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DERIVATION, APPLICATION AND RELATIONSHIP OF TIME CONSTANT IN VENTILATOR GRAPHICS INTERPRETATION

*Dr. T. Rajini Samuel M.D

Associate Professor of Biochemistry Shri Sathya Sai Medical College and Research Institute Sri Balaji Vidyapeeth Deemed to be University Guduvancherry-Thiruporur Main Road Ammapettai, Kancheepuram District.

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***Corresponding author: Dr. T. Rajini Samuel M.D**
Associate Professor of Biochemistry Shri Sathya Sai Medical College and Research Institute Sri Balaji Vidyapeeth Deemed to be University Guduvancherry-Thiruporur Main Road Ammapettai, Kancheepuram District.

ABSTRACT

Ventilator Graphics Interpretation plays a significant role at the bedside for monitoring of mechanical ventilation. The basic mathematical model of breathing mechanics using the Equation of Motion for the respiratory system or the force balance equation consider the respiratory system as a single compartment model and the parameters like pressure, volume and flow are all continuous functions of time. Time constant is an engineering concept applied in medical field and it is relevant when modelling a process using exponential functions. The change in lung volume during inspiration and expiration is due to the variation in pressure but the process is a time consuming process. The time constant describes the speed of this process specifying how much time is required to inhale adequate tidal volume during inspiration and to exhale the tidal volume during expiration. The physical concepts of pressure gradient, resistance, compliance, frequency, tidal volume, flow and work done are required to understand the basics of mechanical ventilation. The study discuss in detail the derivation, application and relationship of time constant with other parameters in mechanical ventilation and concludes that time constant plays a significant role in understanding of the mechanical ventilation that helps in the interpretation of ventilator graphics.

KEYWORDS: Time Constant, Resistance, Compliance, Respiratory Mechanics.

INTRODUCTION

Ventilator Graphics Interpretation plays a significant role at the bedside for monitoring of the mechanical ventilation. The basic mathematical model of breathing mechanics using the Equation of Motion for the respiratory system or the force balance equation consider the respiratory system as a single compartment model and the parameters like pressure, volume and flow are all continuous functions of time.[1,2] 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. The airflow is directly proportional to the pressure difference and inversely proportional to the airway resistance. Airway resistance varies between inspiration and expiration and it is normal that the expiratory resistance is higher than the inspiratory resistance due to the shape of the airway tree.[3,4,5] Compliance denotes the amount of air in ml the lungs can hold for every 1 cm H_20 change in pressure. Elastance is the reciprocal of compliance.[3,6]

Time constant is an engineering concept applied in medical field, relevant when modelling a process using exponential functions and it does not apply for constant functions. The change in lung volume during the process of inspiration and expiration is due to the variation in pressure but it is a **time consuming process**. The **time constant** describes the speed of this process and it specifies how much time is required to inhale adequate tidal volume during inhalation and to exhale the required tidal volume during expiration.[6] **Time constant** is the time that a process would take to complete if its **initial rate of change** remained **constant** and it characterizes the rate of variation of the function over a period of time. The time constant is usually defined as the time required for **inflation up to 63%** of the final volume or **deflation by 63 %**. A time constant is a time interval. Short time constant imply a faster rate of change and a long time constant imply a slower rate of change.[6,7,8]

The **total cycle time (TCT)** or ventilator period denotes the sum of both the **inspiratory time** and **expiratory time** and it is inversely related to the frequency. The **inspiratory time** is measured from the beginning of the positive flow to the beginning of the negative flow. **Inspiratory pause time** is the interval during which inspiratory **flow** has **ceased** but **expiratory flow** is **not** yet allowed. The inspiratory time is the sum of the inspiratory flow time and inspiratory pause time.[2,5] The amount of tidal volume inhaled is the product of inspiratory flow(constant or average) and the inspiratory time.[2] During expiration a **baseline** or **expiratory pressure** is always measured and set relative to atmospheric pressure and a positive value is called as the **positive end-expiratory pressure (PEEP).** This is referred to as the **baseline variable**. In zero setting the baseline pressure is set equal to the **atmospheric pressure.**[2] The derivation, application and relationship of time constant with other parameters in mechanical ventilation are discussed in detail along with the physical concepts of pressure gradient, resistance, compliance, frequency, tidal volume, flow and work done. The study concludes that time constant plays a significant role in understanding of the mechanical ventilation that helps in the interpretation of ventilator graphics.

MATERIALS AND METHODS

The physical concepts involved in the understanding of mechanical ventilation are to be discussed in detail. **Scalar** is a physical quantity which has only magnitude and no direction. **Vector** is a physical quantity which has both magnitude and direction. **Unit vector** is a vector whose magnitude is one and has direction only. If a **vector** is divided by its **own magnitude**, then its **magnitude** becomes **one** and so it has **only direction**.The term **normal** denotes the direction is **perpendicular** to it.[9] Time, volume, mass, density, area, speed and distance are scalars. Flow velocity, cross sectional vector area, Force, displacement, Momentum, velocity and acceleration are vectors.

In a right angled triangle (one angle is 90º), the side **opposite** to **90º** is called as the **hypotenuse**. The side adjacent to the angle A is called **adjacent side** and the side opposite to the **angle A** is called **opposite side**.[9]

Cos A =adjacent side/hypotenuse

If **two vectors** are **multiplied** and the product is a **scalar** quantity, then it is called as scalar or dot product of vectors. It is equal to the **product** of the **magnitudes** of the **two vectors** and the **cosine** of the **smallest angle** between them.[9]

Volumetric Flow Rate

Volumetric flow rate (**Q** or $\dot{\mathbf{V}}$) is defined as the flow of volume *V* of fluid or gas through a surface per unit time *t*. This is the time derivative of volume so the volumetric flow rate is a **scalar quantity**.[10]

$$\mathbf{Q = \dot{V} = dV/dt}$$

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

Q=v.A

Q= vAcosθ

The volume of the fluid or gas passing through the cross-section 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 θ**). As the **angle θ increases**, **lesser volume** of the fluid or gas passes through. The **maximum volume** flowing through the cross sectional area occurs when the flow velocity vector and the cross sectional area vector are in **parallel** (**angle θ** is **zero**). The amount of the **volumetric flow rate** is **zero** when the two vectors are **perpendicular** to each other (angle θ is 90°).[10]

Mass Flow Rate

The mass flow rate (**ṁ**) is the mass of a substance which passes per unit of time. This is a time derivative of mass and so it is a **scalar quantity**.[10,11]

ṁ = dm/dt

The mass flow rate (**ṁ**) is related to the **Volumetric flow rate (Q or $\dot{\mathbf{V}}$)** using the mass density. The **mass density (*ρ*)** is the ratio between mass and volume.

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

Mass flow rate = density x Volume flow rate OR Volume flow rate = Mass flow rate/ density

Relationship of Pressure and Momentum

The relationship of momentum, force, kinetic energy and mass is shown in the following formulas.[12,13]

Momentum = mass x velocity (Momentum = m x v)
Force = mass x acceleration (Force= m x a)
Acceleration = velocity / time {a = v/t }
Kinetic Energy = ½ mv^2
Pressure = force / area

If the gas molecules are enclosed in a container at constant pressure then the pressure is the sum of the forces of all the molecules striking the wall divided by the area of the wall. **Momentum flow** would be the **momentum** passing through a **unit area** per **unit time**.[12]

Momentum flow = momentum / area x time
Momentum flow = mv/ area x time
Momentum flow = ma/area ; {a = v/t}
Momentum flow = force / area

Pressure is force divided by area which is the **same** as the **momentum per area per time**. Pressure has magnitude and no direction. It is a **scalar** quantity and not a vector.

Relationship between Airflow and Pressure Gradient

Airway Resistance (**R_{AW}**) in the airway is equal to the **pressure gradient** (**ΔP**) divided by the **Volumetric Airflow** (**$\dot{V}$**).Hence **resistance** is a **scalar** quantity.[3,4,13]

$\mathbf{R_{AW} = \Delta P / \dot{V}}$ OR $\mathbf{\Delta P = \dot{V} \times R_{AW}}$

Relationship between Resistance and Flow Rate

Pressure is the force divided by the area. The force is the product of mass and acceleration and the acceleration is the rate of change of velocity. These relations are applied in the following derivations.

F= m x a;   a = v/t

F= m x v/t   or F= v x m/t

Substituting these in the pressure relation the following is obtained.

P=F/A

P = {v x m/t}/ A

P = A x {v x m/t}/ A^2 [Multiply & divide by area]

P = [v x A] x (m/t)/ A^2

Volumetric flow rate (Q or $\dot{V}$ = v.A) is the product of flow velocity (v) and the cross sectional vector area (A). This relationship is substituted in the above derivation to get the following.

P = [$\dot{V}$] x (m/t)/ A^2

The above derivation is to be compared with the relationship between pressure gradient (ΔP), Volumetric Airflow ($\dot{V}$) and the airway resistance (R_{AW}).

ΔP = $\dot{V}$ x R_{AW}

The following relationship is obtained by comparing the above two relations.

R_{AW} = (m/t)/ A^2

Mass flow rate (**$\dot{m}$ =ρ.$\dot{V}$**) is the mass of a substance which passes per unit of time (**m/t**) and is related to the **Volumetric flow rate (Q or $\dot{V}$)** with the mass density (**ρ**).

R_{AW}= [ρ.$\dot{V}$] / A^2

The resistance is **inversely** related to the **square** of the cross sectional **area** (or **fourth power** of **radius**). As the **density** and **volume flow rate increases** the **resistance** also **increases**. Thus high flow rate will result in increased resistance which in turn will lead to an increased peak inspiratory pressure.

Relationship between Compliance and Elastance

Compliance = Change in Volume in ml(ΔV) / Change in Pressure in cm H_2O (ΔP)

Compliance = ΔV/ΔP ; Elastance = ΔP/ΔV

The relationship between pressure, volume and compliance can be explained using **pressure volume loop.** [2,3,6,14] The **normal compliance** using the pressure volume variation during the inspiration and expiration is shown in the **figure 1A** using pressure volume loop. If the compliance is **increased**, then the loop **shifts** towards the **left** and if the compliance is **decreased** then it shifts towards the **right** which are clearly seen in the **figure 1B** and **figure 1C** respectively.

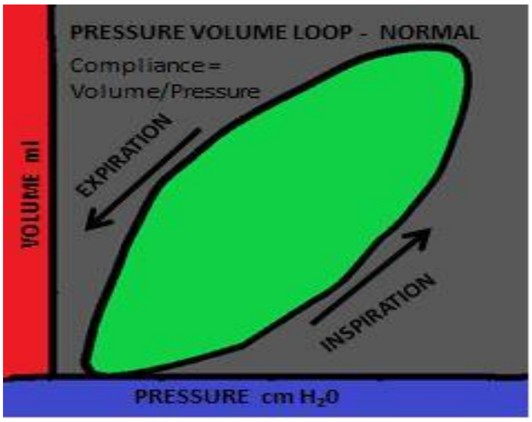

Figure 1A: Normal Compliance.

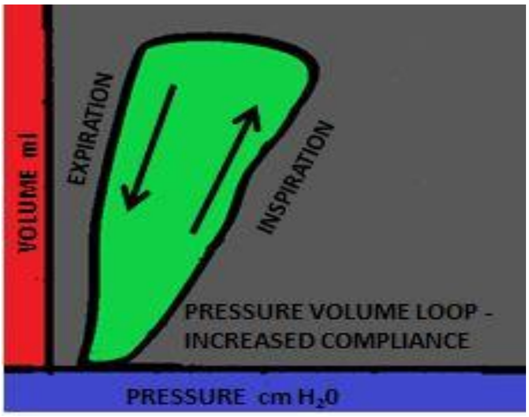

Figure 1B: Increased Compliance.

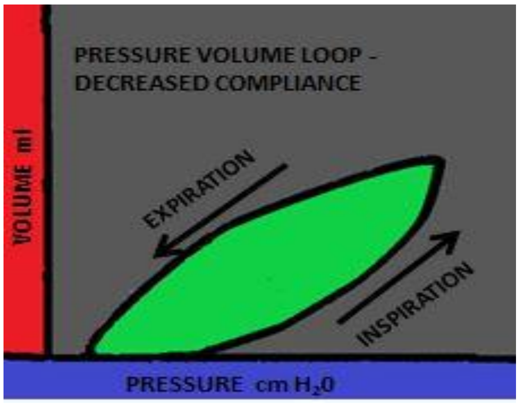

Figure 1C: Decreased Compliance.

Work Done

Work is a scalar quantity, often represented as the product of force and displacement.[2,7,15,16] When the force *F* is constant and the angle between the force and the displacement *s* is θ, then the work done is given by the following relation.

W= Fscos θ

Work done (W) is also the product of pressure (P) and volume (V).[2,7,15,16,17] Pressure-volume work (PV work) occurs when the volume of a system changes (dV) which is clearly depicted in the **figure 2A** for both the inspiration and expiration.

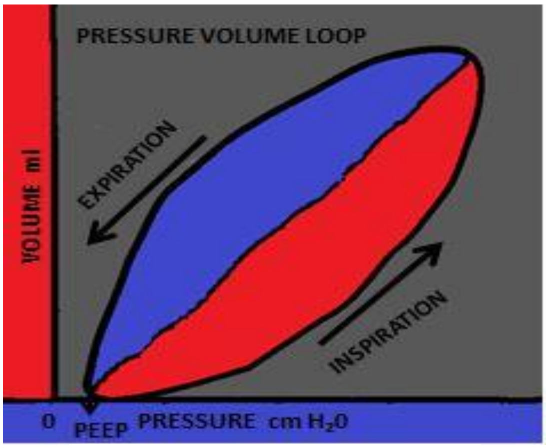

Figure 2A: Pressure Volume Work.

Work = pressure x Volume
Work = Force/area x area x length
Work = Force x Length

Thus product of pressure (P) and volume (V) is the same as the product of force (F) and displacement(s).[2,7,15,16,17] The work required to deliver a tidal breath during inspiration is the product of tidal volume(TV) and airway Pressure. The work done during breathing is increased by the resistance which is clearly shown in the **figure 2B**.

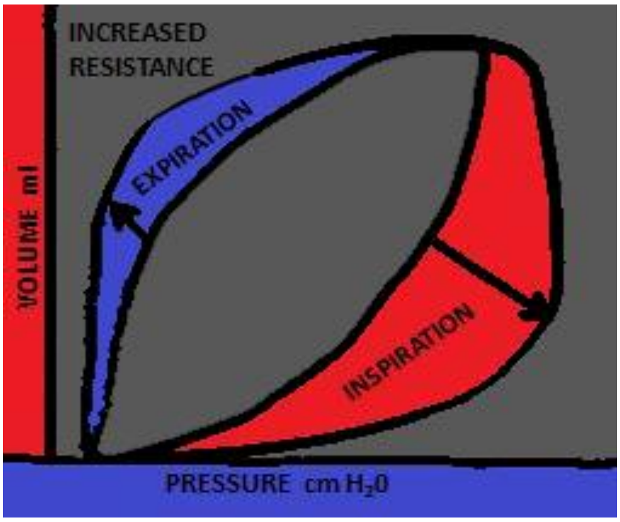

Figure 2B: Increased Resistance Pressure Volume Work.

Exponential Functions
An **exponential function** is a mathematical expression that describes an event where the rate of change of one variable is proportional to its magnitude. The **logarithm** is the **inverse function** to **exponentiation**. A **decaying exponential** function expresses a decrease of one variable as a function of time (shown in **figure 3A**). A **rising exponential** function expresses an increase of one variable as a function of time (shown in **figure 3B**). Exponential functions are often described with time constants.[7,8,16]

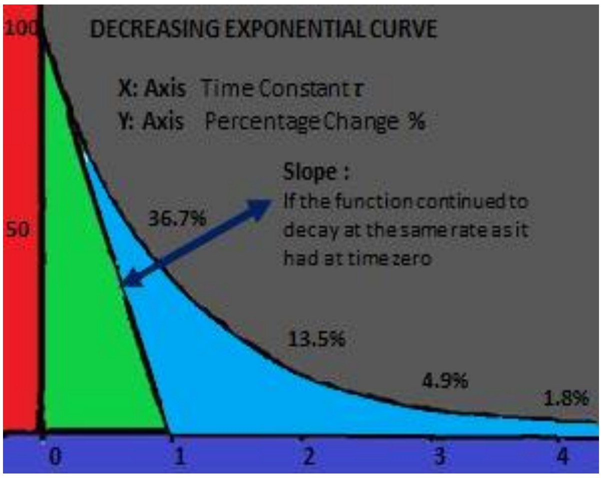

Figure 3 A: Decreasing Exponential Curve.

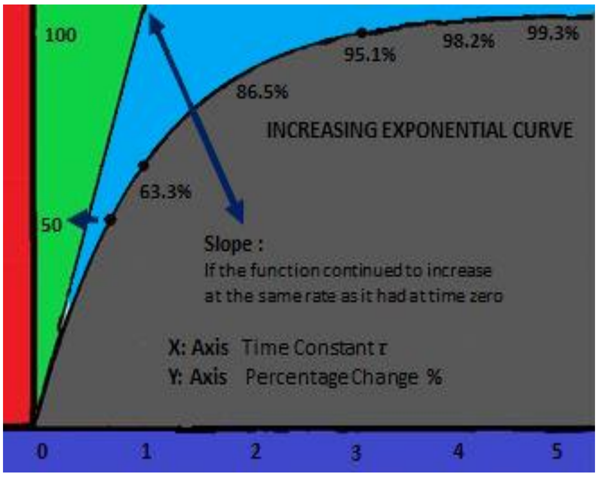

Figure 3 B: Increasing Exponential Curve.

If the function continued to change at the same rate as it had at time zero (without curving exponentially and slowing its rate of change), it would have obviously reached the baseline quickly. The time it would take to reach the baseline is **one time constant**.[18] After one time constant the function has decreased to 37 % (or it has decreased by 63 %) in the **decreasing** exponential curve which is clearly shown in the **figure 3 A**. After one time constant the function has increased to 63 % in the **increasing** exponential curve which is clearly shown in the **figure 3 B**. These two are exponential curves using the base of natural logarithm (e).[6,7,8,16]

Decaying Exponential Curve
A **decaying exponential function** expresses the behaviour of a physical system where the rate of change of one variable is proportional to its magnitude only. Let y be the variable then dy/dt is the rate of change of the variable. The **function y approaches zero** as time progresses and the **rate of change** of y decreases **toward zero**. The value of y is **greatest** at the **beginning** of the event, rate of change is also greatest at the beginning and lowest at the end of the event.[7,16]

$$\mathbf{y = y_o e^{-t/\tau}}$$

At time t= 0,

$\mathbf{y = y_o e^{-0/\tau}}$
$\mathbf{y = y_o}$
y: value of the variable at time t
$\mathbf{y_o}$**:** value of the variable y at time zero. (Max Value at the beginning)
t: period of the time after the onset of the event.
$\boldsymbol{\tau}$**:** Time constant of the respiratory system

Rising Exponential Curve
A rising exponential function expresses the behaviour of a physical system where the rate of change of one variable is proportional to its magnitude and a constant. The constant is usually the final value of the variable in physical systems. Let y be the variable then dy/dt is the rate of change of the variable. **The function y approaches maximum value** as time progresses and the **rate of change** of y **decreases toward zero**. The **difference** between the initial value and the final value of y is **greatest** at the **beginning** of the event, rate of change is also greatest at the beginning and lowest at the end of the event.[7,16]

$\mathbf{y = y_{final}(1- e^{-t/\tau})}$
$\mathbf{y = y_{final} - y_{final}\, e^{-t/\tau}}$
At time t= 0,
y = 0
y: value of the variable at time t
$\mathbf{y_{final}}$**:** final value of the variable y

The time constant values for the **decreasing** and **increasing** exponential functions are calculated and shown in the **table 1** and **table 2** respectively. In **decreasing** exponential function the value of $\mathbf{y_o}$ is **100 %** and in **increasing** exponential function the value of $\mathbf{y_{final}}$ is **100 %**.[7,16]

Table 1: Decreasing Exponential Function Time Constant Values.

One Time Constant	Two Time Constant	Three Time Constant	Four Time Constant	Five Time Constant
$y = y_o e^{-t/\tau}$ $y = y_o e^{-1}$ $y = y_o\,(1/e)$ $y = y_o(0.367)$	$y = y_o e^{-t/\tau}$ $y = y_o e^{-2}$ $y = y_o(1/e^2)$ $y = y_o(0.135)$	$y = y_o e^{-t/\tau}$ $y = y_o e^{-3}$ $y = y_o(1/e^3)$ $y = y_o(0.049)$	$y = y_o e^{-t/\tau}$ $y = y_o e^{-4}$ $y = y_o(1/e^4)$ $y = y_o(0.018)$	$y = y_o e^{-t/\tau}$ $y = y_o e^{-5}$ $y = y_o(1/e^5)$ $y = y_o(0.007)$
y = 36.7 %	**y = 13.5 %**	**y = 4.9 %**	**y = 1.8 %**	**y = 0.7 %**
SUBSTITUTED VALUES e: 2.718 (≈ 2.72)				
$\mathbf{1/e}$	$\mathbf{1/e^2}$	$\mathbf{1/e^3}$	$\mathbf{1/e^4}$	$\mathbf{1/e^5}$
0.367	0.135	0.049	0.018	0.007

Table 2: Increasing Exponential Function Time Constant Values.

One Time Constant	Two Time Constant	Three Time Constant	Four Time Constant	Five Time Constant
$y= y_{final}(1-e^{-t/\tau})$ $y= y_{final}(1-e^{-1})$ $y= y_{final}(1- 1/e)$ $y = y_{final}(0.633)$	$y= y_{final}(1-e^{-t/\tau})$ $y= y_{final}(1-e^{-2})$ $y= y_{final}(1- 1/e^2)$ $y= y_{final}(0.865)$	$y= y_{final}(1-e^{-t/\tau})$ $y= y_{final}(1-e^{-3})$ $y= y_{final}(1- 1/e^3)$ $y= y_{final}(0.951)$	$y= y_{final}(1- e^{-t/\tau})$ $y= y_{final}(1- e^{-4})$ $y= y_{final}(1- 1/e^4)$ $y= y_{final}(0.982)$	$y= y_{final}(1- e^{-t/\tau})$ $y= y_{final}(1- e^{-5})$ $y= y_{final}(1- 1/e^5)$ $y= y_{final}(0.993)$
y= 63.3 %	**y= 86.5 %**	**y= 95.1 %**	**y= 98.2 %**	**y= 99.3 %**
SUBSTITUTED VALUES e: 2.718 (≈ 2.72)				
$\mathbf{1-1/e}$	$\mathbf{1-1/e^2}$	$\mathbf{1-1/e^3}$	$\mathbf{1-1/e^4}$	$\mathbf{1-1/e^5}$
1-0.367	1-0.135	1-0.049	1-0.018	1-0.007
0.633	0.865	0.951	0.982	0.993

Calculation of Resistance, Compliance and Time Constant
Resistance and **compliance** can only be **calculated in volume control mode** with a constant flow rate during inspiration. **Peak Inspiratory Pressure (PIP)** representing the peak dynamic pressure includes the dynamic pressure to drive the gas across the resistance of the bronchial tree and the static pressure to expand the alveoli against the elastic recoil of the lungs and chest wall (Plateau pressure).**Inspiratory hold Manoeuvre** abolishes the pressure contribution from the airway resistance and reveals the pressure in the alveoli. When the **Peak Inspiratory Pressure (PIP)** is reached, a **pause time** or plateau is maintained (seen in the **figure 4**). Then the pressure inside the airways and the breathing circuit equilibrates at **plateau pressure (Pplateau)**.Flow then stops while pressure equilibrates. **Pz** is the **airway pressure** when flow stops **(zero flow)** during **pause time**.[2,5,7]

The **difference** between **Peak pressure** and the **plateau pressure** (Pplat) is proportional to **airway flow dependent resistance**. It is normal that the expiratory resistance (Rexp) is higher than the inspiratory resistance (Rins).[2,5,7]
Rins = (PIP - Pplat) / Peak Inspiratory Flow
Rexp = (Pplat - PEEP) / Peak Expiratory Flow

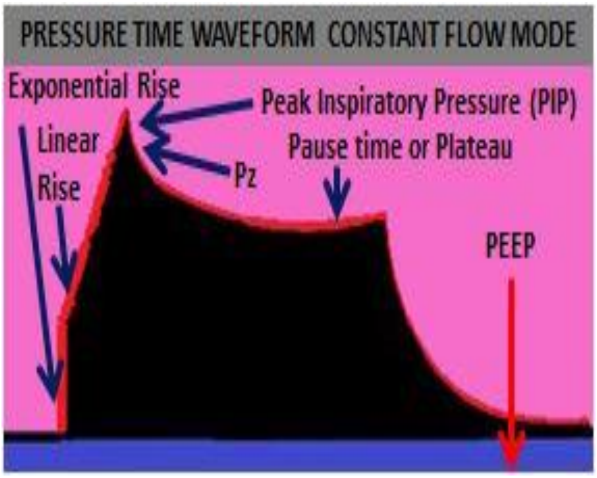

Figure 4: Plateau Pressure - Pressure Time Waveform.

Static compliance(C stat) measures the elasticity of the lung when there is no air movement. **Dynamic compliance** includes **both resistive** and **elastic components**, so it is **not a reliable indicator** of lung elasticity compared to static compliance.[2,5,7,16] The **slope** that denote dynamic compliance is shown in the **figure 5** using the pressure volume loop.

Static Compliance(C stat) = Tidal Volume / {Plateau pressure - PEEP}
Dynamic compliance = Tidal Volume / [Peak Pressure - PEEP]

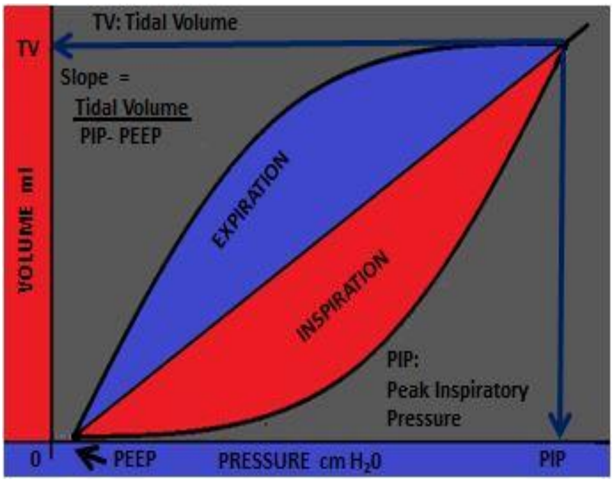

Figure 5: Pressure Volume Loop-Compliance.

The **time constant** measured in seconds is calculated using the **product** of **resistance**(R) and **compliance**(C) in mechanical ventilation. **Inspiratory time constant** (RC ins) and **expiratory time constant** (RC exp) are **not equal** because airway resistance are usually lower during inspiration as compared to expiration. Thus inspiratory time constant is **shorter** than the expiratory time constant.[5,6,18,19,20]

Time constant (in seconds) = Resistance x Compliance
RC ins = Cstat x Rins
RC exp = Cstat x Rexp

The ratio between the expiratory and inspiratory time constant is the same as the ratio between the expiratory and inspiratory resistance. The ratio between the expiratory and inspiratory time constant and the difference between the expiratory and inspiratory time constant varies in different conditions which may have some clinical significance.
RCexp / RC ins = Rexp / Rins
RCexp - RC ins = Cstat x (Rexp - R ins)

Total Cycle Time & Frequency

The total cycle time (TCT) is the sum of both the inspiratory time (T_I or I) and expiratory time (T_E or E) which is clearly shown in the **figure 6**. This is called as the ventilator period measured in seconds. **Total cycle time** is **inversely related** to the **frequency** (number of breaths or number of ventilator cycles per minute).If the frequency is increased, the total cycle time is decreased or if the **frequency** is **decreased** then the **total cycle time** is **increased.**[2]
f = 1/period

f = 60 seconds / T_I + T_E or f = 60 seconds / TCT or TCT = 60 seconds / f
Inspiratory time and expiratory time are represented as I: E ratio. Some ventilators use **duty cycle** or **percent inspiration** as an **alternative** to **I: E ratio**.[2]

% inspiration = {I / (I + E)} X 100%

The duty cycle can be easily converted into I: E ratio.
I: E = (% inspiration): (100 % - % inspiration)

The inspiratory time can be represented using the duty cycle in the following way.
T_I = [T_I/TCT] x TCT

So the inspiratory time is the product of the total cycle time and the duty cycle. The relationship of total cycle time and frequency (TCT = 60 seconds / f) is substituted in the above relation to get the following result.
T_I = [T_I / TCT] x [60 seconds / f]
TCT = T_I + T_E or T_E = TCT - T_I

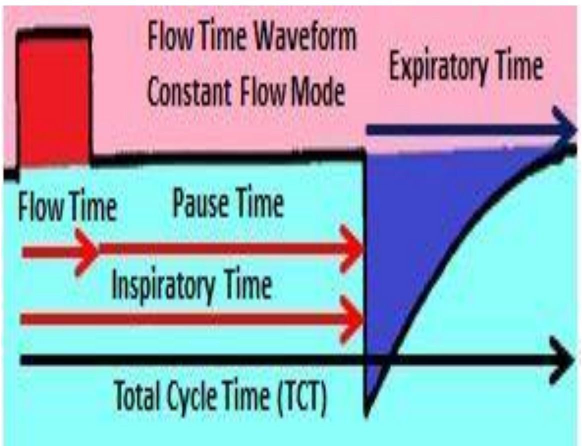

Figure 6: Total Cycle Time.

RESULTS

The relation between frequency, inspiratory time (**T_I**), expiratory time (**T_E**), I**:** E ratio, inspiratory time constant (**τ_i or RC ins**) and expiratory time constant (**τ_e or RC exp**) are assessed using **some arbitrary values** and the results are tabulated. The changes in **frequency** will result in changes in the duration of the **total cycle time**. If the **total cycle time** is **changed,** then either or both the **inspiratory time** and **expiratory time** duration will **change.** Sometimes both the inspiratory time and expiratory time duration may change but the total cycle time remains the same. It depends on the ratio between the inspiratory time and expiratory time duration (**I:E** ratio). The changes in **frequency alone** will **not change** the **I: E** ratio which is clearly shown in the **table 3** using some arbitrary values.

The ratio between inspiratory time (**T_I**) and inspiratory time constant (**τ_i or RC ins**) and the ratio between expiratory time (**T_E**) and expiratory time constant (**τ_e or RC exp**) are used to assess the completion process of inspiration and expiration. The calculated **ratios** namely **T_I/RC ins** and **T_E/RC exp** along with values of frequency, total cycle time and the I: E ratio are clearly depicted in the **tables 4A** and **4B** using some arbitrary values. These ratios are different for the same frequency and I: E ratio which are clearly shown using a different value of inspiratory time constant (**0.2** & **0.3**) and expiratory time constant (**0.4** & **0.5**) in these tables **4A** and **4B** respectively.

Table 3: Relationship of Frequency, Total Cycle Time & I: E Ratio.

S.No	Frequency (Breaths per Minute)	Total Cycle Time (TCT Sec)	Inspiratory Time (T_I Sec)	Expiratory Time (T_E Sec)	I: E Ratio T_I /T_E	Duty Cycle {I/(I + E)}x100%
1	20	3	1.5	1.5	1:1	50%
2	20	3	1.0	2.0	1:2	33%
3	15	4	1.0	3.0	1:3	25%
4	15	4	2.0	2.0	1:1	50%
5	10	6	2.0	4.0	1:2	33%
6	10	6	4.0	2.0	2:1	67%

Table 4A: Frequency, T_I/RC ins, T_E/RC exp & I:E.

S.NO	Freq	TCT (Sec)	RC ins (Sec)	RC exp (Sec)	T_I (Sec)	T_E (Sec)	T_I/ RC ins	T_E/RC exp	Ratio I:E
1	20	3	0.2	0.4	1.0	2.0	5	5	1:2
2	20	3	0.2	0.4	0.6	2.4	3	6	1:4
3	20	3	0.2	0.4	1.8	1.2	9	3	3:2
4	15	4	0.2	0.4	1.6	2.4	8	6	2:3
5	15	4	0.2	0.4	1.2	2.8	6	7	3:7
6	15	4	0.2	0.4	2.0	2.0	10	5	1:1

Table 4B: Frequency, T_I/RC ins, T_E/RC exp & I:E.

S.NO	Freq	TCT (Sec)	RC ins (Sec)	RC exp (Sec)	T_I (Sec)	T_E (Sec)	T_I/ RC ins	T_E/RC exp	Ratio I:E
1	20	3	0.3	0.5	1.0	2.0	3.33	4.0	1:2
2	20	3	0.3	0.5	0.6	2.4	2	4.8	1:4
3	20	3	0.3	0.5	1.8	1.2	6.0	2.4	3:2
4	15	4	0.3	0.5	1.6	2.4	5.33	4.8	2:3
5	15	4	0.3	0.5	1.2	2.8	4.0	5.6	3:7
6	15	4	0.3	0.5	2.0	2.0	6.66	4	1:1

DISCUSSION

Ventilators play a major role in the management of intensive care unit patients and the **Ventilator Graphical tool** helps in monitoring the mechanical ventilation at the bedside. A lot of advancement in Mechanical Ventilator technology has taken place yet the understanding and interpretation of Ventilator Graphics at the bedside seems to be a challenging one.[1] The Equation of Motion for the respiratory system is the basic mathematical model of breathing mechanics.[2] The understanding and application of the various physical concepts involved in it plays a vital role in the management of these patients.

In respiratory physiology, **airway resistance (R_{AW})** is equal to the difference in pressure (called pressure gradient) divided by the air flow.The factors influencing the resistance to gas flow are radius, density and viscosity of gas, the type of flow pattern and shape of the pathway. Three types of flow patterns occur simultaneously in the respiratory tract namely **laminar**, **turbulent** and **mixed** flow pattern. The air flowing in a **laminar manner** has **less resistance** compared to the air flowing in a turbulent manner. If **airflow becomes turbulent**, the **pressure gradient** required to maintain airflow will need to be **increased**, which in turn would **increase turbulence** and **therefore resistance**. The **Hagen–Poiseuille equation** is a physical law that gives the relationship between the pressure drop, flow rate and resistance in fluid dynamics. The application of this equation to the respiratory tract is not strictly correct but helps in understanding that a minimal changes in the radius of the airways results in larger changes in the airway resistance.[3,4,8,13]

$$\Delta P = 8\eta l\, \dot{V}/\pi r^4$$

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

$$R_{AW} = 8\eta l/\pi r^4$$

ΔP: Pressure difference; **$\dot{V}$**: Volumetric flow rate; **R_{AW}:** Airway resistance **η:** viscosity of the gas; **r**: radius of the tube ; l: length of the tube.

Reynold's Number (N_R) is a unitless number that can be used to indicate the type of the gas flow. If the Reynold's Number(N_R) is **less than 2000**, the flow is mainly **laminar** in nature and the value **above 4000** indicates that **turbulent flow** occurs. **Between** these values, flow is **transitional** and both types of flow co-exist.[13] The **factors** like velocity of gas flow, density of gas and the radius of tube **increase the number** and the viscosity of gas will **decrease the number**. This shows that **larger airways** are **more prone** to **turbulent flow** than smaller airways.[13]

$$N_R = v \times d \times (2r/\eta)$$

v: velocity of gas flow ; **d:** density of gas ; **r:** radius of the tube ; **η:** viscosity of the gas

The **time constant** is useful to assess whether the respiratory system fills and empties slowly or quickly. If the time constant is longer, the lung unit fills and empties slowly. Similarly if the time constant is shorter, the lung unit fills and empties quickly. If the resistance and compliance of each alveolus is different, then each lung units will have different time constants. So, gas exchange takes place between them due to redistribution of gases from lower compliance unit into high resistance unit of lungs.[5,7,18] This is called the **pendelluft effect** which is clearly seen in the **figure 7** as a gradual downward drift of the plateau pressure.

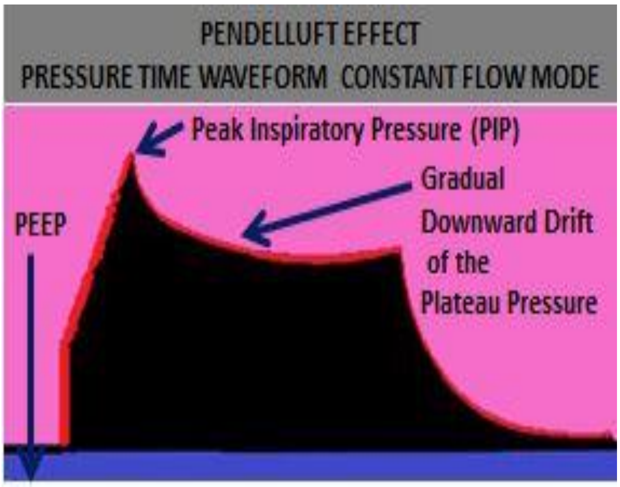

Figure 7: Pendelluft Effect Exchange of Gases.

The inspiratory flow time waveform will be in the exponential form only in the **pressure controlled** ventilation, so during **inspiration** the **time constant** can be evaluated only in this mode. But during **expiration**, the time constant can be evaluated **regardless of the ventilation mode** because the expiratory flow time waveform is an exponential function for passive expiration. Thus the **Expiratory time constant** is very useful for assessing the overall respiratory mechanics and so the **ratio** between **expiratory time** and **expiratory time constant** is very important.[2,5,6] After one time constant (or **ratio T_E/RC exp of one**), the expiratory flow will **decrease by 63.3%** to **reach** a value of **36.7 %**.The expiratory flow will **decrease by 99.3%** to **reach** a value of **0.7%** after five time constant (**ratio of 5**).(shown in **figure 8**)[2,5,6] The **expiratory flow** will **not reach** the **zero** reference baseline if the **ratio** T_E/RC exp **decreases**.

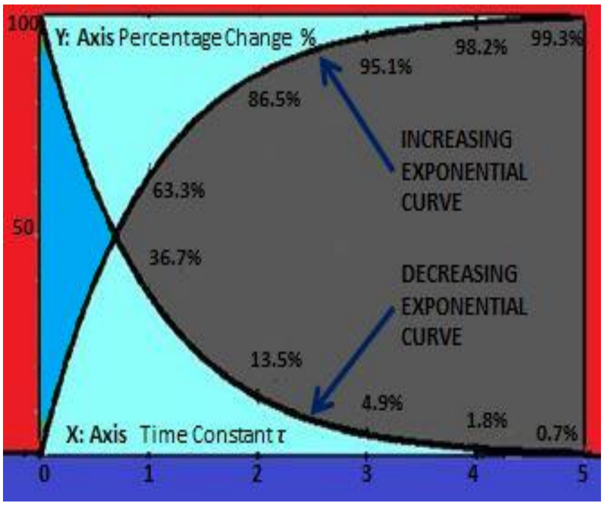

Figure 8: Time Constant for Exponential Functions.

If the **inspiratory time constant** is **shorter**, the tidal volume is inhaled **quickly** or short inspiratory time is sufficient to inhale the tidal volume. If the inspiratory time constant is **longer**, the tidal volume is inhaled **slowly** or long inspiratory time is needed to inhale the required tidal volume. Similarly if the **expiratory time constant** is **shorter**, then short expiratory time is sufficient to exhale the tidal volume and the tidal volume is exhaled quickly, so the expiratory flow time curve has a **rapidly decreasing flow**. If the expiratory time constant is **longer**, the expiratory flow time curve decreases **slowly** due to the prolonged expiratory time required to eliminate the tidal volume which is exhaled slowly. **Increased resistance** leads to a **reduced peak** expiratory flow and an **increased expiratory time constant** that requires prolonged expiratory time which is clearly depicted in **figure 9**.[2,5,6]

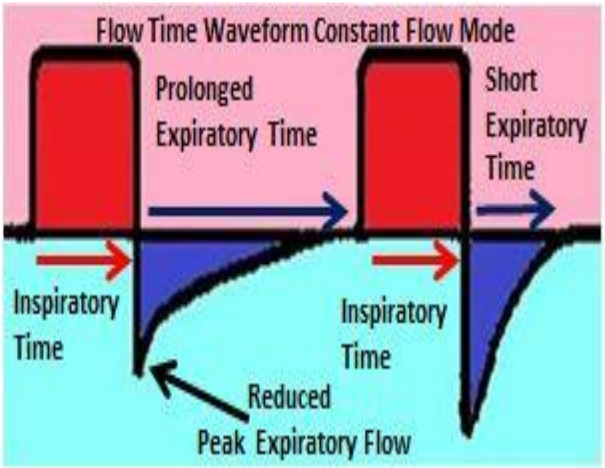

Figure 9: Reduced Expiratory Flow Rate- Flow Time.

If the **inspiratory time is too long** for the patient, the inspiratory flow time waveform after reaching the baseline it continues with **zero flow state** indicated by the **gap as area of no flow**. If the **inspiratory time** provided is **not sufficient** then the inspiratory flow time curve does not reach the baseline (shown in **figure 10**).[14] The mean airway pressure is reduced due to the decreased inspiratory time. If the **expiratory time** is **not sufficient** then the amount of tidal volume exhaled will be incomplete resulting in **trapping of air**.[21,22,23] From the **figure 11**, it is very clear that the inspiratory time is very long which result in zero flow state that indirectly decreases the expiratory time such that the expiratory flow time waveform does not reach the baseline resulting in **air trapping**.

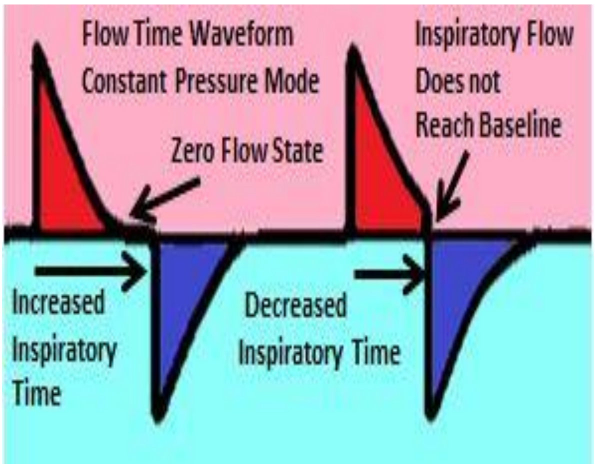

Figure 10: Effect of Increased and Decreased Inspiratory Time on Flow

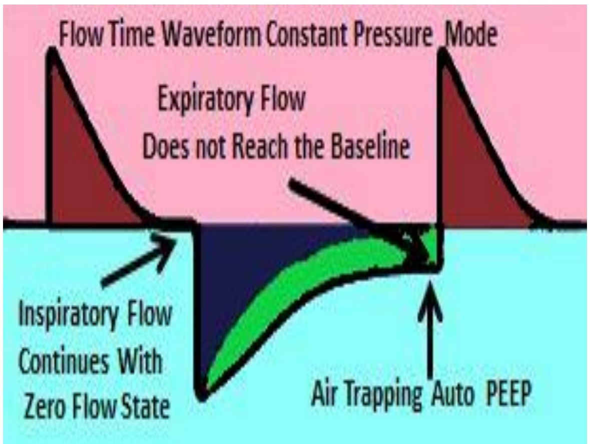

Figure 11: Air Trapping - Decreased T_E/RC exp ratio.

When the **expiration time** is **insufficient**, the expiratory flow will decrease leading to an increase in end expiratory lung volume that results in **dynamic hyperinflation**.This **prevents** the respiratory system from **returning** to its **resting end expiratory equilibrium volume** between breath cycles. **Trapped gas volume** or **residual volume** refers to the gas volume associated with dynamic hyperinflation and auto PEEP.[21,22,23] **Auto PEEP** could be more effectively **reduced** by **increasing expiratory time** to increase the ratio between expiratory time and time constant **rather** than by **decreasing** the **inspired tidal volume**.[21,22,23] The inhaled tidal volume is the product of constant or average inspiratory flow and inspiratory time. If the **inspiratory flow** is **increased** then the required tidal volume is inhaled with a **short inspiratory time** that will help in **increasing the expiratory time**. The frequency and total cycle time duration are inversely related. So **decreasing** the **frequency** will **increase** the **total cycle time** (TCT) duration that may help in increasing the expiratory time **depending** on **I: E ratio**. The inspiratory time and expiratory time can be adjusted to maintain a required **I: E ratio**. The understanding and application of time constant is an essential part in the management of patients in mechanical ventilation.

CONCLUSION

The interpretation of ventilator graphics plays a significant role in monitoring the mechanically ventilated patients which helps in timely management. The understanding of the relationship of various physical concepts like pressure gradient, resistance, compliance, frequency, tidal volume, flow and work done involved in mechanical ventilation is very important in the management of these patients. The study concludes that understanding the relationship of time constant and its application in the mechanical ventilation plays a major role in the interpretation of ventilator graphics.

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