforms during the real mechanical ventilation process for normal and abnormal cases. Moreover, the simulator displays the pressure/volume (PV) loop of the modeled lungs during ventilation.

The rest of the paper is divided into three sections, and a conclusion. The first section describes briefly the related works. The second part represents the methodology and designing of our proposed model. Finally, the results are analysed in the third section. The conclusion part shows the importance of modeling in the biomedical field generally through this development of such computational model representing both medical ventilator with a patient respiratory system.

II – RELATED WORK

Modelisation and simulation of any system are very important in biomedical engineering domain especially the models representing the respiratory system due to its importance in saving human life. Systems can be modeled by several simulation programs such as LabView or Matlab/Simulink [5][6].

In this computational MM of PCV ventilation mode with lungs model, PCV output signals can be represented using linear, quadratic and exponential equations that combine with already MM of a healthy lung. This model is represented by PEEP to reflect the efficiency of the respiratory activities. The

PCV output signal (pressure), and the modulated output signals of ventilation (flow and volume) are recorded from the developed computational system model. The figure 1 shows the main components of Maltab/Simulink system model, which includes three major components: ventilator model, lungs model and the results' display (screen).

In addition, the Matlab/Simluink program displays the dynamic compliance that reflects the patient response during artificial ventilation process. Finally, the model can present the output signals of PCV during artificial ventilation for an ideal case (healthy lung) and a practical case (unhealthy lung) [6].

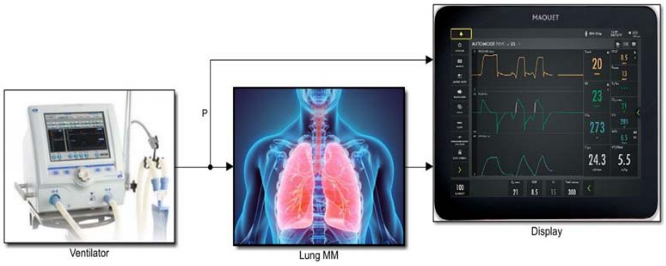


Figure 1: Subsystems' block diagram.

IV – METHODOLOGY AND SYSTEM DESIGN

Figure 2 shows the block diagram of the proposed method of the computational MMs combination representing the full system of the lungs with the medical ventilator. It includes the MM of the PCV, which gives the pressure wave output applied to the single and multi-series and parallel-compartmental models of lungs. Respiratory system compartmental models laterally are converted to mathematical models represented by their transfer functions.

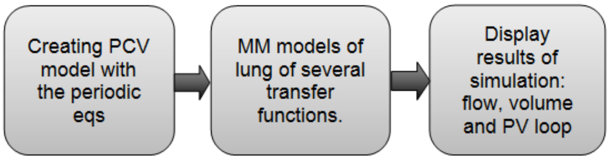


Figure 2: Block diagram of the proposed method of MMs' combination.

4.1. Modeling the PCV signal with PEEP

Figure 3 shows the block diagram of the ventilator. The PCV model gives a real pressure wave that represents the breathing (inspiration and expiration) cycle of human lung. It gives information about the inspiration pressure (*IP*), inspiration and expiration durations, and the respiratory rate (breathing per minute) depending on the total cycle time.

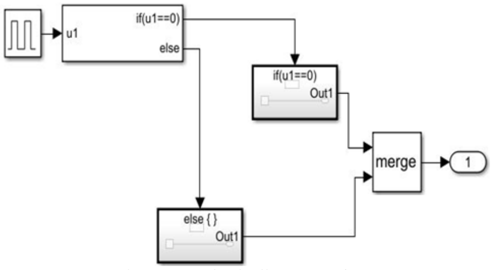


Figure 3: Block diagram of PCV.

MM for Pressure Controlled Ventilation Signal

Figure 4 shows the pressure waveform of the PCV signal and its components of normal (a) and abnormal (b) cases: inspiratory pressure (*IP*), inspiratory duration (T_{in}), expiratory duration (T_{ex}), breathing cycle (*BPM*), and PEEP.

The pressure signal of the normal case and the abnormal case are obtained from the PCV model depend on the values of the parameters that formulates these pressure waveforms. Table 1 shows the parameter values of the normal and abnormal cases.

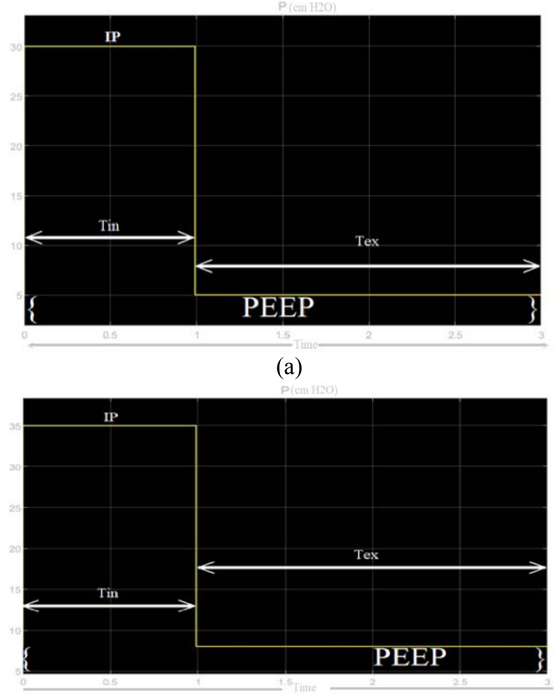
The waveforms shown in Figure 4, represent the inspiratory and expiratory activity cycles. The pressure waveform of the PCV signal was expressed by the periodic functions as seen in equations (1) and (2).

$$P(t) = \begin{cases} Paw + PEEP & 0 \le t \le Tin \quad (1) \\ PEEP & Tin \le t \le Tex \quad (2) \end{cases}$$

Where:

P(t) – the pressure signal of PCV, PEEP – positive end-expiratory pressure, and Paw – pressure in respiratory airways.

The time-based function *P(t)* represents the ventilation pressure signal of PCV reflecting the respiratory activity cycles (inspiration and expiration). The pressure signal *P(t)* composed of inspiratory pressure (*IP*) plus expiratory pressure (*EP*). Therefore, equation (1) represents the IP during the inspiratory duration (T_{in}), while equation (2) represents the EP during the expiratory duration (T_{ex}) assuming that EP = PEEP.



(a)

(b)

Figure 4: Pressure waveform of PCV signal, (a) normal case (b) abnormal case.

Although, parameters in this pressure signal waveform are considered for a normal adult with an approximate time of inspiration ranges between 0.7 and 1 second [7].

- The total cycle time (*TCT*) is measured by the equation (3) as seen: $TCT = Tin + Tex$. So, the TCT of this pressure cycle is written as follows:

$$TCT = 1\,sec\,(Tin) + 2\,sec\,(Tex) = 3\,\text{sec} \qquad (3).$$

- The Respiratory Rate (RR) is obtained by the following equation (5).

$$RR = \frac{1\,min}{TCT} = \frac{1\,min}{3\,sec} = \frac{60\,sec}{3\,sec} = 20\frac{breaths}{min} \quad (4).$$

Which is a normal value of RR of an adult since it ranges between 10 – 20 breathes per min [7].

Table 1: Parameter values of the PCV signal.

Parameters	IP	PEEP	T_{in}	RR (breaths/min)
Normal case	25	5	1	20
Abnormal case	27	8	1	20

4.2. Modeling the Respiratory System

Lungs can be modeled as mechanical systems. In this system, we are using the electrical circuits representing lungs where the pressure, flow, and volume are represented by voltage, current, and charge. The mathematical models of the lungs can be represented by the transfer functions of one and multi-compartmental models (series and parallel). The most common electrical circuits used to model the lungs are of R-C circuit, with a voltage source where the resistance and the compliance are represented by resistance and capacitance respectively.

4.2.1. One compartmental model

The one-compartmental electrical circuit is done in Simscape shown in Figure 5.

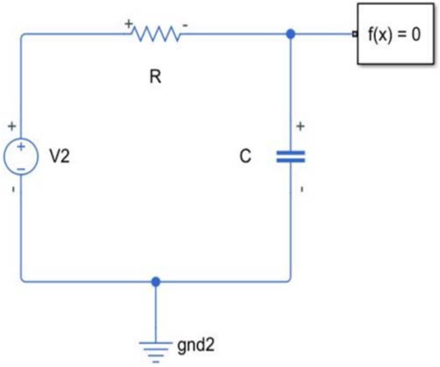


Figure 5: One-compartment electric circuit.

This electrical circuit is transferred to a mathematical model after deriving its transfer function H: $H = \frac{1}{RC.s+1}$; where Z=RC is the impedance of the electrical circuit. This transfer function changes depending on the values of R and C in the circuit.

Where R=2 cm H2O/L/s
C=0.1 L/cm H2O

4.2.2. Two-compartmental model

i- Series:

The mathematical model of the lungs represented in this part is the one suggested by Khoo [8], a series multi-compartmental model. This model is the same as the previous one combined with the MM of the PCV signal to form the whole system for normal, and abnormal cases. The MM, in this case, uses the following transfer function

$$H = \frac{s^2+\left(\frac{s}{R2.C2}\right)}{R1.s^2+\left(\frac{1}{C1}+\frac{R1}{R2.C2}\right).s+\left(\frac{1}{R2.C1}\right).\frac{1}{C2}} \quad (5)$$

ii- Parallel:

The parallel two-compartmental model is created using by Simscape as shown in Figure 6.

Where C1 and C2 represent the lung's compliance, while Rc1 and R2 represent the lung's resistance and the resistor R1 represents the central airway resistance that is added in this model's circuit. The transfer function is derived to obtain the mathematical model of this circuit.

$$H = \frac{s^2+\left(\frac{s}{R2.C2}\right)}{Rc1.s^2+\left(\frac{1}{C1.R1}+\frac{Rc1}{R2.C2}\right).s+\left(\frac{1}{R1.C1}\right).\frac{1}{R2}}. \quad (6)$$

Where the values of R and C are the same as that used in the series two-compartmental model.

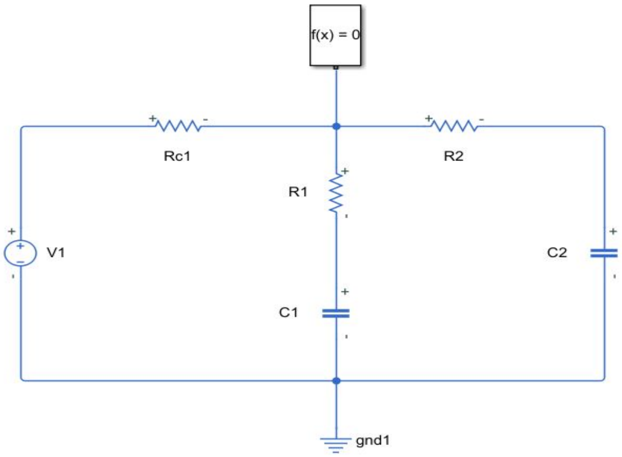


Figure 6: Parallel two-compartment electric circuit.

4.3. Displaying Results' Curves of PCV Signals

The output result waveform curves are derived and displayed by the constructed simulator. The flow (Q) is measured directly from the output of the simulator, then it is integrated into the volume (V). Finally, the dynamic compliance P-V Loop is calculated by equation $PV = {}^{\Delta V}/_{\Delta P}$ and graphically displayed.

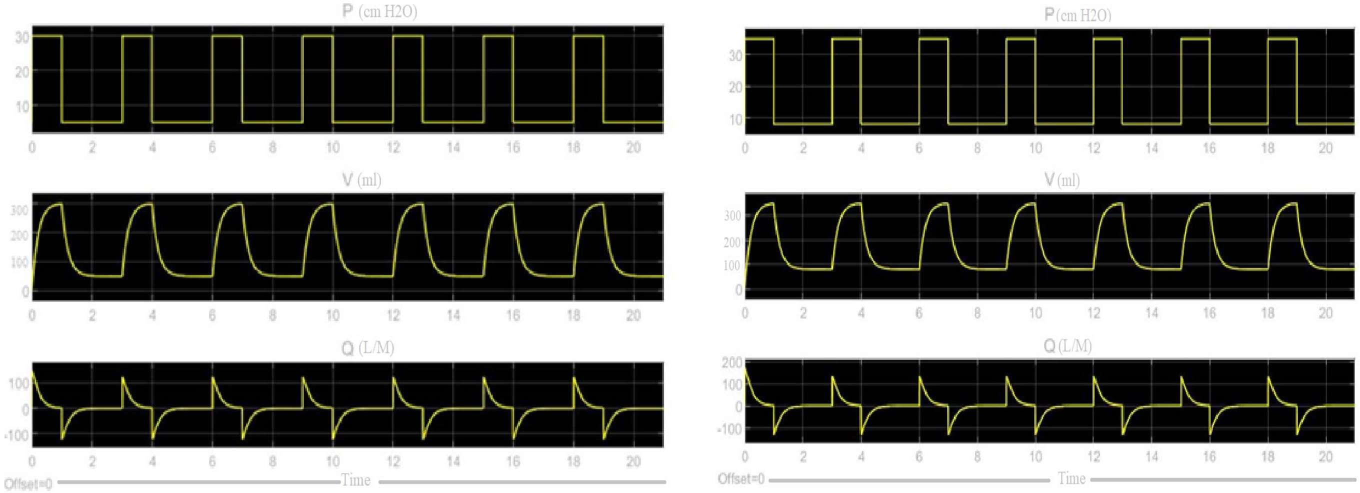
V – RESULTS AND DISCUSSION

The simulation results of the respiratory activities inspiration and expiration of the PCV in both cases the normal and abnormal applied to the several MMs of the lungs are illustrated graphically in the following Figures.

Figures 7, 8 and 9 show the results of pressure (P), volume (V), and flow (F) after applying the normal and abnormal cases of the PCV signal to the several MMs of the lungs illustrated above. These results indicate that the simulator can provide the monitoring respiration waveforms of instantaneous pressure, airflow, and lung volume; similar to the real monitoring waveforms system.

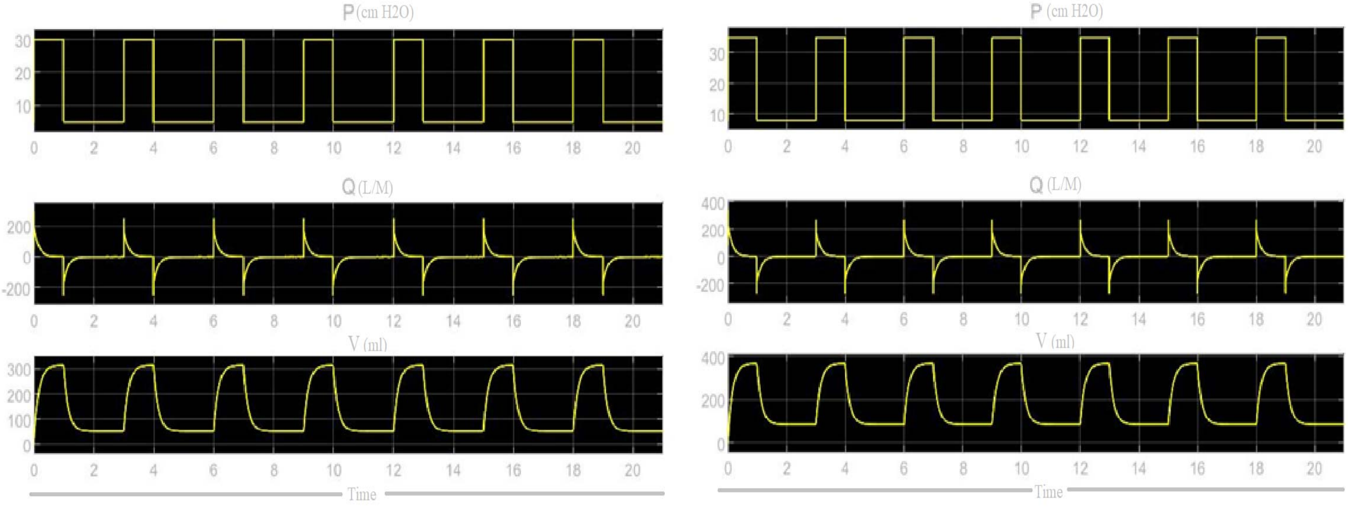
Figure 7(a) and 7(b) show the results when applying both cases of PCV signal to the one-compartmental lung model.

Figure 7(a) shows that the flow returns to zero at the end of the inspiratory cycle and it takes the inverse of the inspiratory flow at the beginning of the expiratory phase. The amplitude is (150L/min) at the expiration and inspiration and that is due to



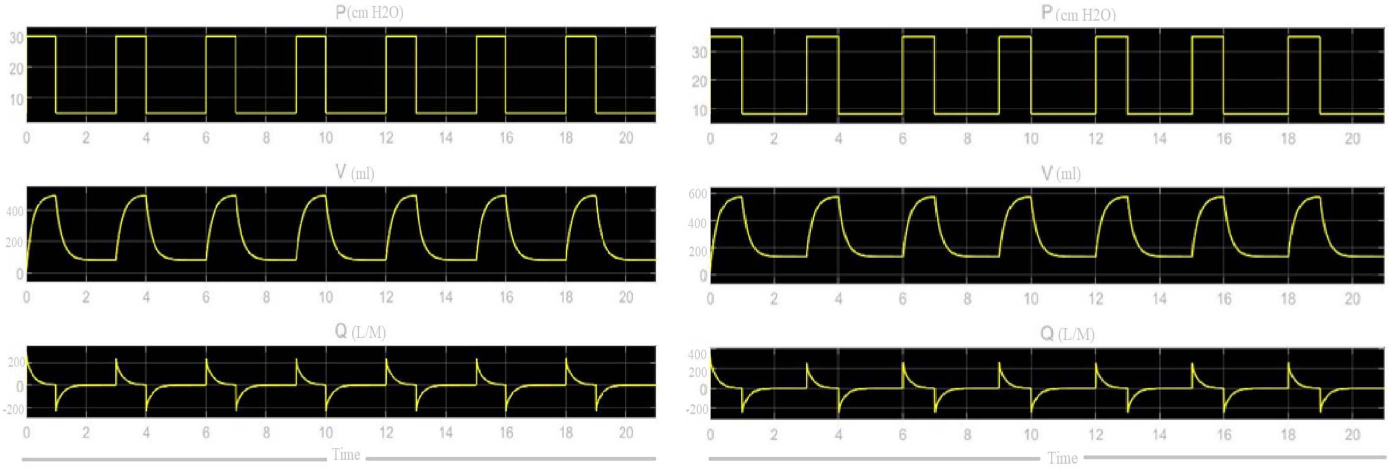
(a) (b)

Figure 7: Simulation results of the one-compartmental model (a) normal case (b) abnormal case



(a) (b)

Figure 8: Simulation results of the series two-compartmental model (a) normal case (b) abnormal case.



(a) (b)

Figure 9: Simulation results of the parallel two-compartmental model (a) normal case (b) abnormal case.

the constant duration of the inspiration and expiration cycles. The normal behavior of PCV is that the flow at the beginning of the inspiration takes a higher numerical value than that of the beginning of expiration. It also shows the waveform of the volume of the air in the inspiration and expiration cycles that gives the maximum value of 300ml which is normal value in adults.

Figure 7(b) shows the pressure, volume, and flow waveforms at IP=27 cm H2O and PEEP = 8 cm H2O. The waveforms stay the same in shapes except for the value of volume increased to approximately 350 ml.

Figure 8(a) and 8(b) show the results of applying both cases of PCV signal to the series two-compartmental lung model. Figure 8(a) shows the same results of the one-compartmental model except for a higher value of flow (200L/m) at the beginning of the inspiration and expiration. Figure 8(b) shows an increase in the tidal volume to 350 ml and the shape of the flow waveforms and volume stays the same.

Figure 9(a) and 9(b) show the results of applying both cases of PCV signal to the series two-compartmental lung model.

Figure 9(a) shows that the flow varies from the high value (200 L/m) at the beginning of inspiration and expiration, and the volume reaches a high value of approximately 500 ml.

Figure 9(b) shows that the shape of the waves stays the same with an increase in the volume and the flow at the beginning of the inspiration and expiration with a high value of approximately (300 L/m).

Figures 10, 11, and 12 show the curve of the dynamic compliance loop (P-V Loop). This loop can add important characteristics to the MMs and the simulators since these curves illustrate the relation between the volume and pressure that indicates the patient level response for mechanical ventilation.

The created MM of the PCV signal combined with the mathematical models of the lungs can represent the system of the mechanical ventilation simulator. This system simulator shows the results of the lung models susch as the flow, and volume after applying the pressure of the PCV signal to each model.

Moreover, the system shows the dynamic compliance of the lung which is the P-V loop that reflects the mechanical changes in the lungs.

VI – CONCLUSION

Computational modeling becomes an essential and major field in biomedical engineering domain that can be used to represent, simulate and develop a medical device connected to a patient. Computational models can be used to mimic virtually the hospital clinical situation, and consequently reduce the need to use human subject in clinical trials prior getting market approval such as FDA approval, CE Mark and others. This has been applied to study the performance of medical ventilator with human respiratory system. Precisely, PCV ventilation mode has examined with two lung models, one-compartment and two-compartment lung models. PCV ventilation parameters had been varied during the simulation to study its mechanical impact on lungs models. Results are promising, and encouraging further investigation for other ventilation modes. Additional parameters and more conventional as well as novel ventilation modes should be added and examined in the future work.

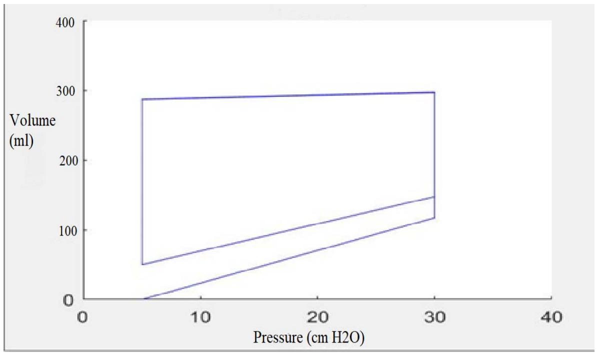


Figure 10: PV-Loop of the one-compartmental model.

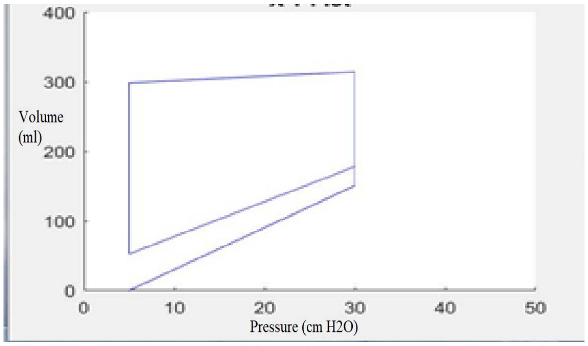


Figure 11: PV-Loop of the series two-compartmental model.

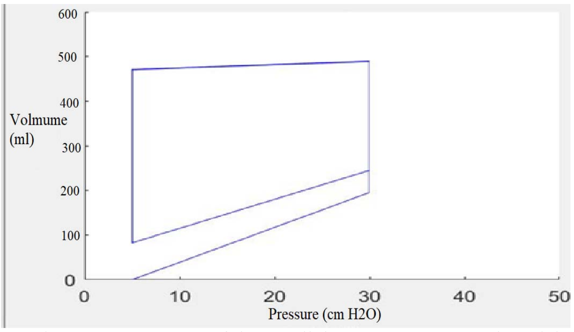


Figure 12: PV-Loop of the parallel two-compartmental model.

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