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# Enhanced Study of Pressure-Controlled and Proposed Volume-Controlled Ventilation Using Electrical Model

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***Abstract:*** **Mechanical ventilation is a cornerstone in the management of severe respiratory failure. Almost all surgeries with general anesthesia require mechanical ventilation, which may trigger ventilator-induced lung injury through various mechanisms. Large tidal volume and high airway pressure may cause overextension of the alveoli, which will result in barotraumas and volutrauma. In this work, a volume-controlled ventilation system was proposed and we provide a comparison of two multi-compartment models of volume-controlled and pressure-controlled ventilation based on electrical and mathematical models. After that we present an analysis to determine whether pressure-controlled ventilation (PCV) or volume-controlled ventilation (VCV) has demonstrated advantages over control ventilation. This study can be helpful in controlled ventilation treatment and respiratory diagnostics, and very important to testing and monitoring PCV and VCV signals trigged by devices.**

***Keywords:*** **Mechanical Ventilator, Mathematical Model, Volume Controlled Ventilator, pressure Controlled Ventilator, Respiratory System.**

## I. INTRODUCTION

Mechanical ventilation carries the risk of ventilator induced lung harm (VILI), caused by too much stress and strain to the lung tissue [1]. As an alternative mode of ventilation, volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV) can be used in respiratory crash [2], and they are used for supporting many respiratory failures [3].

Previous studies [4] [5] have focused on small detail behaviors of respiratory system, considered lungs as pure pneumatic system [6] It should be noted that there are many designs for investigating characteristics of physical systems (15).the evaluation of respiratory function by The mathematical model of mechanical ventilation has been proposed in several medical and scientific studies [5]-[6].However, In the present modeling and simulation studies of the mechanical ventilation system, the system is commonly considered as an electrical model [7] .

In this paper, in order to improve the flexibility and applicability of the mathematical models of the VCV systems, a volume-controlled ventilation system was proposed, then it will be compared with an existing multi compartmental model of respiratory system during pressure controlled mechanical ventilation [7] so as to confirm whether pressure-controlled ventilation (PCV) or volume control ventilation (VCV) has demonstrated advantages over artificial ventilation.

In the following, we describe the detailed process of PCV and the proposed VCV, and then we present the results through illustration curves, followed by the discussion and interpretation of the obtained results. The conclusion provides the significant achievements.

## II. MODELLING VOLUME AND PRESSURE CONTROLLED VENTILATION

### *A. Modelling volume-controlled ventilation signal*

The air flow signal generated by VCV machine in reality takes the same breathing behavior as the respiratory activities.

The air flow signal of volume-controlled ventilation depends on setting parameters in real VCV device Fig. 1 show the mathematical model during inspiration and expiration activities and reflect the main key parameters during this mode.

The periodic functions method was used to express the mathematical model of VCV signal as seen in the Equations (1), (2) and (3).

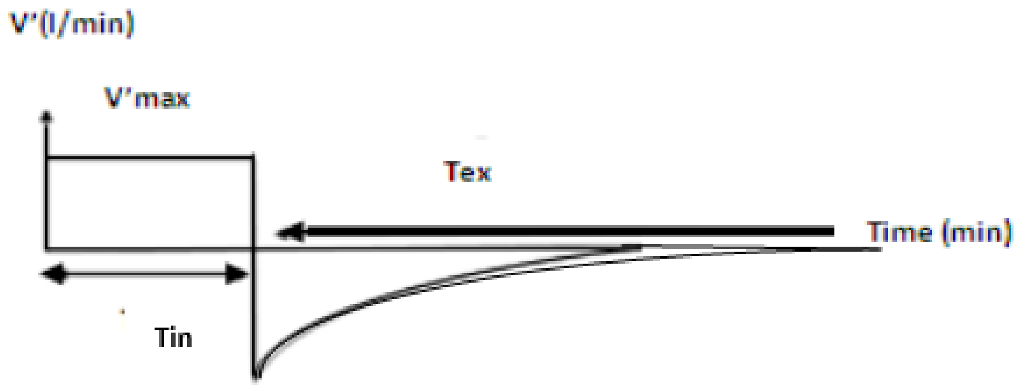


**Fig. 1: Typical waveform of air flow signal for VCV [8].**

Where,

V (t)—the air flow signal of VCV as function of time.

t—time equal to (Tin) inspiratory time, and Tex— expiratory time.

As shown from these equations, the air flow was represented as time based function V' (t) to reflect the respiratory activities—inspiration and expiration during ventilation. These activities are generated from changes in the air flow amount in respiratory system during inspiration and expiration processes.

$$V'(t) = V'max \qquad 0 < t < Tin \qquad (1)$$

$$V'(t) = (-k*\Delta P)/Rrs.Exp(-TE)/(\tau) \qquad Tin < t < Tex \qquad (2)$$

V '(t) - the air flow, V'max the maximum of air flow in the respiratory airway, Tin: Inspiratory time, Tex: expiratory time, τ: constant time [8], K : Gain

K =18, 4, AP= 40 CH2O, Rrs=1.5 CH2O/L/s, Tin =1 minute , Tex=2 minutes, Vmax = 40 l/minute, τ =0.4 s.

The two air flow equations were tired by the motion equation of the respiratory system [9]:

$$Pao = Rrs. V' + V/Crs \qquad (3)$$

Where:

Crs: Respiratory compliance, Rrs: Respiratory resistance. ; PEEP: positive end expiration pressure; V: tidal volume.

The Created mathematical model of VCV signal is combined with a new multi-compartmental model of respiratory system.

Main Parameters for VCV [10]:

Tidal Volume (vt) -set in ml

Respiratory Rate (Battement Par Minute)

I:E Ratio -setting for the ratio of Inspiratory time (TI) to expiratory time (TE)

PEEP-Positive end expiratory pressure

Tp% = Inspiratory Pause (0-50% of Tin)

Pressure Limit, Pmax (cmH2O).

***B. The proposed multi compartment model of respiratory system during volume-controlled ventilation***

The suggested mathematical model of VCV system was integrated as air flow that is applied to a new multi compartment model of lung and chest wall. Fig. 2 demonstrates the electric model of respiratory system as a multi compartment model.

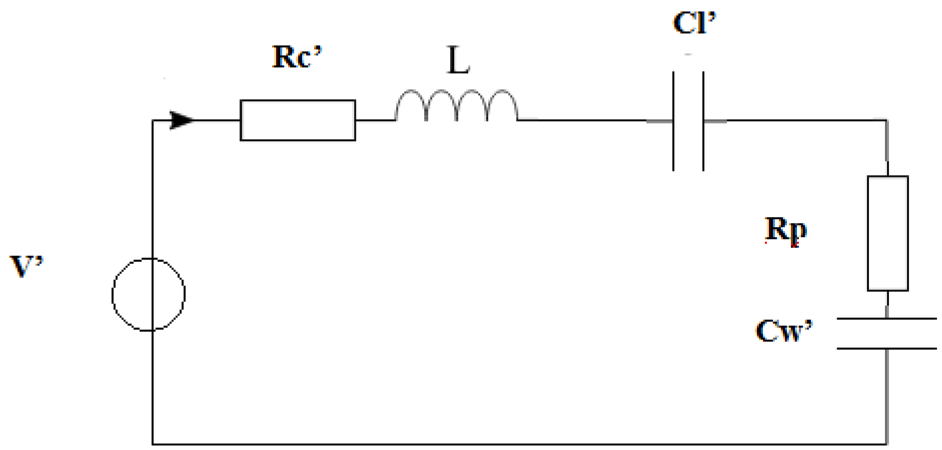


**Fig. 2: The equivalent electrical model of respiratory system—multi compartments model.**

Where:

All parameters refer to the normal lungs:

- The current flow (I) represents the air flow (V').
- Rc = 1 cm H2O/L/s, Shows the air flow resistance in the central airway.
- Rp = 0.5 CmH2O/L/s: Shows the peripheral resistance of chest wall.
- CL = 200 ml/CmH2O: Represents the lungs capacities.
- Cw = 200 ml/Cm H2O : Indicates the chest wall capacities;
- L = 0.009 Cm H2O/L/s: Represents the inertia of respiratory system.
- Rc' =Rc.k1; Cw'=Cw.k2; CL'=K3.CL; k1=2.97; K2=0.005; K3=0.001
- K1 : Resistance coefficient [cm H2O/L/s]
- K2 : Compliance coefficient, [ml/CmH2O]
- K3 : Compliance coefficient [ml/CmH2O

Applying Kirchhoff's first Law to the electrical circuit, we get:

$$F(s) = \frac{P(s)}{U(s)} = Gain.\frac{Rp.s+\frac{1}{C'w};}{L.s^2+(Rp+R'c)..s+\left(\frac{1}{C'w}+\frac{1}{C'L}\right)} \qquad (4)$$

***C. The multi compartment model of respiratory system during pressure-controlled ventilation***

The mathematical model of mechanical ventilation during pressure-controlled ventilation in this work includes the pressure support triggered from pressure-controlled ventilation (PCV) device; Fig. 4 shows the typical curve of pressure and its mechanism, Also, it clarifies the setting variables in PCV device such as: inspiratory pressure (IP), inspiratory time (Tin)...this mathematical model was formulated to represent the inspiration and the expiration activities.

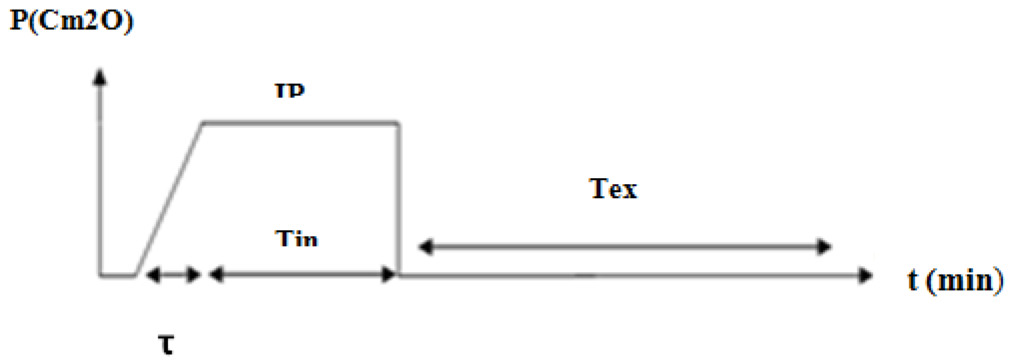


**Fig. 4: Typical waveform of pressure signal for PCV [11]**

The cyclic function process was used to express mathematical model of PCV signal as shown in the equations (1), (2) and (3) [11].

$$P(t) = \begin{cases} Paw.\left(\frac{t}{\tau}\right) + PEEP & 0 < t < \tau \quad (6) \\ Paw + PEEP & \tau < t < Tin \quad (7) \\ PEEP, & Tin < t < Tex \quad (8) \end{cases}$$

Where:

P (t) - the pressure signal of PVC, PEEP: Positive end expiratory pressure, Paw: Pressure in the respiratory airway, Tin: inspiratory time, Tex: expiratory time, τ the rise time.

As exposed from these equations, the ventilation pressure of PCV was represented as time-based function P(t) to reflect the breathing activities—inspiration and expiration during ventilation.

The inspiratory pressure (IP) and expiration pressure (EP) were represented by Paw and PEEP.

The mathematical model of PCV signal was integrated as a pressure that is applied to a multi compartment model of respiratory system, so as to get a model of respiratory system during pressure-controlled ventilation.

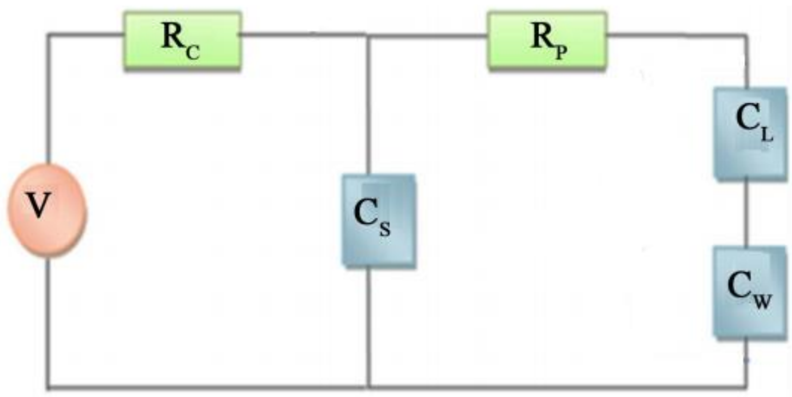


**Fig. 5: Model of respiratory system**

Where:

All parameters refer to normal lungs:

- Rc = 1 cm H2O/L/s, shows the air flow resistance of the central airways.

- Rp = 0.5 cm H2O/L/s, demonstrates the resistance of the peripheral airways.
- CL = 200 ml/cm H2O, represents the capacity of the alveoli.
- Cw = 200 ml/cm H2O, indicates the chest wall capacity, which is in series with the alveoli
- Cs = 5 ml/cm H2O represents a shunt capacitance known as “dead space” of air, which does not contribute in the exchange of oxygen and carbon dioxide between air and blood.
- $Rs = K1 + K2.V'$
- V’ : $\frac{dv}{dt}$ air flow: First order derived

Applying Kirchhoff’s first Law to the circuit, we get:

$$Rp.V'A + \left[\frac{1}{CL} + \frac{1}{CW}\right].\int V'Adt = \frac{1}{Cs}.\int (V' - V'A)dt \qquad (9)$$

$$Paw = (Rc + RS).V' + \frac{1}{Cs} * \int (V' - V'A).dt \qquad (10)$$

$$V'A = V' - Cs.\frac{dPao}{dt} + Rc.Cs.V'' \qquad (11)$$

$$(Rc + Rs).\frac{dv^2}{dt} + \left(\frac{1}{Cs} + \frac{RC+RS}{Rp*CT}\right).\frac{dv}{dt} + \frac{1}{Rp*Cs}.\left[\frac{1}{CL} + \frac{1}{CW}\right]v = \frac{dPao^2}{dt} + \frac{1}{Rp*CT}.\frac{dPao}{dt} \qquad (12)$$

This model has been converted to the mathematical model using transfer functions that represent the air flow (output) changes as a function of input pressure shown in equation (14), therefore, the function V’(s)/P(s) using laplace transform is :

$$F(s) = \frac{V'(s)}{P(s)} = \frac{s^2 + \frac{s}{Rp.CT}}{Rc * s^2 + \left(\frac{1}{Cs} + \frac{Rc}{Rp*CT}\right)*s + \left(\frac{1}{Rp*Cs}\right)*\left(\frac{1}{Cw} + \frac{1}{CL}\right)} \qquad (13)$$

Main parameters for PCV:

- P inspiratoire in cmH2O
- Inspiratory time (Ti) in seconde. or I: E Ratio determines the cycling time.
- Respiratory rate in breaths/min determines the start of inspiratory time
- PEEP in cmH2O
- Pmax-Maximum airway pressure, at which time the ventilator will alarm.

## III. RESULTS

The results of this study is performed using Simulink of Matlab, in the following we illustrate the curves of input pressure

### *A. Volume controlled ventilation*

The created mathematical model of VCV signal was modeled and simulated as a generator of the air flow, which was combined with a new respiratory system model to obtain simulator of the mechanical ventilation system. Fig. 6 shows the block diagram of building simulator and demonstrates the simulation sequences that were constructed using simulink tools in MATLAB platform.

The numerical transfer function is:

$$F(s) = \frac{P(s)}{U(s)} = 7.2\frac{0.1.s+1}{0.009.s^2+6.04.s+4.8} \qquad (5)$$

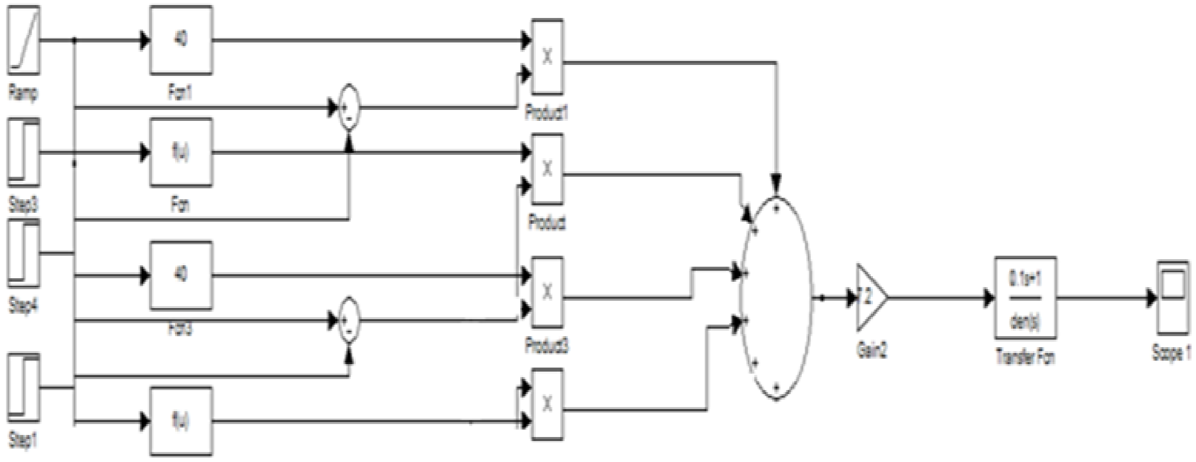


**Fig. 6: Block diagram of transfer function.**

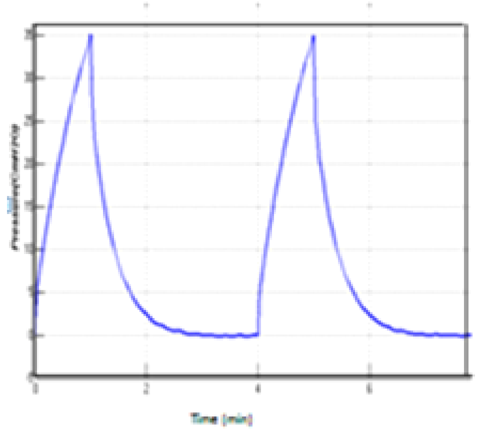

**Fig.7: waveform of air pressure or Pao**

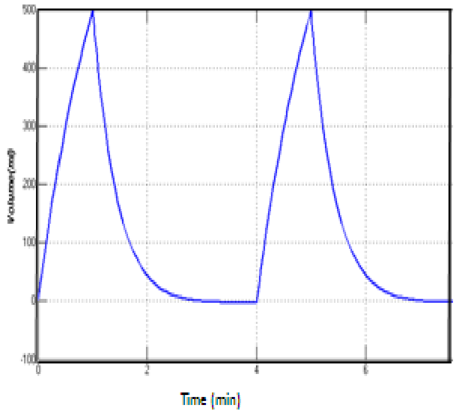


**Fig.8: Waveform of tidal volume or Vt**

### *B. pressure-controlled ventilation*

The created mathematical model of PCV signal was modeled and simulated using this numerical transfer function:

$$F\,(s) = \frac{V'(s)}{P(s)} = \frac{s^2+420.s}{s^2+620.s+4000} \qquad (14)$$

Fig. 9 Shows the block diagram of building simulator and demonstrates the simulation sequences that were constructed using simulink tools in MATLAB platform.

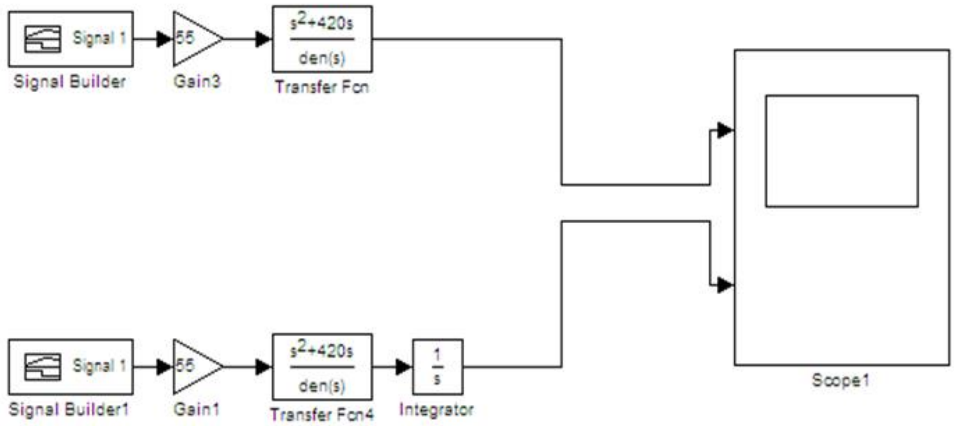


**Fig.9. the simulator of the transfer function during pressure-controlled ventilation.**

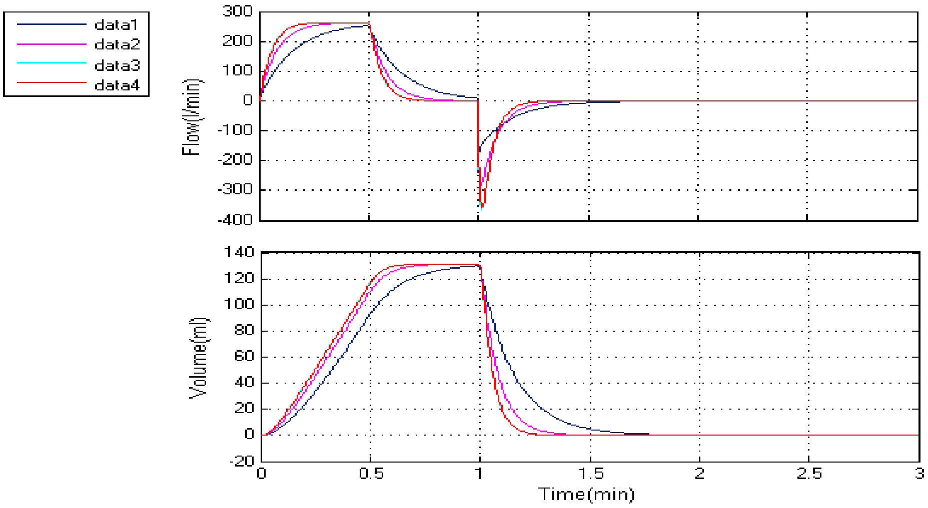


**Fig.10: Waveforms of tidal volume and air flow at PEEP = 0 cm H2O and IP = 25 cm H2O and with a variety of Rc.**

### *C. Discussion*

Volume controlled ventilation (VCV) has been the habitual controlled ventilation mode in anesthesia. In VCV, the ventilator delivers the fixed tidal volume (TV) with a constant flow during the preset inspiratory time (Ti) at the preset respiratory rate. The benefits of VCV are the well-known technique and the controllable minute volume. But the fear of VCV is the constant flow that may cause high peak pressures and therefore expose the patient to the risk of barotraumas.

Gas distribution in the lungs may not be optimal during VCV, as difficult to fill alveoli may not fill until late in the inspiratory time, leaving less time for gas exchange. VCV may not be the ideal ventilation mode for patients with lung disease or for pediatrics. Because Pediatric patients have very small airways and the small bore endo tracheal tubes. The combination of constant flow and high resistance can produce very high inspiratory pressures.

Pressure Control Ventilation (PCV), the ventilator generates the preset pressure during a preset inspiratory time at the preset respiratory rate. The pressure is constant during the inspiratory time and the flow is decelerating. PCV provides advantages over volume-controlled breaths:

- Lower peak airway pressures to deliver the same volume
- Better volume distribution within the lungs
- Better oxygenation
- Less risk of barotraumas
- Leak compensation without affecting volume delivery to the patient
- Ability to ventilate every patient type.

The one significant disadvantage of pressure control ventilation is that tidal volume delivery will increase and decrease with changes with patient compliance, and is not guaranteed. Extra clinical vigilance is required when using pressure control ventilation to avoid under or over ventilating patients whose compliance changes. These compliance changes may occur due to underlying disease, surgical positioning, presence of surgical packs or retractors, and changes in the degree of relaxation or insufflations.

## III. CONCLUSION

In this work, we had created and simulated a proposed mathematical model of the VCV signal and combined it with the electrical model of lungs and chest wall, in order to obtain the mechanical ventilation system simulator during volume controlled mechanical ventilation. The new system is able to represent setting parameters and its settings values, and therefore represents the real VCV signal by simulator. Then, we had simulated an existing mathematical model of PCV signal and combined it with a multi-compartment of lung and chest wall simulator to obtain the mechanical ventilation system. This simulator is able to examine the input and output signals as continuous waveforms to mimic the real artificial ventilation process.

By combining these two modes VCV and PCV, we are able to realize the advantages of both modes by delivering the preset tidal volume (TV) with a decelerating flow at the lowest possible peak inspiratory pressure during a preset inspiratory time, at the preset respiratory rate thereby enhancing and facilitating patient ventilation.

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