A Simple Model Illustrating the Respiratory System’s Time Constant Concept

The variation of lung volume ($\Delta V$) depends on the compliance ($C$) of the respiratory system and the variation of pressure ($\Delta P$) to which the system is subjected (1). This may be noticed in the following equation:

$$\Delta V = C \times \Delta P$$  \hspace{1cm} (1)

This notion is true for a perfect elastic body. Because the lungs do not present perfect elastic behavior, the relationship among $\Delta V$, compliance, and $\Delta P$ is not linear along all the vital capacity range, as showed by Eq. 1.

When the respiratory system is subjected to $\Delta P$, time is needed until $\Delta V$ occurs, and the time necessary to inflate 63% of its volume is called the time constant ($\tau$) (3). It describes the monoexponential behavior of the time profile of the simplest model of respiratory system: the single-compartment linear model, which incorporates, in series, two lumped elements—one single compartment of elastance served by a pathway of resistance (2). The one-compartment linear model cannot describe the variations of resistance and elastance associated with the frequency of ventilation, tidal volume, and mean lung volume. These complex mechanical behaviors of the lung reflect many physical properties of the system, including viscoelastic properties, “series” and “parallel” inhomogeneities in the distribution of ventilation, nonlinearities, and plastic behavior. Therefore, to better describe and quantify the respiratory system mechanical profile, more complex models are needed, and, when the respiratory system exhibits parallel inequalities of resistance and compliance, the overall mechanical behavior of the lung cannot be described by a single $\tau$ value.

One way to calculate $\tau$ is to multiply the resistance ($R$) by the compliance of the respiratory system, according to following equation:

$$\tau = R(\text{cmH}_2\text{O}1^{-1}s) \times C(\text{ml/cmH}_2\text{O}) = s$$  \hspace{1cm} (2)

The concept of this variable is applied to expiration, because it allows the anticipation of the necessary expiratory time to exhale enough air until the static equilibrium volume of the respiratory system is reached. It means that the greater the value of $\tau$, be it due to resistance and/or compliance, the greater will be the time necessary to reach the static equilibrium volume. This concept is extremely important for the understanding of the mechanical consequences of different diseases related to the respiratory system, such as chronic obstructive pulmonary disease, acute respiratory distress syndrome, and asthma, as well as a possible cause for ventilation inequality. Below, you will find a quite simple description of the analog two-compartment model arranged “in parallel,” composed by two alveolar units that may have their constant value altered by resistance and compliance manipulation of each unit. This model also allows us to understand the relationship among $\tau$, respiratory rate (RR), auto-positive end-expiratory pressure (PEEP), and dynamic hyperinflation.

To build a lung model with two alveolar units, three plastic tubes of the same diameter and length, a plastic piece in Y format (three-way hose connector), two artificial rubber lungs, gauze, a rubber band, and a self-inflating bag for manual mechanical ventilation are necessary. The material necessary
and instructions to make the analogical model are shown in Fig. 1.

First, it is necessary to demonstrate the model and stress that the two alveolar units have the same \( r \) value. It happens because 1) as the tubes have the same length and diameter, the resistance to the air flow is similar; and 2) the compliance of the artificial lungs is similar too, because the balloons are built with the same material and have the same volume.

After the demonstration, the first step of the experiment consists of insufflating the system with a RR of 10 cycles/min, using the inflating bag, and observing that both alveolar units inflate at the same moment because they have the same \( r \). Afterward, the RR is increased to 20 cycles/min to show that, when the constant value is equal for both units, even with higher RR, the artificial lungs also inflate and deflate in the same time. At the moment \( r \) is equal to both units, both in the low and high RR, both contribute to the total compliance of the system.

The second step is to introduce gauze into the tube that feeds one of the artificial lungs. Thus the resistance (and, consequently, the \( r \) of that unit) is greater. Then, inflate the system with 10 cycles/min and observe that, at a low RR, the alveolar units inflate and deflate in different time intervals. In this case, both units still contribute to the compliance of the total system. It occurs because there is enough time for the diseased unit (with greater resistance) to respond. The next step is to increase RR to 20 cycles/min and observe that the diseased unit does not respond to the pressure changes because the \( r \) of that unit is very high. As a result, the lung is less compliant. Besides, with a high RR, there is not time enough for complete exhalation, which results in dynamic hyperinflation and a decrease of total lung compliance. Because by the end of the expiration the lung volume is greater than predicted, that is, lungs do not deflate completely, the alveolar pressure continues to be positive by the end of the exhalation, thus resulting in auto-PEEP.

Next, take the gauze from the tube and involve one of the artificial lungs with the rubber band to decrease the compliance of this lung. Repeat the steps described above and compare the compliance with \( r \). After this demonstration, the gauze should be inserted into one of the tubes, and the artificial lung should be involved in the same side with the rubber band. Repeat the steps described above and compare the compliance and the resistance with \( r \). The last step of the experiment consists of increasing the resistance of one of the alveolar units and decreasing the compliance of the contralateral artificial lung. Repeat the steps described above and compare the compliance with \( r \).

In summary, we present a simple, low-cost, interesting lung model that permits the understanding of the respiratory system’s \( r \) concept and its relationship with RR, auto-PEEP, and dynamic hyperinflation.

REFERENCES

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