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Simulation of Respiratory Mechanics

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Submitted in partial fulfillment of the requirements for the module
BM2102 Modelling and Analysis of Physiological Systems

8 th April 2025

Contents

1 Introduction

Respiratory mechanics play a crucial role in understanding pulmonary function under various physiological and pathological conditions. The lungs and airways, through their compliance and resistance, regulate airflow and gas exchange within the human body. Simulation tools provide an effective method to visualize and analyze these mechanics, particularly in the context of respiratory diseases.

This report utilizes the simulator developed by David Leonardo Rodriguez Sarmiento and Daniela Acevedo Guerrero (2020), titled *Simulation of Respiratory Mechanics on Simulink with GUI*, available on the MATLAB Central File Exchange. The simulator enables real-time modeling of lung behavior through adjustable parameters representing various clinical conditions.

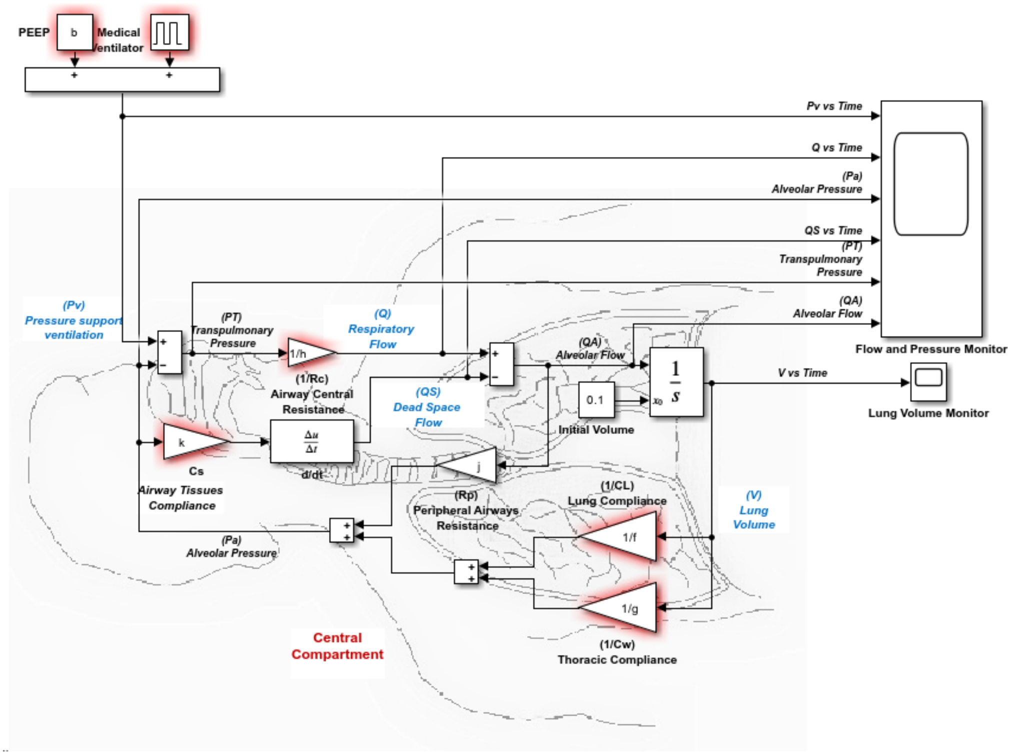


Figure 1: Simulink model of the respiratory system used for simulation

The objective of this assignment is to simulate three different respiratory conditions—normal, restrictive, and obstructive pulmonary scenarios—using consistent ventilator settings. By analyzing the resulting ventilation graphs, especially the minute ventilation, the report aims to highlight the physiological differences and challenges associated with each condition.

Understanding these differences can aid in both educational and clinical settings by reinforcing the impact of mechanical properties such as lung compliance and airway resistance on breathing dynamics.

2 Key Parameters of the Model

The system's structural overview highlights several visible components. Notably, both central and peripheral airways introduce airflow resistance, labeled as h and j respectively. Additional aspects like alveolar and dead space volumes also contribute to the simulation. However, the graphical user interface (GUI) mainly allows users to configure the following important variables.

2.1 Physiological Parameters

These parameters represent the biological characteristics of the lungs:

- **Lung Compliance** – Indicates how easily the lungs can expand during inhalation.
- **Thoracic Compliance** – Reflects the expansion capability of the chest wall.
- **Central Airway Resistance** – Denotes the resistance to airflow within the main airways (e.g., trachea).
- **Peripheral Airway Resistance** – Measures airflow resistance in smaller airways like bronchi and bronchioles.
- **Airway Tissue Compliance** – Represents the flexibility and stretchability of airway tissues.

2.2 Ventilator Parameters

Instead of simulating diaphragm function, this system employs an external ventilator to mimic the breathing cycle. The following ventilator settings can be adjusted to control aspects such as breathing rhythm:

- **Breathing Frequency** – Determines how often inhalation and exhalation occur.
- **Positive End-Expiratory Pressure (PEEP)** – Defines the pressure in the airways at the end of exhalation.
- **Peak Pressure** – Sets the highest pressure reached during the inhalation phase.

3 Simulation Under Normal Conditions

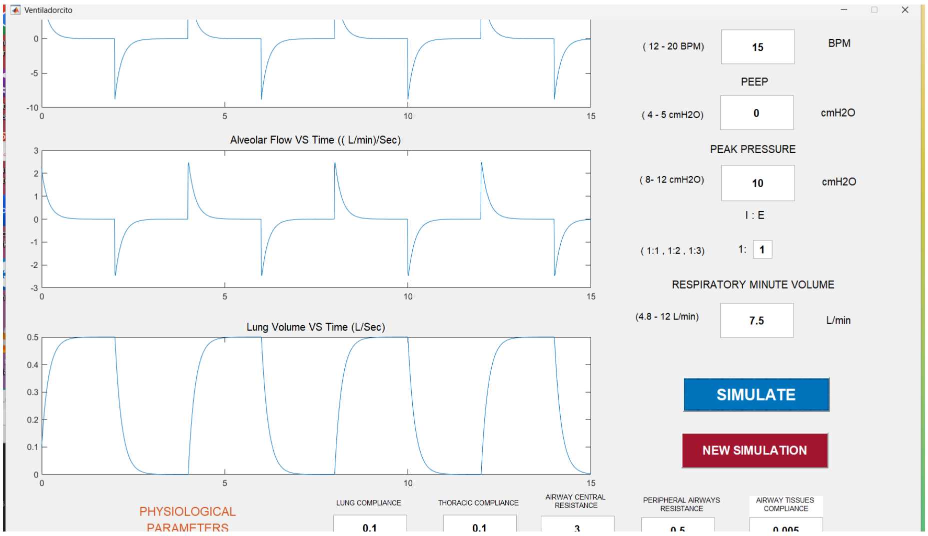
Following the approach demonstrated in the reference video, the physiological parameters were configured to reflect the respiratory function of a healthy individual. The values used for this simulation are as follows:

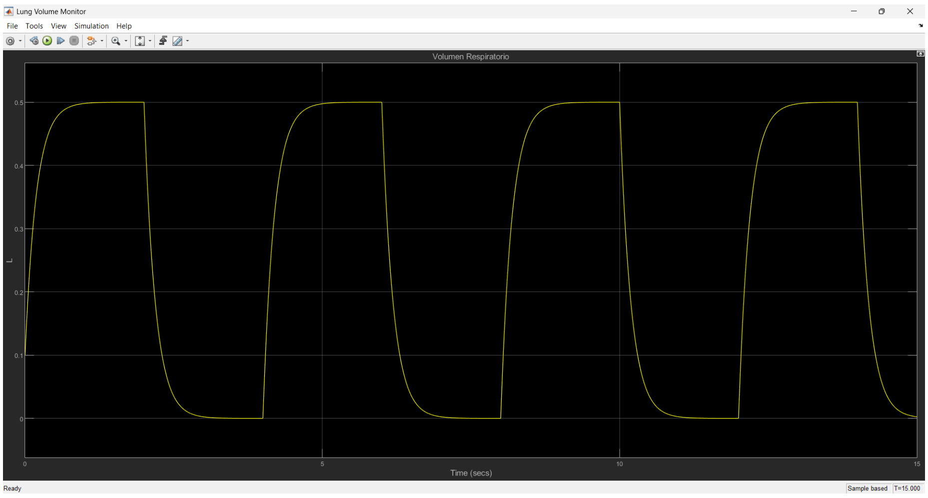
- **Lung compliance**: 0.1 L/cmH_2O
- **Thoracic compliance**: 0.1 L/cmH_2O
- **Central airway resistance**: 3 cmH_2O/L/s
- **Peripheral airway resistance**: 0.5 cmH_2O/L/s
- **Airway tissue compliance**: 0.005 L/cmH_2O

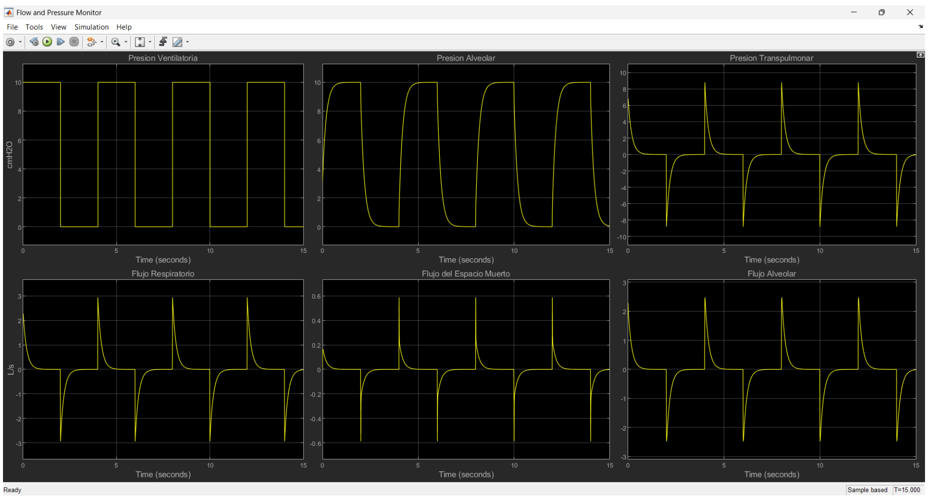
To maintain consistency across all simulations, the same ventilator settings were applied for each condition:

- **Breathing rate**: 15 breaths per minute (BPM)
- **PEEP**: 0 cmH_2O
- **Peak pressure**: 10 cmH_2O

The simulation results under these normal parameters are presented below.



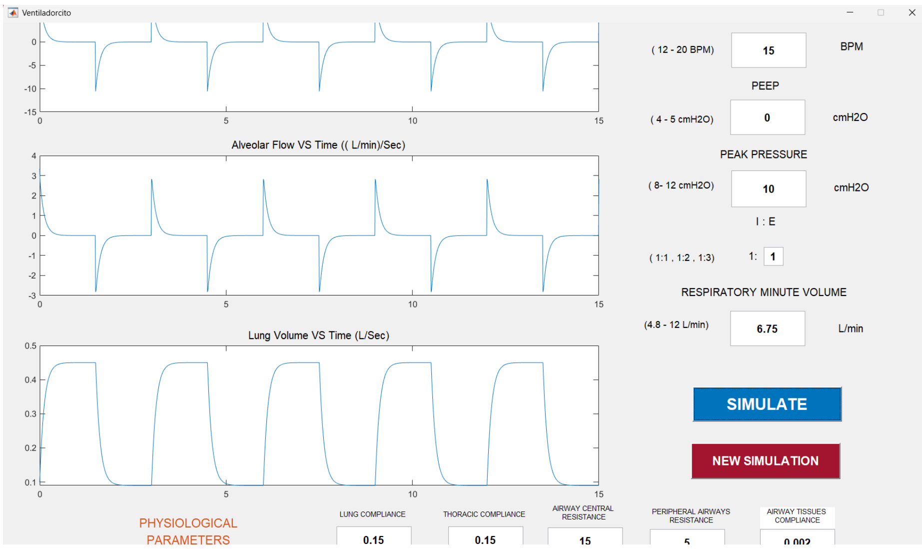




4 Simulation for Obstructive Lung Disease

Obstructive lung disease is characterized by increased resistance to airflow, particularly during exhalation, due to narrowed or blocked airways. Conditions like asthma, chronic bronchitis, and chronic obstructive pulmonary disease (COPD) fall under this category. In obstructive lung diseases, central and peripheral airway resistance significantly increase, which makes it harder for air to flow out of the lungs. To overcome this resistance, positive end expiratory pressure (PEEP) also rises above the normal range. And lung compliance may be slightly increased due to the loss of elastic recoil, as seen in emphysema. However, this is not always beneficial, as it leads to air trapping and hyperinflation. Thoracic compliance may also increase slightly, while airway tissue compliance may show a slight decrease due to inflammation or remodeling. To allow sufficient time for exhalation and prevent dynamic hyperinflation, the breathing rate is often reduced, usually below normal values. Patients with obstructive lung disease often exhibit prolonged exhalation and increased work of breathing due to the elevated airway resistance.
Considering following values for the selected obstructive pulmonary disease,

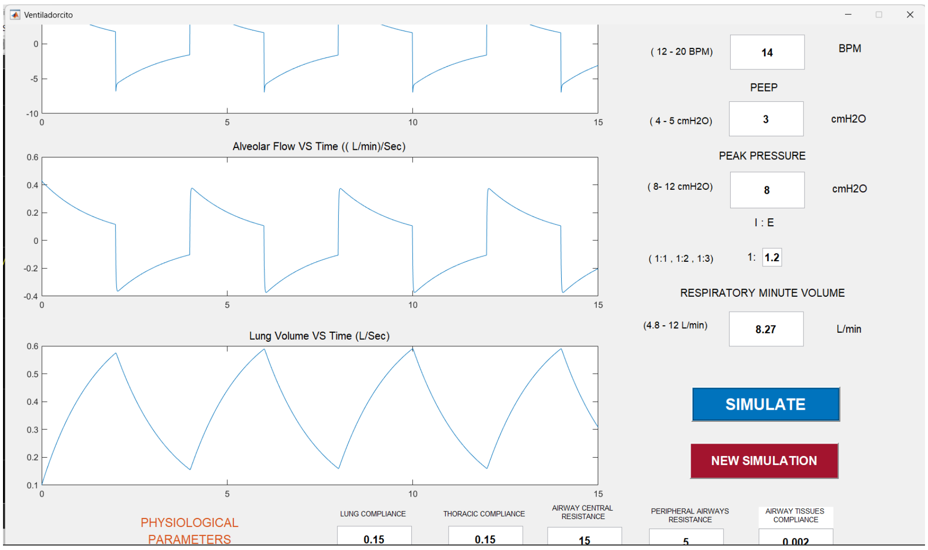
- **Lung compliance**: 0.15 L/cmH_2O
- **Thoracic compliance**: 0.15 L/cmH_2O
- **Central airway resistance**: 15 cmH_2O/L/s
- **Peripheral airway resistance**: 5 cmH_2O/L/s
- **Airway tissue compliance**: 0.002 L/cmH_2O

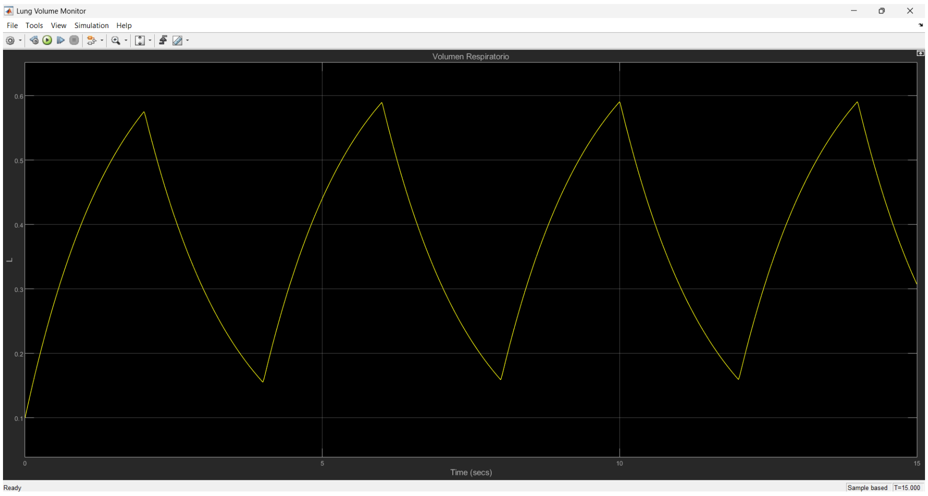


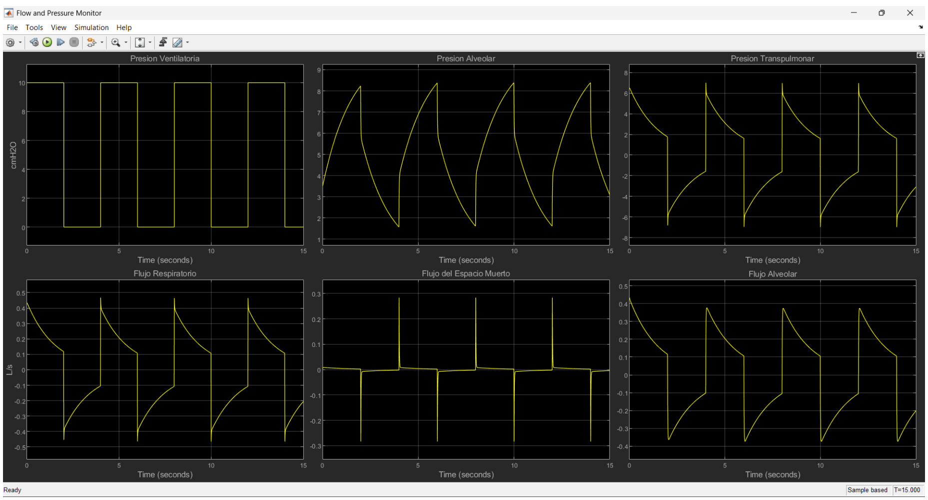
By adjusting the ventilator parameters,

- **Breathing rate**: 14 breaths per minute (BPM)
- **PEEP**: 3 cmH_2O
- **Peak inspiratory pressure**: 8 cmH_2O
- **I:E Ratio**:1:1.2

Following are the simulation results.





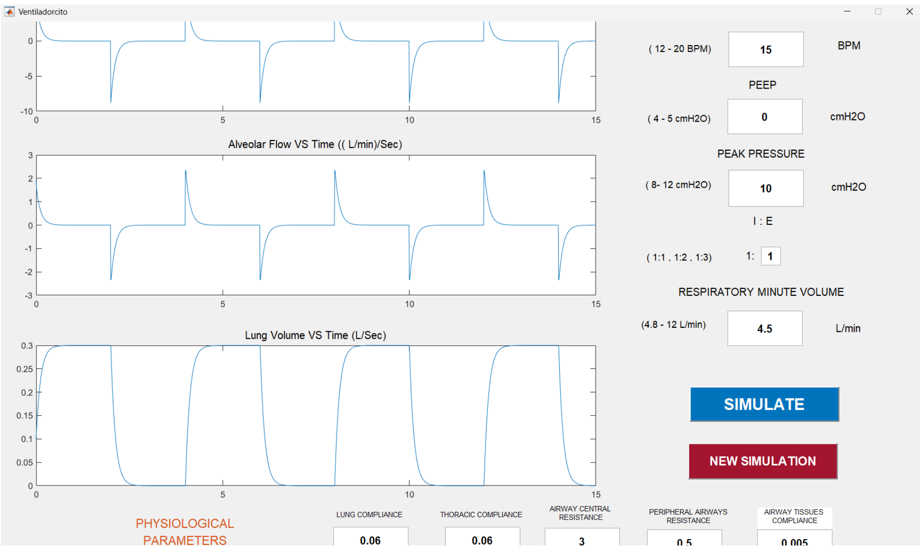


5 Simulation for Restrictive Lung Disease

Restrictive pulmonary disease is characterized by a reduction in lung expansion, leading to decreased lung volumes and impaired gas exchange. This condition typically results from stiff lung tissue (e.g., in pulmonary fibrosis), abnormalities in the chest wall, or neuromuscular disorders. One of the hallmark changes in restrictive disease is a decrease in lung compliance and thoracic compliance, which means greater pressure is needed to inflate the lungs. As a result, positive end respiratory (PEEP) increases significantly, often exceeding normal levels to deliver adequate tidal volumes. In the restrictive pulmonary disease airway central resistance, peripheral airway resistance and airway tissue compliance will not be changed significantly. Overall, restrictive pulmonary diseases result in a ventilatory pattern marked by shallow, rapid breaths and increased work of breathing.
Considering following values for the selected restrictive pulmonary disease,

- **Lung compliance**: 0.06 L/cmH_2O
- **Thoracic compliance**: 0.06 L/cmH_2O
- **Central airway resistance**: 3 cmH_2O/L/s
- **Peripheral airway resistance**: 0.5 cmH_2O/L/s
- **Airway tissue compliance**: 0.005 L/cmH_2O

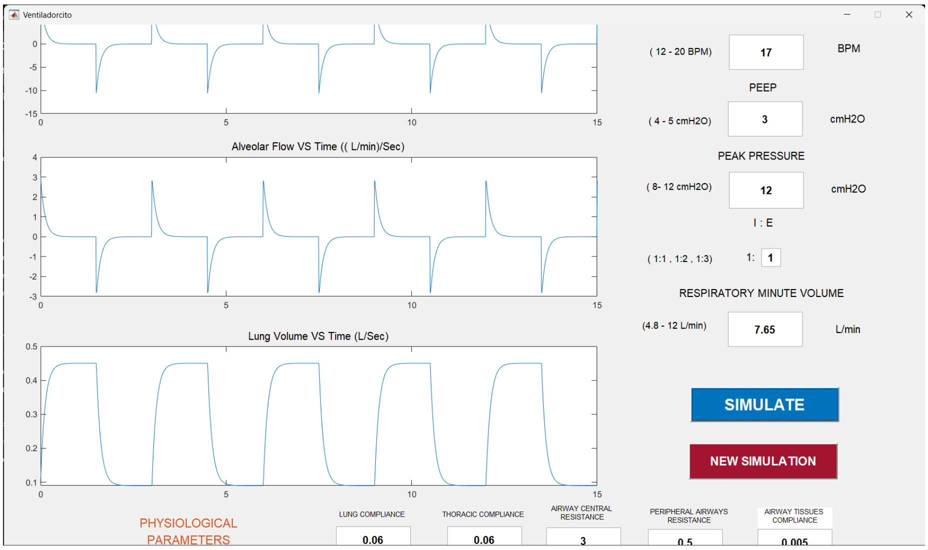
We can see the respiratory minute volume has been reduced.



By adjusting the ventilator parameters,

- **Breathing rate**: 17 breaths per minute (BPM)
- **PEEP**: 3 cmH_2O
- **Peak inspiratory pressure**: 12 cmH_2O
- **I:E Ratio**:1:1

Following are the simulation results after ventilator parameters are adjusted.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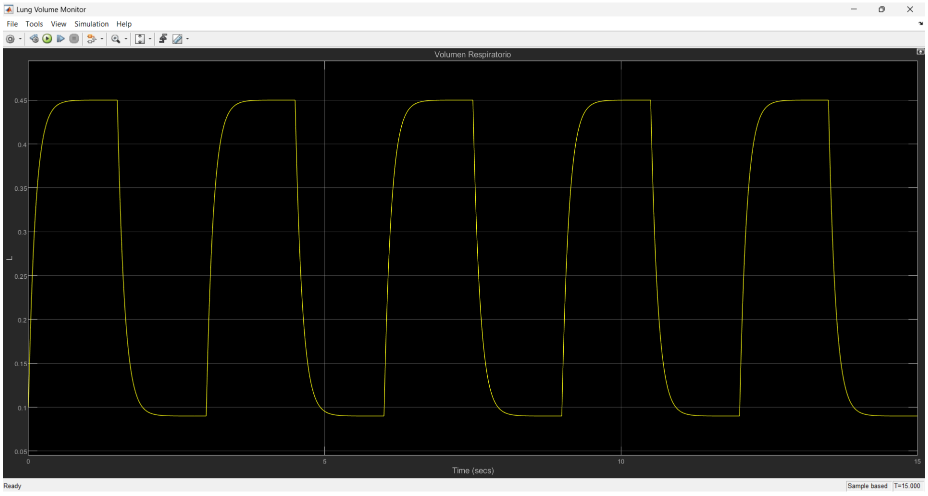
Alveolar Flow VS Time ((L/min)/Sec)
Lung Volume VS Time (L/Sec)
(12 - 20 BPM)
17
BPM
PEEP
(4 - 5 cmH2O)
3
cmH2O
PEAK PRESSURE
(8- 12 cmH2O)
12
cmH2O
I : E
(1:1 , 1:2 , 1:3)
1:
1
RESPIRATORY MINUTE VOLUME
(4.8 - 12 L/min)
7.65
L/min
SIMULATE
NEW SIMULATION
PHYSIOLOGICAL PARAMETERS
LUNG COMPLIANCE
0.06
THORACIC COMPLIANCE
0.06
AIRWAY CENTRAL RESISTANCE
3
PERIPHERAL AIRWAYS RESISTANCE
AIRWAY TISSUES COMPLIANCE


Lung Volume Monitor
File Tools View Simulation Help
Volumen Respiratorio
Time (secs)
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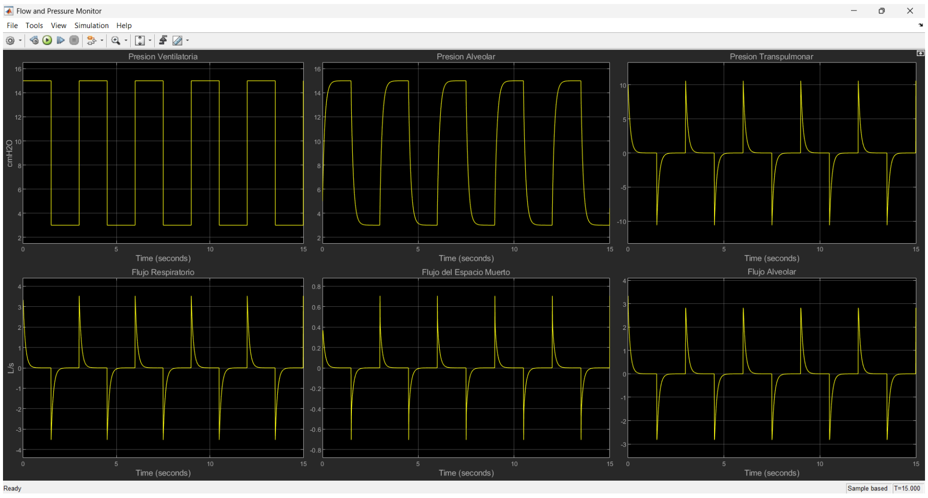
Flow and Pressure Monitor
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Presion Ventilatoria
Presion Alveolar
Presion Transpulmonar
Flujo Respiratorio
Flujo del Espacio Muerto
Flujo Alveolar
Time (seconds)
Ready
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T=15.000

6 Differences in Minute Ventilation for the Same Ventilator Settings

Minute ventilation (also called respiratory minute volume) refers to the total amount of air the patient breathes in or out per minute. It is calculated as:

$$\text{Minute Ventilation} = \text{Tidal Volume (TV)} \times \text{Breathing Rate (BPM)}$$

While a ventilator may be set to deliver the same breathing rate and peak inspiratory pressure for different patients, the actual minute ventilation can vary significantly depending on the patient's lung compliance, airway resistance, and overall respiratory mechanics.

6.1 Lung Compliance

Higher compliance allows the lungs to expand more easily, resulting in a larger tidal volume for the same pressure.
Lower compliance (as seen in restrictive diseases) causes the lungs to resist expansion, leading to smaller tidal volumes and hence reduced minute ventilation.

Example:
Two patients on the same ventilator setting of 10 BPM and peak pressure of 20 cmH_2O:

- Patient A (normal lungs): TV = 500 mL → Minute ventilation = 5 L/min
- Patient B (restrictive lungs): TV = 300 mL → Minute ventilation = 3 L/min

6.2 Airway Resistance

In obstructive diseases like COPD or asthma, airway narrowing increases resistance, which may reduce the volume of air delivered during inspiration.
Even if the pressure setting is the same, the ventilator may not be able to deliver the full intended tidal volume.

Example:

- Patient C (normal resistance): Receives 600 mL tidal volume
- Patient D (high airway resistance due to COPD): Receives only 400 mL

Despite both having 10 BPM, their minute ventilations are:

- Patient C: 6 L/min
- Patient D: 4 L/min

6.3 Dead Space Ventilation

Increased anatomical or physiological dead space means more of each breath does not participate in gas exchange.
While minute ventilation may appear normal, effective (alveolar) ventilation is reduced, especially in obstructive conditions.

Example:

- Patient E (healthy): Dead space ≈ 150 mL → Effective alveolar ventilation = TV - 150
- Patient F (emphysema): Dead space ≈ 250 mL → Much less air reaches alveoli despite same minute ventilation

6.4 I:E Ratio and Breath Timing

In obstructive diseases, the expiratory phase is often prolonged (e.g., I:E = 1:3) to avoid air trapping. This can reduce inspiratory time, limiting the volume of air delivered in each breath.

Example:

Same BPM and pressure, but with I:E of 1:3 in an obstructive patient → Less inspiratory time → Smaller tidal volume → Lower minute ventilation

6.5 Conclusion

Even with identical ventilator settings, minute ventilation can differ based on underlying respiratory pathophysiology. Variations in lung compliance, airway resistance, and timing dynamics cause significant changes in the actual air volume exchanged per minute. Therefore, individual patient monitoring and adjustment are essential to ensure optimal ventilation and gas exchange.

7 References

- Rodriguez Sarmiento, D.L., & Acevedo Guerrero, D. (2020). *Simulation of Respiratory Mechanics on Simulink with GUI*. Available at: MathWorks File Exchange
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- Sharma, S., Hashmi, M.F., & Burns, B. (2023). *Physiology, Lung Compliance*. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing. Available at: NCBI Bookshelf