

<https://africanjournalofbiomedicalresearch.com/index.php/AJBR>

Afr. J. Biomed. Res. Vol. 27(4s) (November 2024); 1040-1048

Research Article

Clinical Utility Of Six Novel Equations Of Motion For Ventilator Graphics Display

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ABSTRACT

INTRODUCTION: Ventilator Graphics display have immense clinical value to analyze the respiratory system mechanics in the management of mechanically ventilated patients. The Equation of Motion for the respiratory system is the basic fundamental concept to understand the respiratory mechanics. Based on this equation, novel equations of motion for ventilator graphics interpretation were derived and already published by the current author in previous research studies.

AIM: The aim of this current research study is to focus the clinical utility of six novel equations of motion in ventilator that helps to correlate and understand the various physical concepts involved in the mechanics of breathing.

MATERIALS AND METHODS: The relationship between various physical concepts like pressure, volume, flow rate, resistance, compliance, time constant, total cycle time, frequency, work done and novel derived equations of motion were utilized.

RESULTS: Six novel equations of motion of ventilator that are used to understand the changes in pressure gradient, inspiratory flow, expiratory flow, time constant and passive elastic recoil pressure are tabulated. The calculation of work done during inspiration and expiration using these equations are tabulated. A sample of ventilator graphics for interpretation in different clinical conditions were graphically depicted.

CONCLUSION: These six novel equations of motion may play a significant role in the qualitative identification of the changes observed in ventilator graphics display. Therefore it may serve as an effective teaching tool for ventilator graphics interpretation which in turn helps to improve the patient care of mechanically ventilated patients.

KEY WORDS: Six Novel Equations of Motion, Ventilator Graphics Interpretation, Auto PEEP, Work of Breathing

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Received: 06/10/2024

Acceptance: 06/11/2024

DOI: <https://doi.org/10.53555/AJBR.v27i4S.3748>

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INTRODUCTION:

Ventilator Graphics serve as an indispensable tool in the management of mechanically ventilated patients. Therefore better understanding and efficient interpretation of the changes observed in the ventilator graphics display have immense clinical value to analyze the respiratory system mechanics that provides the information about the patient-ventilator interaction (Amanda M Dexter et al., 2020). The **Equation of Motion** for the respiratory system or the **force balance equation** is the basic fundamental concept to understand the respiratory mechanics (Robert L chatburn 2003, Alysson Roncally Carvalho et al., 2011). Air movement between atmosphere and lung alveoli during breathing is driven by the pressure gradient and hindered by airway resistance. **Airway resistance** is different during inspiration and expiration, expiratory resistance being higher than the inspiratory resistance due to the shape of the airway tree. **Compliance** denotes the amount of air in ml the lungs can hold for every 1 cm H₂O change in pressure. **Elastance** is the reciprocal of compliance (Alysson Roncally Carvalho et al., 2011, Cordioli et al., 2016, Jean-Michel Arnal 2018).

During expiration a baseline or expiratory pressure is always measured which is set relative to atmospheric pressure and their positive value is called as the **positive end-expiratory pressure (PEEP)**. In zero setting the baseline pressure is set equal to the atmospheric pressure (Robert L chatburn 2003). The lung volume changes during inspiration and expiration due to the changes in pressure gradient. This process is a time consuming process, therefore the physical concept of **time constant** is utilized to describe the speed of this process. Time constant is used to specify the time needed to inhale adequate inspiratory tidal volume and to exhale the required expiratory tidal volume. One time constant is the time required for **inflation** up to 63% of the final volume or **deflation** by 63 % (Iotti GA et al., 2001, Shevade MS 2019, Koca et al., 2020, Dean R Hess 2014). Time constant measured in seconds is calculated as the product of **resistance** and **compliance** (Al-Rawas N et.al., 2013, Depta F et. Al., 2022). Inspiratory time constant is shorter than the expiratory time constant because inspiratory airway resistance is usually lower. A quicker rate of change is denoted by a short time constant and a slower rate of change is denoted by a long time constant.

Functional Residual Capacity (FRC) is the volume of gas that remains in lungs at the end of expiration which is the resting state. In the presence of **positive end expiratory pressure (PEEP)** it is called **end-expiratory lung volume (EELV)**. FRC is a lung volume measured without PEEP (at atmospheric pressure). An **increase** in end expiratory lung volume result in **dynamic hyperinflation** which prevents the respiratory system from returning to its resting end expiratory equilibrium volume between breath cycles (Lutfi, M.F. et al., 2017, Dean R Hess 2015, Dellamonica N et al., 2011, Bellani G 2010, Ido G

Bikker et al., 2008). During inhalation **total work done** is required to overcome both the **resistive** and **elastic** elements of the respiratory system and this work done during inhalation is stored as potential energy which is recovered during exhalation. Elastic energy due to elastic recoil of the lung is stored as potential energy and this provides the necessary pressure needed to exhale the tidal volume (Lutfi, M.F. et al., 2017). **Inhalation** is an active process but tidal breathing during **exhalation** is a passive process that does not require active energy. The energy required for inspiration is more than that required for expiration under physiological conditions because only resistive work of breathing is required for expiration. The **elastic energy stored** during inspiration is **partly** utilized as **resistive work** of breathing for **expiration** and partly dissipated as **heat energy** (Lutfi, M.F. et al., 2017).

The purpose of this research article is to discuss in detail the clinical utility of **six novel equations of motion** derived and already published by the current author (Dr.T.Rajini Samuel). This article mainly focus on the basic concepts involved in the formulation of the six novel equations of motion in ventilator graphics. The knowledge acquired may help especially the junior medical staffs to understand the changes observed in the ventilator graphics display in clinical settings which helps to improve the patient care of mechanically ventilated patients.

MATERIALS AND METHODS:**Volumetric Flow Rate & Mass Flow Rate:**

Volumetric flow rate (Q or $\dot{V}$) is defined as the volume V of fluid or gas flowing through a surface per unit time (t). **Mass flow rate ($\dot{m}$)** is the mass of a substance which passes per unit time (t). Mass density (ρ) is the ratio between mass and volume (Rajini Samuel T 2021, Engineers Edge 2016).

$Q = \dot{V} = dV/dt$ (time derivative of volume)

$\dot{m} = dm/dt$ (time derivative of mass)

$\dot{m} = \rho \cdot \dot{V}$

Volumetric flow rate (Q or $\dot{V}$ is a **scalar** quantity) can also be defined using **dot product** of **two vectors** namely the flow velocity (v) and the cross sectional vector area (A).

$Q = v \cdot A$; $Q = vA \cos \theta$

Q depends on the magnitude of the **flow velocity vector** and the **cross sectional area vector** and the **cosine of the smallest angle** between them ($\cos \theta$). From this relation it is clearly evident that as the **angle θ increases, lesser volume** flows, volumetric flow rate is **zero** if both are **perpendicular** (angle θ is 90°) and volumetric flow rate is **maximum** if they are **parallel** (angle θ is zero). The **acceleration** is calculated as the ratio between velocity and time and **pressure** is the ratio between force and area. The physical concept **force** is represented as the product of **mass** and **acceleration** and **momentum** is denoted as the product of **mass** and **velocity** (Rajini Samuel T 2021, Engineers Edge 2016).

Kinetic Energy = $\frac{1}{2} mv^2$

Where m denotes mass and v denotes velocity.

$$R_{AW} = \Delta P / \dot{V} \quad \text{OR} \quad \dot{V} = \Delta P / R_{AW}$$

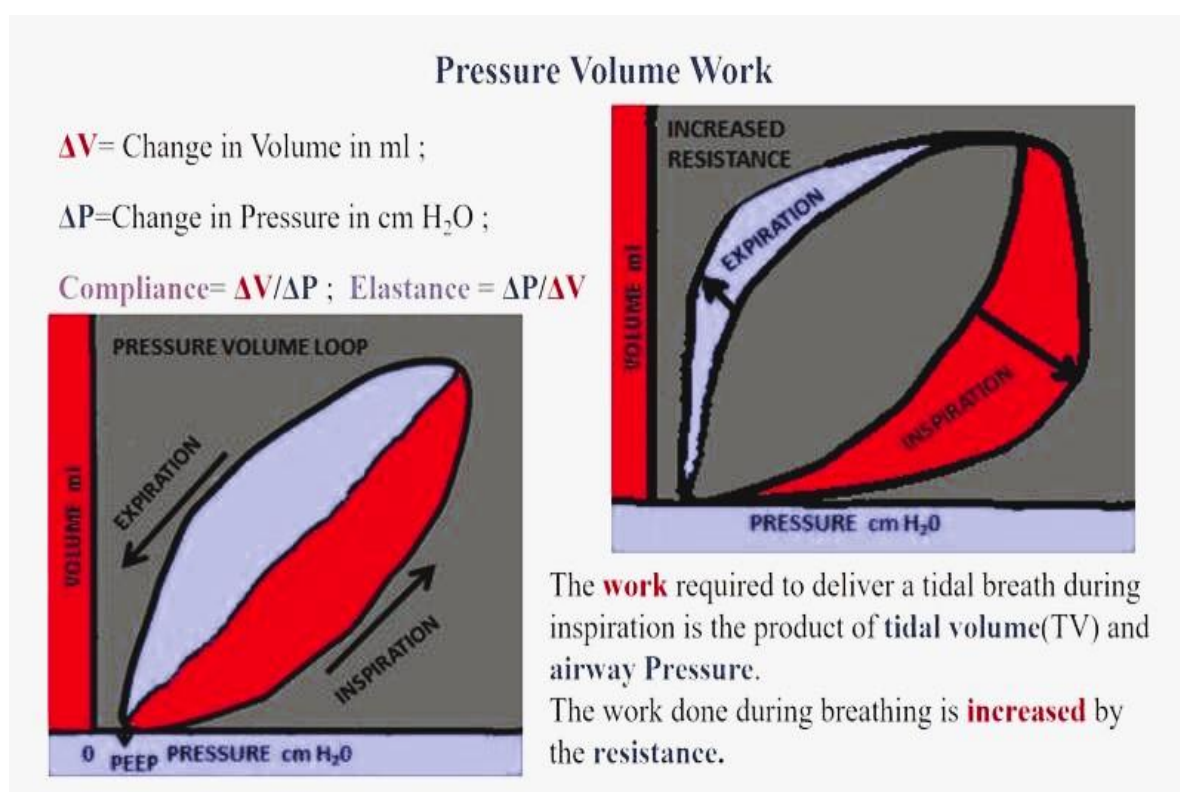
Airway Resistance (R_{AW}) is equal to the **pressure gradient (ΔP)** divided by the **Volumetric Airflow ($\dot{V}$)**. Another equation that relates the resistance and flow is given below.

$R_{AW} = [\rho \cdot \dot{V}] / A^2$ Where **Mass flow rate ($\dot{m}$)** = $\rho \cdot \dot{V}$
In the above equation (which was published by the current author in previous research study), the volume flow rate and resistance are directly related but in the previous equation ($\dot{V} = \Delta P / R_{AW}$) they are inversely related.

This relationship ($R_{AW} = [\rho \cdot \dot{V}] / A^2$) helps to understand the variations seen in resistance during high flow rate in certain conditions. As the density and volume flow rate increases, the resistance also increases in certain

conditions. **High flow rate** will result in **increased resistance** which in turn result in **increased peak inspiratory pressure**(Rajini Samuel T 2021).The resistance is inversely related to the square of the cross sectional area or the fourth power of radius. **Static compliance(C_{stat})** measures the elasticity of the lung when there is no air movement (Koca et al., 2020, Dean R Hess 2014, Paul Ouellet 1997). Work done (W) is the product of **force** and **displacement** ($W = F \cos \theta$). Hence it is a scalar quantity. Work done is also the product of pressure and volume. Product of **pressure (P)** and **volume (V)** is the same as the product of force (F) and displacement(s) (Koca et al., 2020, Dean R Hess 2014, Paul Ouellet 1997).The relationship between pressure, volume, compliance and elastance is clearly shown in **figure 1**.

Figure 1: Pressure Volume Work



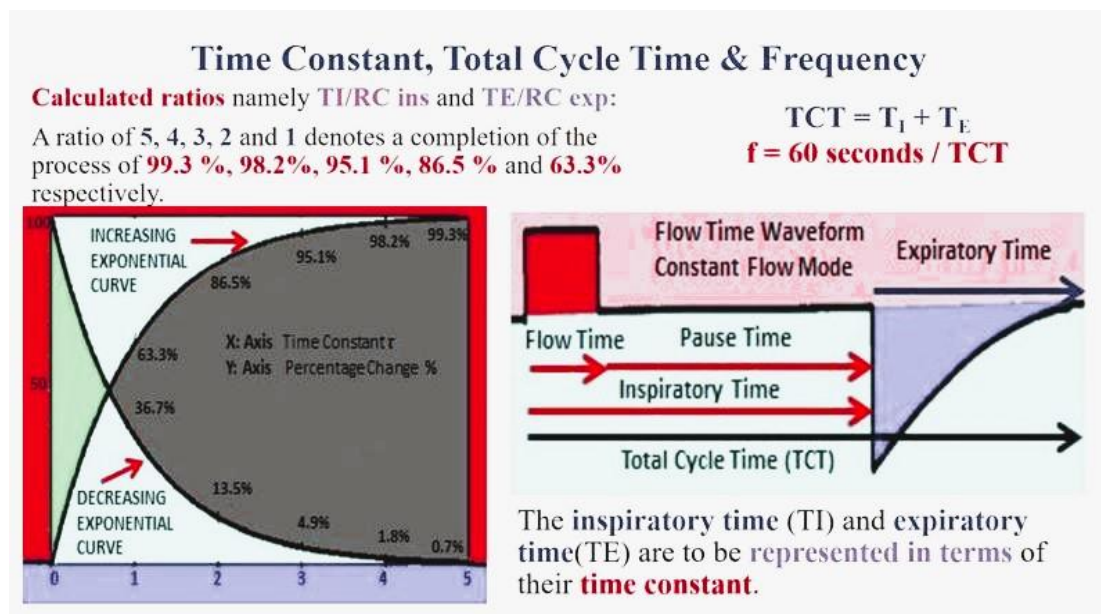
The inspiratory time (TI) and expiratory time (TE) are to be represented in terms of their time constant. **Time constant** measured in seconds is calculated as the product of **resistance** and **compliance** (Iotti GA et al., 2001, Shevade MS 2019, Koca et al., 2020, Dean R Hess 2014, Al-Rawas N et.al., 2013, Depta F et. Al., 2022).

Time constant (seconds) = Resistance x Compliance

RC ins = Cstat x Rins

RC exp = Cstat x Rexp

The inspiration process will increase and expiration process will decrease by the percentages which are clearly depicted in the **figure 2**. Total cycle time (TCT) or ventilator period is the sum of both inspiratory time (TI or I) and expiratory time (TE or E). Total cycle time is inversely related to the frequency (Robert L chatburn 2003).

Figure 2: Time Constant, Total Cycle Time and Frequency

Equation of motion of respiratory mechanics OR Force balance equation:

Total pressure required to **inflate** the lung is the sum of the pressure required to overcome the **airway resistance** and the **elastance** of the respiratory system. Airway pressure during inspiration must exactly balance the forces opposing lung and chest wall expansion. The **opposing pressures** are the sum of flow **resistive** pressure (P_{RES}), **elastic recoil** pressure (P_{EL}) and **inertance** pressure ($P_{inertance}$) of the respiratory system (Alysson Roncally Carvalho et al., 2011, Cordioli et al., 2016, Paul Ouellet 1997).

$$P_{AW} = P_{RES} + P_{EL} + P_{inertance}$$

The inertial forces are usually negligible during conventional ventilation. The **inertance pressure** ($P_{inertance}$) of the respiratory system can be **omitted** and the simplified form of equation of motion is given below.

$$P_{AW} = P_{RES} + P_{EL}$$

In the presence of positive end expiratory pressure (PEEP), it is rewritten as follows.

$$P_{AW} = P_{RES} + P_{EL} + PEEP$$

Positive pressure will be generated by the **ventilator** but a **negative pressure** will be generated by the **muscle** at the **other end** and the flow of gas takes place through the pressure gradient (Rajini Samuel T 2021, Umberto Lucangelo et al., 2007).

$$P_{VENT} = P_{RES} + P_{EL} - P_{MUS} + PEEP$$

The above equation has **negative sign** for P_{MUS} because it acts by creating a negative pressure at the other end and this equation can be **re-written** in the following form (Rajini Samuel T 2021, Umberto Lucangelo et al., 2007).

$$P_{VENT} + P_{MUS} = P_{RES} + P_{EL} + PEEP$$

$$P_{AW} = P_{RES} + P_{EL} + PEEP; \text{ where } P_{AW} = P_{VENT} + P_{MUS}$$

$$P_{AW} - PEEP = P_{RES} + P_{EL}$$

$$\Delta P = P_{RES} + P_{EL} \text{ where } \Delta P = P_{AW} - PEEP$$

$$P_{RES} = F \times R; P_{EL} = E \times TV$$

$$\Delta P = \text{Flow} \times \text{Resistance} + \text{Elastance} \times \text{Tidal Volume}$$

P_{AW} is the **pressure generated** either by the **ventilator** or the **muscle**. It is very clear that the pressure generated by the ventilator and/or muscle has to increase above the PEEP level for the development of pressure gradient that helps in flow of gas across the respiratory system (Robert L chatburn 2003).

If inspiration begins before the completion of previous expiration, some air gets trapped inside the lungs. This **trapped gas volume** will contribute to a positive pressure called as the **auto PEEP** or **intrinsic PEEP** because it is not set directly by the clinician (Lluís Blanch et al., 2005, Natalini G et al., 2016, Stephen E. Lapinsky 2015). The **pressure** generated due to this **trapped air volume** (V_{trap}) is the product of **elastance** (E) and **residual volume**. Auto PEEP is also represented as the product of **Residual Flow** (rF) and **Expiratory Resistance** (Robert L chatburn 2003, Rajini Samuel T 2021).

$$\text{Auto PEEP} = V_{trap} \times E \text{ or } R \times rF$$

$$\text{Total PEEP} = \text{Auto PEEP} + \text{Set PEEP}$$

$$\text{Total PEEP} = R \times rF + \text{Set PEEP}$$

RESULTS:

The novel equations of motion for interpretation of ventilator graphics were utilized. **Six novel equations** were used to understand the changes observed in pressure gradient, inspiratory flow, expiratory flow, expiratory time constant and passive elastic recoil pressure. In these equations, ΔP and eF have to be substituted by $[\Delta P - R \times rF]$ and $[eF + rF]$ respectively for the presence of **residual flow** that contributes to the development of **auto PEEP**. These were clearly depicted in **table 1**. **Work done** during inspiration and expiration can be calculated using these equations which are clearly shown in **table 2**. A sample of ventilator graphical display for interpretation in different clinical conditions were clearly depicted in **figure 3** and **figure 4**.

Table1: SIX NOVEL EQUATIONS OF MOTION FOR VENTILATOR

S.NO	NOVEL EQUATIONS OF MOTION FOR VENTILATOR GRAPHICS
1	ΔP : Pressure Gradient for Inspiration with constant Flow $\Delta P = iF(R + EXT_i)$ OR $\Delta P = iFXE(\tau_i + Ti)$
2	iF : Inspiratory Flow with constant Pressure Gradient $iF = [\Delta P \times C] / (\tau_i + Ti)$
3	iF_{start} : at the start of Inspiration; iF_{end} : at the end of Inspiration $iF_{start} = [1/R] \times \{\Delta P - E \times V\}$ $iF_{end} = [1/R] \times \{\Delta P - E \times \Delta V\}$
4	eF : Expiratory Flow eF_{start} : at the start of expiration; eF_{end} : at the end of expiration $eF_{start} = [1/R] \times \{E \times \Delta V - Set PEEP\}$ $eF_{end} = [1/R] \times \{E \times V - Set PEEP\}$
5	τ_e : Expiratory Time Constant $\tau_e = \Delta V - V / eF$
6	P_{EL} : Passive Elastic Recoil Pressure denoted by $E \times \Delta V$ $P_{EL} - Set PEEP = R \times eF$

R: Resistance; **C**: Compliance; **E**: Elastance; **Ti**: Inspiratory Time;
 τ_i : Inspiratory Time Constant ; **τ_e** : Expiratory Time Constant
 $\Delta P = P_{AW} - Set PEEP$;
 Passive Elastic Recoil Pressure(**P_{EL}**): $E \times \Delta V$;
 End expiratory alveolar pressure: $E \times V$
 ΔP & eF have to be substituted by $[\Delta P - R \times rF]$ & $[eF + rF]$ respectively for the equations depending on the **presence** or **absence** of residual flow contributing to **Auto PEEP**.

Table 2: WORK DONE DURING INSPIRATION AND EXPIRATION

S.NO	Work Done During Inspiration and Expiration
1	The work required to deliver a tidal breath during inspiration is the product of tidal volume (TV) denoted as ΔV and airway Pressure gradient. $\Delta P = P_{AW} - Set PEEP$ $\Delta P = iF(R + EXT_i) + R \times rF$ OR $\Delta P = iFXE(\tau_i + Ti) + R \times rF$ W_{TOT} : Total Work done during active inspiration $W_{TOT} = \{ iF(R + EXT_i) + R \times rF \} \times \Delta V$ OR $W_{TOT} = \{ iFXE(\tau_i + Ti) + R \times rF \} \times \Delta V$
2	The work required to exhale a tidal volume during expiration is the product of amount of tidal Volume exhaled (dV) and the passive elastic recoil pressure gradient. Passive Elastic Recoil Pressure (P_{EL}) is denoted by $E \times \Delta V$. $\{E \times \Delta V - Set PEEP\} = R \times [eF + rF]$ $P_{EL} - Set PEEP = R \times (eF + rF)$ W_{EL} : Work done during passive expiration by Elastic Recoil Pressure $W_{EL} = R \times (eF + rF) \times dV$

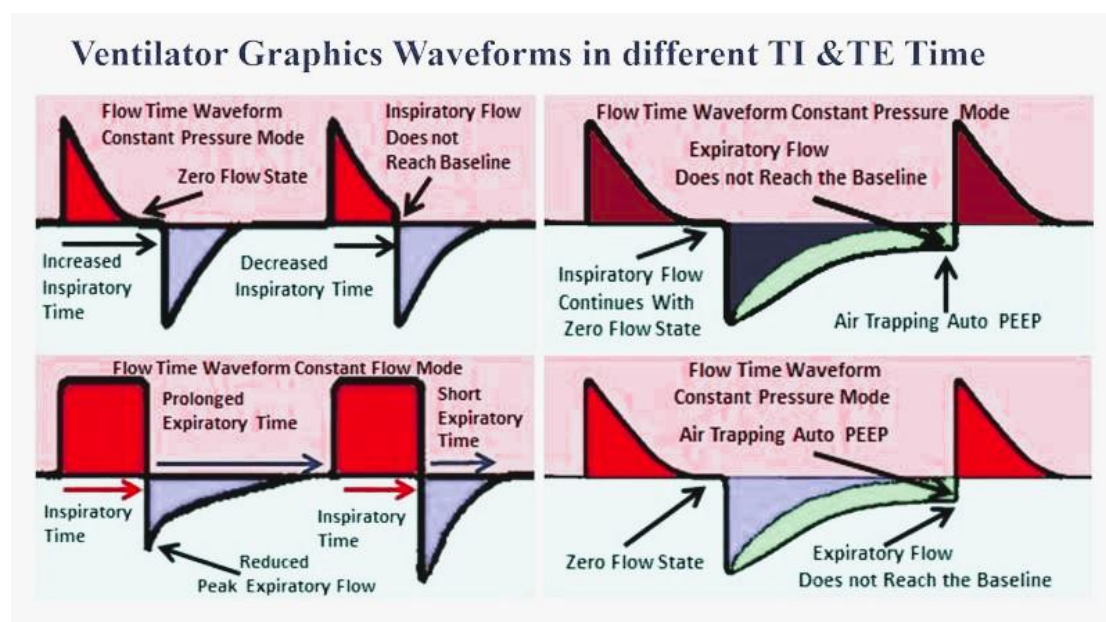
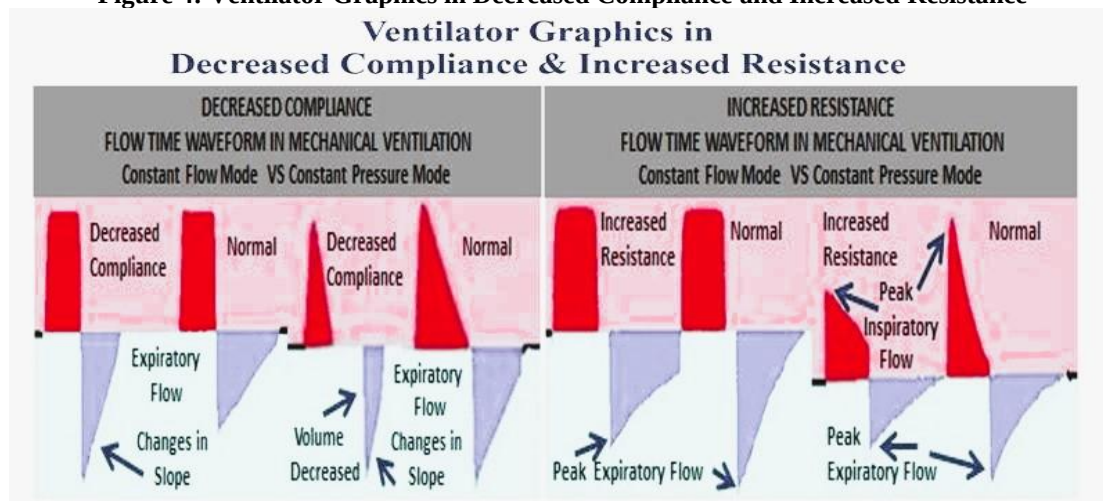
Figure 3: Ventilator Graphics Waveform in different TI and TE period

Figure 4: Ventilator Graphics in Decreased Compliance and Increased Resistance**DISCUSSION:**

The amount of **tidal volume inhaled** is the product of inspiratory flow (constant or average) and inspiratory time. The **inspiratory time** is measured from the beginning of the **positive flow** (denotes **inspiration**) to the beginning of the **negative flow** (denotes **expiration** whose direction is opposite to inspiration). The inspiratory time is the sum of the inspiratory flow time and inspiratory pause time (flow has ceased but expiratory flow is not yet allowed) which are clearly depicted in **figure 2**. **Total cycle time (TCT)** or **ventilator period** is the sum of both inspiratory time (TI or I) and expiratory time (TE or E). **Frequency** denotes the number of breaths or number of ventilator cycles per minute. Total cycle time is inversely related to the frequency (Robert L chatburn 2003).

The **inspiratory rise time** determines the amount of time it takes to reach the desired airway pressure or peak flow rate. It determines the rate at which the ventilator achieves a target pressure in constant pressure mode of ventilation or flow rate in constant flow mode of ventilation. Peak inspiratory pressure or peak inspiratory flow rate is seen at the beginning of the inspiratory cycle (depending on the set inspiratory rise time), then it is constant throughout the inspiratory cycle and it ceases once the preset or target value is achieved (Murata S et.al., 2010, Yang SH et.al., 2023, Joshua F Gonzales et. Al., 2013, Rajini Samuel T 2021). The **novel equation of motion** for the **pressure gradient (ΔP)** during inspiration with constant flow is given below.

$$\Delta P = iF(R + EXTi) \text{ Where } \Delta P = P_{AW} - \text{Set PEEP}$$

Pressure gradient is increased by the resistance at the start of inspiration then as the inspiratory time increases it depends mainly on the elastance, the slope of which denotes the stress index in the second portion of the pressure time waveform (Amanda M Dexter et al., 2020, Rajini Samuel T 2021). The **novel equation of motion** for the **inspiratory flow (iF)** with constant pressure gradient is given below.

$$iF = [\Delta P \times C] / (\tau_i + Ti)$$

In constant pressure mode of ventilation, inspiratory flow is directly proportional to the pressure

gradient(driving force), compliance and inversely proportional to inspiratory resistance, elastance and inspiratory time constant. The **novel equation of motion** for inspiratory flow at the start of inspiration(**iF_{start}**) is given below.

$$iF_{start} = [1/R] \times \{\Delta P - E \times V\}$$

Inspiratory flow will decrease with increase in resistance. The inspiration starts at the end expiratory alveolar volume (V) and **End expiratory alveolar pressure (E X V)**. The pressure gradient at the start of inspiration is denoted by $\{\Delta P - EXV\}$ and the pressure gradient is maximum at this starting point. **Peak inspiratory flow** is always seen at the **beginning** of the **inspiration** due to this maximum pressure gradient $\{\Delta P - EXV\}$. As the **tidal volume(ΔV)** is inhaled during inspiration, this pressure gradient decreases. The pressure gradient at the **end of inspiration** will be denoted by $\{\Delta P - E \times \Delta V\}$. Inspiratory flow ceases if the pressure gradient is **zero** $\{\Delta P = E \times \Delta V\}$. The inspiratory flow will decrease with an increase in resistance, so more inspiratory time is needed to deliver the required volume. The **novel equation of motion** for inspiratory flow at the end of inspiration(**iF_{end}**) is given below.

$$iF_{end} = [1/R] \times \{\Delta P - E \times \Delta V\}$$

If the inspiratory flow stops and does not reach baseline with **reduced inspiratory time**, then the amount of inspired tidal volume will be reduced. **Zero flow state** will be seen if **inspiratory time is prolonged** which are clearly shown in **figure 3**. The **novel equation of motion** for expiratory flow at the start of expiration(**eF_{start}**) is given below.

$$eF_{start} = [1/R] \times \{E \times \Delta V - \text{Set PEEP}\}$$

The **resistive work of expiration** is provided by the **elastic energy stored** during inspiration. The difference between the end inspiratory alveolar pressure $\{[V + \Delta V] \times E\}$ and end expiratory alveolar pressure $[V \times E]$ will provide the required **Passive Elastic Recoil Pressure (P_{EL})** which is clearly denoted by $E \times \Delta V$. The **novel equation of motion** for **Passive Elastic Recoil Pressure(P_{EL})** to exhale a tidal volume during expiration is given below.

$$P_{EL} - \text{Set PEEP} = R \times eF$$

Passive expiratory flow (eF) is directly proportional to **elastic recoil** pressure and **inversely** proportional to **expiratory resistance** and **compliance** which are clearly shown in **figure 4**. **Peak expiratory flow** is seen at the beginning of expiration due to maximum pressure gradient. Then as the expiratory time increases, the expiratory flow rate decreases due to the expired tidal volume that decreases the pressure gradient till it reaches the baseline at the positive end expiratory pressure (PEEP) (Rajini Samuel T 2021). The **novel equation of motion** for expiratory flow at the end of expiration (eF_{end}) is given below.

$$eF_{end} = [1/R] \times [E \times V - \text{Set PEEP}]$$

If the **expiratory flow stops** without reaching the baseline set PEEP, due to reduced expiratory time, then the amount of expired tidal volume will be reduced (due to decreased expiratory flow) that increases residual flow and volume resulting in **air trapping** which are clearly shown in **figure 3**. **Auto PEEP** is generated due to the product of residual flow and resistance (Robert L chatburn 2003, Rajini Samuel T 2021). The inspiration starts at the **end expiratory alveolar volume (V)** during inspiration, lung volume increases by the amount of **inhaled tidal volume (ΔV)** and then during expiration the lung volume decreases, reaching the resting volume by the **exhaled tidal volume (dV)** at the end of expiration.

$$\Delta V - dV = V \quad \text{OR} \quad \Delta V - V = dV$$

The **difference** between the **inhaled tidal volume** and the **exhaled tidal volume** will be the **normal resting lung volume**. Increased resting lung volume results if the exhaled tidal volume is lower than the inhaled tidal volume (Lluis Blanch et al., 2005, Natalini G et al., 2016, Stephen E. Lapinsky 2015, Rajini Samuel T 2021). The **novel equation of motion** relating **expiratory time constant (τ_e)**, expiratory flow and tidal volume is given below.

τ_e : Expiratory Time Constant

$$\tau_e = [\Delta V - V]/eF$$

The above **simple relation** can be used to assess the **expiratory time constant** which is the ratio between the exhaled tidal volume and the peak expiratory flow. It treats the lung as single compartment and does not account for time constant heterogeneity of lungs (Dean R Hess 2014). The expiratory flow is a passive process so the **ratio** between **expiratory time** and **expiratory time constant** is very important in assessing the respiratory mechanics. Higher resistance leads to a longer time constant, so the lung unit fills and empties slowly. Lower compliance will result in shorter time constant, so the lung unit fills and empties quickly. After **one time constant** (or **ratio of one** between **expiratory time** and **expiratory time constant**), the expiratory flow will decrease by **63.3%** to reach a value of **36.7%**. Expiratory flow will decrease by **99.3%** to reach a value of **0.7%** after **five time constant** or ratio of 5 (Iotti GA 2001, Paul Ouellet 1997). The passive expiratory flow is inversely proportional to expiratory time constant (τ_e). The ratio **expiratory time/expiratory time constant** is important for the expiratory flow to exhale the inhaled tidal volume to prevent **air trapping**. The relation between end

expiratory alveolar pressure and volume, externally set PEEP and auto-generated PEEP is clearly shown in the below equation.

$$E \times V = (\text{Auto PEEP} + \text{Set PEEP})$$

$$\text{Auto PEEP} = E \times V - \text{Set PEEP}$$

Auto PEEP (also known as **intrinsic** or **occult PEEP**) is the positive difference between end expiratory alveolar pressure and the end expiratory airway pressure (PEEP set by the clinician). **Total end expiratory pressure** is the sum of the auto-PEEP and the extrinsically applied PEEP in the mechanically ventilated patient. The set PEEP (positive end-expiratory pressure) increases the volume by recruitment of alveoli as well as distension of previously open alveoli (Dean R Hess 2015, Dellamonica N 2011). If there is no auto PEEP and the set PEEP is zero, then end expiratory alveolar pressure will be at the atmospheric pressure level. **Auto PEEP** is present if the **flow does not reach zero** before the beginning of inspiration which is clearly depicted in **figure 3**. If the expiratory time is insufficient, the residual flow will increase leading to **dynamic hyperinflation**. Auto PEEP is generated due to the product of residual flow and resistance or the product of volume of the gas trapped (dynamic hyperinflation) and the elastance of the respiratory system. The residual flow and air trapping that generates auto PEEP is independent of frequency unless it alters I:E ratio (Paul Ouellet 1997, Rajini Samuel T 2021).

The **work** required to deliver a tidal breath during **inspiration** is the product of **tidal volume (ΔV)** and **airway Pressure gradient** that includes both resistive and elastic work. **Total Work done during active inspiration (W_{TOT})** calculated using the **novel equation of motion** is given below.

$$W_{TOT} = \{ iF(R + EXT_i) + R \times rF \} \times \Delta V \quad \text{OR}$$

$$W_{TOT} = \{ iFXE(\tau_i + T_i) + R \times rF \} \times \Delta V$$

$$\text{Where } \Delta P = P_{AW} - \text{Set PEEP}$$

$$\Delta P = iF(R + EXT_i) + R \times rF \quad \text{OR}$$

$$\Delta P = iFXE(\tau_i + T_i) + R \times rF$$

The **work** required to exhale a tidal volume during **expiration** is the product of amount of **tidal volume exhaled (dV)** and the **passive elastic recoil pressure gradient**. The **work done** during **passive expiration** by the Elastic Recoil Pressure (W_{EL}) calculated using the **novel equation of motion** is given below.

$$W_{EL} = R \times (eF + rF) \times dV$$

$$\text{Where } P_{EL} - \text{Set PEEP} = R \times (eF + rF) ;$$

$$P_{EL} = E \times \Delta V$$

The **work done** during **inspiration** is increased by **low compliance (or high elastance)** because more effort is needed to inhale the required tidal volume in the lungs. But the **work done** during **expiration** is increased by **high compliance (or low elastance)** because more effort and time is needed to exhale the required tidal volume out of the lungs due to the decreased **passive elastic recoil pressure ($P_{EL} = E \times \Delta V$)**. **High compliance** is seen in conditions where the lungs can easily stretch and the air can **easily fill** in the lungs but the **air cannot easily come out** of the lungs due to the decreased **passive elastic recoil pressure**. **Low**

compliance is seen in conditions where the lung parenchyma is stiff and does not easily stretch and the air **cannot easily fill** in the lungs but the **air can easily come out** of the lungs due to the increased **passive elastic recoil pressure**. (Shevade MS 2019, Rajini Samuel T 2021). Therefore, abnormal compliance (or elastance) will contribute to the increased work done for breathing but it is different for active inspiration and passive expiration.

Total Work done during active inspiration (W_{TOT}) is decreased by set PEEP and compliance and increased by inspiratory resistance, elastance, inspiratory time, inspiratory time constant, tidal volume and auto PEEP generated due to the residual flow. **Work done** during **passive expiration** is provided by the **elastic recoil pressure (P_{EL})** due to the elastic energy stored during inspiration. W_{EL} is increased by the expiratory resistance, auto PEEP due to residual flow (rF) and the amount of the exhaled tidal volume (dV). The understanding of the various physical concepts like pressure, volume, flow rate, resistance, compliance, time constant, total cycle time, frequency and work done and their relationship plays a significant role in the management of mechanically ventilated patients.

These **six novel equations of motion** derived from the force balance equation should be **considered** as **differential equations** and not as algebraic equations because some of the parameters are constant while others are variable quantity in these equations that changes with changes in other parameters. In the presence of **residual flow** that contributes to the generation of **auto PEEP**, parameters like ΔP and eF should be replaced by $[\Delta P - R \times rF]$ and $[eF + rF]$ respectively in **these six novel equations of motion of ventilator**. These equations can be easily remembered, appropriately utilized and effectively taught to understand and interpret the qualitative changes observed in the ventilator graphical display.

CONCLUSION:

The application of the various physical concepts involved in the formulation of these six novel equations of motion of ventilator may play a significant role in the qualitative identification of the changes observed in the ventilator graphical display. These six novel equations of motion not only helps for its better interpretation but also mainly focus on the factors that contribute to the generation of auto PEEP and increased work of breathing. Therefore it may serve as an effective teaching tool for ventilator graphics interpretation that helps in the reduction of intrinsic PEEP and work of breathing thereby minimizing or preventing lung injury which in turn helps to improve the patient care of mechanically ventilated patients.

Source(s) of support: NIL

Acknowledgement: NIL

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