Review Article

Time Constant: What Do We Need to Know to Use It?

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Abstract

Mechanical ventilation is an important strategy to manage patients with respiratory ailments in the acute as well as chronic setups. To be able to do so, we need a good understanding of the physiology of the respiratory system and the disease pattern. Two major components of the lung physiology are compliance and resistance and these define time constants (TCs). Compliance is the measure of distensibility of lungs. It is the change in pressure by the change in volume. Resistance is the opposing force that is created when air flows in the airway. Compliance and resistance together produce an entity called TC. TC defines the amount of time taken in seconds for the lung unit to fill or empty. TCs normally vary within the lungs and do more so in the diseased lungs. This article gives an overview of TCs and its components for the better understanding of the reader.

Keywords: Compliance, resistance, time constant

Introduction

In India, millions of patients suffer from respiratory diseases such as asthma, chronic obstructive pulmonary diseases (COPDs), acute respiratory distress syndrome (ARDS), tuberculosis, pneumonia, and lung cancer.[1,2] Management of these diseases involves pharmacological management and adjunct therapies such as mechanical ventilation, pulmonary rehabilitation, nutrition, and counseling. Out of all these therapies, mechanical ventilation is definitely an important aspect of managing patients with acute as well as chronic respiratory illnesses. It reduces the work required for the lungs to breathe, thereby allowing them to rest and resolve the underlying issue. Every decision right from the selection of the ventilator to choosing the mode and its settings depends on the patient's history, age, gender, pathophysiology of the disease as well as the severity of the disease. It is therefore pertinent for clinicians to have a thorough understanding of the basic physiology of the respiratory system before proceeding to decide the mode and its settings. The fundamental characteristics of lung physiology, compliance, and resistance determine how the lungs inflate or deflate and the amount of time required for it is known as the time constant (TC). This article discusses these characteristics and the concept of TC.

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Compliance

Compliance is nothing but the measure of how stretchable or elastic the lungs are. It is determined by the change in volume (ΔV) by the change in pressure (ΔP) in the lungs as follows:[3]

$$\text{Compliance} = \frac{\Delta V}{\Delta P} L / \text{cmH}_2\text{O}$$

Normal lung compliance is 60–100 ml/cmH_2O.[4] In general, a high compliance is seen in disease conditions such as COPD, where the lungs can easily stretch but do not recoil back to normal due to the obstruction within the airways. It takes a longer amount of time to exhale the volume out. In such cases, air is unable to effectively come out from the lungs causing air trapping and hyperinflation. Poor compliance or low compliance is seen in diseases such as cystic fibrosis where the lung parenchyma is stiff and does not easily stretch. This abnormal lung compliance results in an increased work of breathing. With high compliance, it takes more work for the lungs to remove the air, whereas, with low compliance, more effort is required to fill air in the lungs.

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Resistance

The resistance or opposing frictional forces to the flow of air during respiration are known as airway resistance.[5,6] It is the difference in pressure at the mouth and pressure in the alveoli (ΔP), divided by the flow of air ($\dot{V}$).

Airway resistance (R_{aw}) is generally calculated by using $R_{aw} = \frac{\Delta P}{\dot{V}}$ $cmH_2O/L/s$.

According to fluid dynamics, resistance can be calculated using the Hagen–Poiseuille equation as shown below:[6]

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

where

- ΔP is pressure difference between two ends of a cylinder (alveoli and mouth)
- Ƞ is the viscosity of the gas
- l is the length of the airway
- $\dot{V}$ is airflow
- r^4 is the radius raised to the power of 4.

Thus, $R_{aw} = \frac{8hl}{\pi r^4}$

Normally, some amount of resistance of about 0.5 cm $H_2O/L/s$–2.5 cm $H_2O/L/s$[7] is always present in the airways. This means, to move 1 L/s flow of gas in or out of the lungs, a healthy individual requires to generate a pressure of about 0.5 cmH_2O–2.5 cmH_2O less than the atmospheric pressure.[7] This resistance changes through the various generations of the airways within the lungs due to the structural differences.

R_{aw} depends on multiple factors that either increase or decrease resistance. One of the factors is the radius or the cross-sectional area of the airway. R_{aw} is high when the diameter of the airway is small and as per Hagen–Poiseuille equation discussed previously in this article, a reduction in the radius increases the resistance multifold.

Laminar airflow or turbulent airflow also determines the amount of resistance that is created in the airway. When the air tends to flow in a straight or linear fashion, it is said to be laminar flow. Laminar airflow has less resistance and generally seems to be present in the smaller airways. Turbulent flow is created when there is a high flow of gas passing through a large diameter airway. The flow of the air is nonlinear or random [Figure 1].

Airway resistance is varied throughout the airway and tends to be highest in the midsized airways in the 4–8 generations.[3] Further, along the generations of airway, even though the diameter reduces, the resistance also tends to reduce as the airways are shorter with multiple branches. Thus the resistance is distributed within the small airways making the combined resistance effectively small.

These characteristics help us understand the variations that are seen in various disease conditions. It must also be remembered

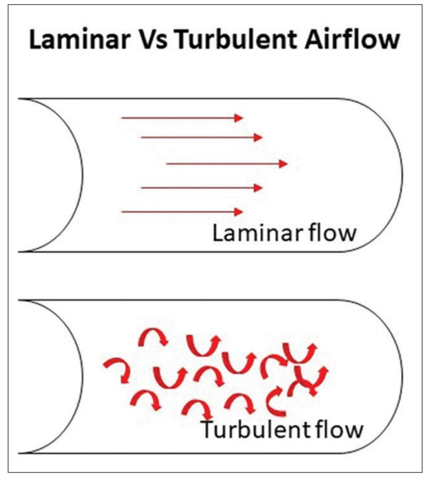

Figure 1: The pattern of laminar flow versus turbulent airflow

that both lung compliance and airway resistance are affected by external factors such as the endotracheal tube and ventilator settings.

With increased obstruction in the lungs, the airway resistance increases. Obstruction may be caused by excessive mucous secretions, inflammation in the airway, contraction of the smooth muscle during an asthma exacerbation, or tumors in the wall of airway or outside the surrounding airway. Resistance tends to reduce with bronchodilation.

Clinically, resistance is measured with the advanced pulmonary function test called the body plethysmography and the values obtained help understand the extent of the disease.[6]

What is Time Constant?

TC is the amount of time taken by the lung unit to fill during inhalation (inspiratory TC) or empty during exhalation (expiratory TC) at a stable pressure.[7,8] TC is a single parameter that can tell us about the overall respiratory characteristics. It is measured in seconds and is a product of compliance and resistance.

$TC = C_L \times R_{aw}$

where

- TC is 1 TC
- C_L is the lung compliance
- R_{aw} is the airway resistance.

One TC is the time required to fill or empty 63% of the lung unit.[7,9] Two TCs fill 86% of the lung unit and three TCs fill 95% of the lung unit.[7,9] At the end of five TCs, the lung is said to be 100% full.[7,9] This happens when the lung is free from any disease condition. For normal lungs with a total compliance of 0.1 L/cmH_2O and R_{aw} of 1.0 $cmH_2O/L/s$, the TC is 0.1 s.[8]

Exponential functions

Respiratory system correlates with exponential functions which are mathematical expressions that give an account of an event where the rate of change of one variable is proportional to its magnitude.[10,11]

For example, the flow at the beginning of the expiration is greater than that at the end of expiration. In mechanical ventilation, there are two functions that are of clinical significance. The rising exponential function denotes an increase in one variable as a function of time.[10,11] For example, in a pressure-controlled mode, the rate of change of volume at the beginning of expiration is greater than that at the end. The exact opposite happens in decaying exponential function where there is a decrease in one variable as a function of time.[10,11]

This information forms the basis of TC and has a major impact on disease management such as diagnosing a lung condition and selection of appropriate settings on the mechanical ventilator. Certain ventilators are manufactured with an inbuilt setting that can display a real-time TC value.[12] This is helpful while the patient is in the prone position for lung recruitment.

Kinking, biting, dislodged tube, or secretions in the endotracheal tube can also be identified by assessing TC.

What Role Does TC Play on the Respiratory System and Disease Management?

There are various factors that govern how much time it takes to fill the lung. As mentioned above, TC depends on the person's lung compliance and airway resistance. Normally, these factors vary throughout the lungs. This variation affects how ventilation takes place in the lungs. The pressures and volumes will differ depending on TC of the lung unit [Figure 2].

Obstructive airway disease

When obstruction and inflammation is present in the airways of patients with diseases such as COPD and asthma, there is an increase in the airway resistance.[8] Thus, it takes a longer time to fill or empty the lung unit, giving rise to a longer TC. Such patients require higher expiratory times typically followed while setting respiratory rates on the mechanical ventilator. If longer expiratory times are not given to these patients, it may lead to incomplete exhalation causing breath stacking and air trapping.[8] The resultant hyperinflation leads to an increase in the work of breathing, making the patients breathless and fatigued. This hyperinflation also increases the workload on the heart leading to heart failure. Bronchodilator therapy also improves TC by reducing R_{aw} in an asthmatic lung and reduces the severity of sleep apnea.[13]

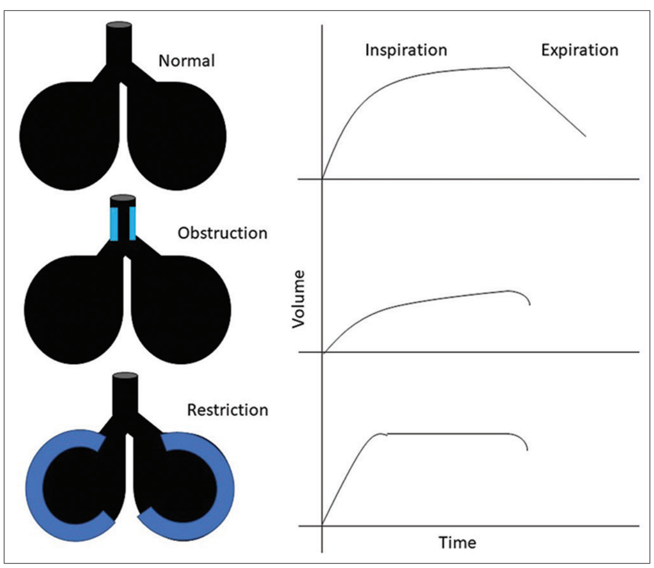

Figure 2: The effect of obstruction and restriction on the breath and time constant during inspiration and expiration (Adapted from West JB, Respiratory Physiology: The essentials, 4th Ed, 2000, Williams and Wilkins)

Fibrotic lung disease

In fibrotic lung diseases such as cystic fibrosis and interstitial lung diseases, the compliance of the lungs is low. This results in lungs filling with air quicker than lungs with normal compliance. In the same way, they empty quickly due to the high elastic recoil. Thus, the resultant TC is smaller.

Obstructive sleep apnea

In disease conditions such as obstructive sleep apnea (OSA), which are often found overlapping with COPD, lung characteristics affect the severity of the disease.[13] Interestingly, increased C_L along with hyperinflation proves to be a protective mechanism from sleep apnea. However, an increase in R_{aw} alleviates sleep apnea and its symptoms.[13] High C_L and R_{aw} in such patients delay the lung emptying leading to an increased TC. A recent study has shown that an increased expiratory TC of more than 0.5 s is associated with 11 times more chances of developing severe sleep apnea.[13] Thus, strategies to reduce increased R_{aw} will perhaps be an important key in the management of OSA.

Acute respiratory distress syndrome

Conventionally, TC is calculated using the single breath technique with the assumption that all lung units have homogeneous TC. However, as discussed above, TC varies with external factors such as disease state, the resistance caused by endotracheal tube, the ventilator circuit, and the expiratory valve of the ventilator.[14] These variables are flow dependent, so an increase in flow leads to elongated expiratory time leading to increased TC.[14] ARDS is a very heterogeneous disease condition with a significant amount of lung injury, and the time needed to inflate and deflate the lung unit is different. As compared to the uninjured lung, the heterogeneity within the lung characteristics and TC is much greater.[15] To determine the inflation/deflation time more accurately, imaging studies of the lung using computed tomography scans have proven to be a better method in animal studies.[15] These imaging studies can calculate the actual values of TC, which can perhaps be used in clinical practice as a disease management tool. With this technique, difference between localized TC and the overall TC of the lung can also be seen.[15] Further research is warranted to have a better clarity of this area.

Mechanical ventilation

The type of mechanical ventilatory mode (volume vs. pressure) that is set results in different TCs and its effects.[7] In disease conditions leading to abnormal compliance and resistance, TCs vary even more.

It is important to know the TC and the variations in it while managing the patient on the mechanical ventilator.

For example, if the compliance is 0.1 L/cmH_2O and resistance is 2 cmH_2O/L/sec, the TC is $TC = C \times R_{aw} = 0.1 \times 2 = 0.2$ s. The lungs will completely fill after five TCs, i.e., $0.2 \times 5 = 1$ s. This means that the patient will require 1 s to complete inspiration. Based on this, if one would like to set the I: E ratio to 1:2, then the expiratory time would be 2 s, making the total breath cycle of 3 s. Hence, the respiratory rate would be 60 s/3 s = 20 breaths in a minute.

In a diseased lung, certain portions may be more affected than others. TC for these portions of the lungs may be different. Thus, when selecting settings such as the respiratory rate, a balance needs to be achieved to allow the lung to inflate and deflate for appropriate ventilation. Setting the inspiratory and expiratory rates of <3 TCs results in incomplete inhalation and exhalation.[16] If the rate is set high, the affected lung units do not fill or empty completely while the unaffected portion receives good amount of air.

Positive end-expiratory pressure (PEEP) and tidal volume (V_T) have shown to have an effect on the TC of the lungs. A study reported that an increase in the PEEP and V_T led to an increase in the time required to exhale the air out of the lungs completely.[17] Thus, the mechanical ventilatory settings need to be carefully set to avoid any possible increase in patient's work of breathing.

A study reported that plateau pressures, total compliance, and total lung resistance can be calculated using techniques that directly measure TC.[18] The authors claim that this real-time measurement which was shown to be used in various modes is a good tool to monitor the pressures in the lung to avoid barotrauma and lung injury.[18]

Conclusion

Understanding the fundamental characteristics that govern how the respiratory system works is essential and there is still a lot to explore when it comes to lung physiology. TCs represent the condition of the respiratory system and can be utilized in identifying and modifying strategies in mechanical ventilatory and disease management. Continuous scientific evidence needs to be generated that can further explore and understand the role of TCs in diseased lung and mechanical ventilation.

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Conflicts of interest

There are no conflicts of interest.

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