

How to measure respiratory mechanics during controlled mechanical ventilation

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Abstract

Bedside measurement of respiratory mechanics allows to closely monitor the lung function in critically ill patients. The two fundamental parameters describing the respiratory system mechanics are resistance and compliance. Resistance of the respiratory system describes the opposition to gas flow during inspiration. During volume-controlled ventilation, resistance can be calculated as the ratio between the peak to plateau pressure drop and the resulting flow rate. Compliance describes the elastic property of the respiratory system, comprising the lung and the chest wall. It is the ratio between a change in volume (i.e. tidal volume) and the corresponding change in pressure, calculated as the difference between plateau pressure and total positive end-expiratory pressure, measured by end-inspiratory and end-expiratory manual occlusion, respectively. In this review, we describe how to measure respiratory mechanics at the bedside, starting from the physiological background of the equation of motion of the respiratory system.

Keywords: Compliance, Mechanical ventilation, Resistance, Respiratory mechanics

Introduction

Measurement of respiratory mechanics provides information about the alteration of lung and respiratory system homeostasis through analyses of their mechanical properties during mechanical ventilation (1, 2). The bedside assessment of mechanics in ventilated patients allows to evaluate the lung condition and to monitor the respiratory function during the clinical course of the patient in the intensive care unit. It is a fundamental complement to the clinical evaluation in patients with respiratory failure aiding diagnosis of aetiology (e.g. restrictive vs. obstructive disease) and in all patients requiring recognition and prompt treatment of critical events such as bronchospasm or endotracheal tube displacement. Moreover, increasing attention has been dedicated to limit the deleterious effects of mechanical ventilation (i.e. ventilator-induced lung injury) (3, 4). In this context, monitoring airway pressure is essential to characterize, diagnose and assess the therapeutic response.

The two main elements of respiratory mechanics are resistance and compliance. The purpose of this article is to measure these at the bedside and to explain the rationale. We will only focus on passive mechanically ventilated patient with no respiratory effort.

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Theory and definition

The respiratory system can be assimilated to a closed system, comprising a flow generator (the mechanical ventilator), a conductive system (endotracheal tube and lower airways) and an elastic system (the alveoli). Several variables are measured by the mechanical ventilator, and many more can be derived:

- The *pressure* at airway opening, which is normally measured at the proximal tip of the endotracheal tube or in the ventilator itself. More often this pressure is referred to as “airway pressure” (P_{aw}): albeit widely used (and we will also use this nomenclature), it is worth noting that, whenever a flow is present a pressure gradient must exist. Therefore, airway pressure will not be uniform along the airway, by definition.
- The *airflow or flow*: this is the flow (amount of volume in the time unit) leaving the ventilator towards the airway opening and the alveoli (positive flow, inspiration) or vice versa (negative flow, expiration). It is usually expressed as L/min or L/s.
- The *volume*: this is calculated from the ventilator as the digital integration of flow over time and it is assumed to be expanding the alveoli. This might not always be the case, for example, in the presence of leaks. It is normally expressed in mL.

The measurement of pressure, flow and volume allows to calculate the two fundamental parameters describing the respiratory system mechanics:

- *Resistance of the respiratory system* (R_r) describes the opposition to a gas flowing into the airways during inspiration. Resistance comprises two elements: the “ohmic” resistance (which depends on the frictional force opposing

airflow) and the viscoelastic resistance (due to the resistance to deformation of the respiratory system) (5). We will consider both components as a single entity. R_{rs} is calculated as the ratio between the pressure difference (ΔP) at the two ends of the airways (the ventilator unit and the alveoli, in this case) and the resulting flow rate. $R_{rs} = \Delta P / \text{Flow}$. R_{rs} is usually expressed as $\text{cmH}_2\text{O}/\text{L/s}$.

- The *compliance of the respiratory system* (Cpl_{rs}) describes the elastic property of the respiratory system, including the lung and the chest wall. Cpl_{rs} is the ratio between the inspired volume and the corresponding change in pressure. Cpl_{rs} is usually expressed as $\text{mL}/\text{cmH}_2\text{O}$. The elastic properties of the respiratory system can also be described as elastance (E), which is the reciprocal of compliance and expressed as $\text{cmH}_2\text{O}/\text{mL}$.

All the variables expressed above are linked by a very simple equation, known as the Equation of Motion of the respiratory system, according to which pressure at the airway opening (P_{aw} , displayed on the ventilator screen) equals, at *any instant* of the breathing cycle, the sum of the elastic (P_{el}) and resistive (P_{res}) pressures, plus the total positive end-expiratory pressure (PEEP, see below), which, being constant throughout the cycle, can be considered as the constant term.

$$P_{aw} = P_{res} + P_{el} + \text{PEEP} \tag{Eq. [1]}$$

As stated, P_{res} is the pressure necessary to overcome the resistance to airflow, whereas P_{el} is the pressure due to the elastic recoil of the respiratory system when a certain volume (V) is inflated.

$$P_{res} = \text{Flow} * R_{rs} \tag{Eq. [2]}$$

$$P_{el} = V / C_{rs} \tag{Eq. [3]}$$

Figure 1 graphically describes P_{aw} and its components during the respiratory cycle.

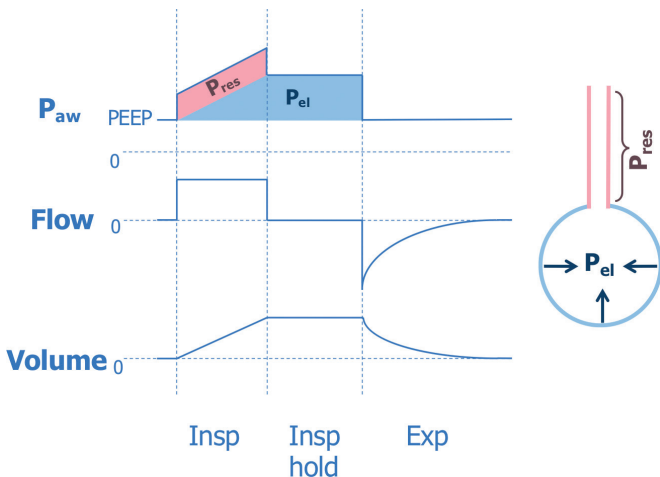


Fig. 1 - Airway pressure (P_{aw}) and flow during a volume-controlled breath. PEEP, positive end-expiratory pressure; P_{res} , resistive pressure; P_{el} , elastic pressure.

Describing respiratory mechanics in a spontaneously breathing patient is beyond the scope of the current article.

However, in the presence of patient’s effort, the equation is simply modified by adding the term P_{musc} (i.e. the pressure generated by the patient’s respiratory muscles) in the equation:

$$P_{ao} = P_{res} + P_{el} + P_{musc} + \text{PEEP} \tag{Eq. [4]}$$

It might actually be more correct to consider Eq. [1] as a simplification of the more general Eq. [4] with the term $P_{musc} = 0$.

Measuring respiratory mechanics during volume-controlled ventilation

Ventilators in volume-controlled modality deliver a constant flow rate during inspiration (i.e. square flow waveform) until the set volume (tidal volume, V_T) is entirely delivered. Therefore, P_{aw} progressively increases, starting from the set PEEP level. This is due to the presence of P_{res} (normally constant during inspiration, given the use of a constant flow) and P_{el} , which increase gradually due to the increase of the lung volume ($P_{el} = V / \text{Cpl}_{rs}$). At the end of tidal volume insufflation, peak inspiratory pressure (P_{peak}) is reached. P_{peak} represents the highest pressure during the ventilatory cycle, and it is the sum of pressures resulting from inspiratory flow resistance (resistive pressure, P_{res}), elastic recoil of the lung and chest wall (elastic pressure, P_{el}) and the alveolar pressure present at the beginning of the breath (PEEP).

$$P_{peak} = \text{Flow} * R_{rs} + V / \text{Cpl}_{rs} + \text{PEEP} \tag{Eq. [5]}$$

After interruption of the inspiratory flow, when the expiratory valve is still closed, the plateau pressure value is reached (P_{plat}). When gas flow is zero, there is no resistive pressure between the alveoli and the ventilator; therefore, plateau pressure equals alveolar pressure.

$$P_{plat} = V / \text{Cpl}_{rs} + \text{PEEP} \tag{Eq. [6]}$$

Hence, the difference between peak inspiratory pressure (P_{peak}) and plateau pressure (P_{plat}) allows the calculation of the resistance of the respiratory system:

$$P_{peak} - P_{plat} = (\text{Flow} * R_{rs} + V / \text{Cpl}_{rs} + \text{PEEP}) - (V / \text{Cpl}_{rs} + \text{PEEP}) = \text{Flow} * R_{rs} \tag{Eq. [7]}$$

$$R_{rs} = (P_{peak} - P_{plat}) / \text{Flow} \tag{Eq. [8]}$$

Figure 2 shows the pressure drop during an inspiratory hold and an example of how to calculate R_{rs} during volume-controlled ventilation.

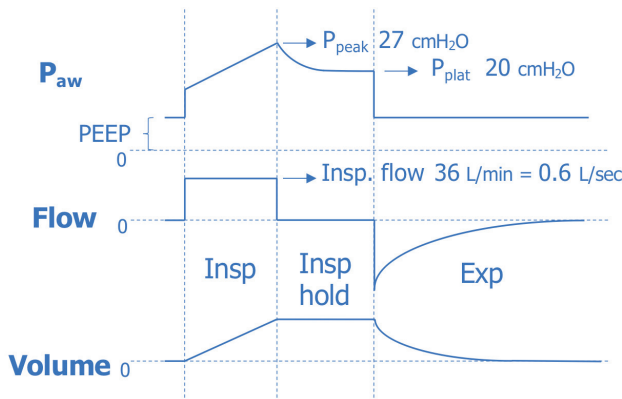
Since P_{plat} and PEEP reflect alveolar pressure at the end of inspiration and expiration, respectively, their difference (also known as “driving pressure”, DP) allows the calculation of respiratory system compliance:

$$P_{plat} - \text{PEEP} = (V / \text{Cpl}_{rs} + \text{PEEP}) - \text{PEEP} = V / \text{Cpl}_{rs} \tag{Eq. [9]}$$

$$\text{Cpl}_{rs} = V / (P_{plat} - \text{PEEP}) = V / \text{DP} \tag{Eq. [10]}$$

During expiration, alveolar pressure decreases from P_{plat} towards PEEP. The ventilator is designed to adjust the opening of the expiratory valve to maintain the set PEEP during the expiratory phase. However, if an expiratory flow is still present at the end of the expiration, the alveolar pressure



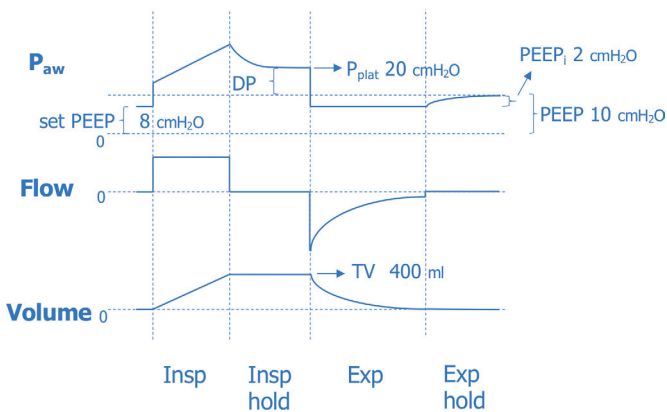


$$R_{rs} = (27-20) / 0.6 = 11.67 \text{ cmH}_2\text{O/L/sec}$$

Fig. 2 - An example of how to measure resistance of the respiratory system (R_{rs}) during volume-controlled ventilation. During an inspiratory hold, the drop in airway pressure (P_{aw}) corresponds to the amount of pressure generated during inspiration to overcome the resistance of the respiratory system. Insp, inspiratory phase; Exp, expiratory phase; PEEP, positive end-expiratory pressure; P_{res} , resistive pressure; P_{el} , elastic pressure; P_{peak} , peak inspiratory pressure; P_{plat} , plateau pressure.

will exceed the pressure at the airway opening. For this reason, to measure the real alveolar pressure at the end of the expiration, an expiratory hold is required to measure the total PEEP ($PEEP_{tot}$). $PEEP_{tot}$ is the sum of the PEEP set at the ventilator by the clinician and the intrinsic PEEP ($PEEP_i$), which results from incomplete emptying of the alveoli at the end of the expiratory time (6, 7). All the calculations indicated above should include the $PEEP_{tot}$ (rather than set PEEP) if these differ.

Figure 3 reports an example of inspiratory and expiratory holds during volume-controlled ventilation to measure Cpl_{rs} .



$$Cpl_{rs} = 400 / [20 - 10] = 40 \text{ ml/cmH}_2\text{O}$$

Fig. 3 - An example of how to measure compliance of the respiratory system (Cpl_{rs}) during volume-controlled ventilation (VCV). Insp, inspiratory phase; Exp, expiratory phase; P_{aw} , airway pressure; PEEP, positive end-expiratory pressure; P_{plat} , plateau pressure.

Clinical and practical aspects

Measuring plateau pressures requires an inspiratory hold (flow = 0), which can be part of each tidal breath if an inspiratory pause time is set. However, for a more accurate measurement, a longer (e.g. 2-3 seconds) inspiratory hold (manually performed) allows better equilibration of pressure at the airway opening and at the alveoli.

R_{rs} is primarily made up of the resistance of the airways and the endotracheal tube, because in normal condition the resistance of the lung tissue is low. R_{rs} (usually expressed as $\text{cmH}_2\text{O/L/s}$) can only be measured in volume control mode, which provides a constant flow rate during inspiration. It should be considered that R_{rs} may be influenced by inspiratory flow variations. Therefore, in clinical practice, in order to obtain comparable values over time, a 10 mL/kg/s inspiratory flow should be set at the ventilator (i.e. 70 kg = 700 mL/s = 0.7 L/s = 42 L/min). In mechanically ventilated patients with a normal lung and an artificial airway, inspiratory resistances rarely exceed 15 $\text{cmH}_2\text{O/L/s}$ (8). A narrow endotracheal tube or a heat and moisture exchanger may cause an increase in resistances, which increases with flow in an exponential relationship. Incorrect positioning or kinking of the endotracheal tube may also increase resistances. Increased airway resistance also occurs in some pathological conditions such as asthma or chronic obstructive pulmonary disease.

As recommended for the measurement of Cpl_{rs} , when measuring resistances, the manual holds must be long enough to allow equilibration of pressure at the airway opening with the alveolar one. For this reason, plateau pressures automatically displayed by the ventilators can be inaccurate, especially when resistances of the respiratory system are high.

In order to obtain reliable measurements of respiratory mechanics during controlled mechanical ventilation, the patient must be perfectly adapted (i.e. passive). An unstable pressure tracing during the inspiratory hold suggests the presence of patient effort, which may induce misinterpretation of respiratory mechanics. In these situations, a brief increase of patient sedation may allow a more accurate assessment.

In healthy mechanically ventilated patients Cpl_{rs} is around 50-60 mL/cmH₂O, or 0.7-1 mL/cmH₂O/kg (8). During general anaesthesia in healthy subjects, a reduction in Cpl_{rs} mainly depends on decrease of aerated lung volume (9). Decreased compliance is common in pathological conditions such as acute respiratory distress syndrome (ARDS), atelectasis, pneumothorax, lung fibrosis or chest wall stiffness.

ARDS patients typically have a reduced Cpl_{rs} that decreases with ARDS severity; therefore, monitoring compliance in ARDS patients can provide information about the volume of the aerated lung (10). It must be noted that in many conditions, including ARDS, patients' airway closure may strongly influence the assessment of static respiratory mechanics (11).

Contrarily, an increase in compliance occurs in the case of lung emphysema.

In contrast to what we explained for the measurement of the resistances, Cpl_{rs} can also be measured during pressure-controlled ventilation. It must be noted that inspiratory pressure during PCV, despite having a flat shape, does not always reflect plateau pressure (12). Figure 4 shows an

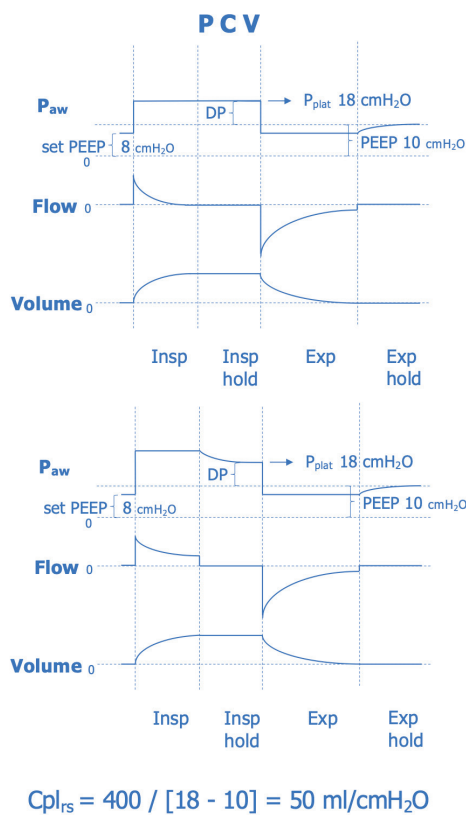


Fig. 4 - Measurement of respiratory system compliance (Cpl_{rs}) during pressure-controlled ventilation (PCV). Manual holds are displayed at the end of inspiration (Insp) and expiration (Exp). The first example (upper panel) shows a case where the inspiratory flow reaches zero before the inspiratory hold, thus no pressure drop is observed. In the second patient (lower panel), the inspiratory hold interrupts a residual inspiratory flow, thus airway pressure decreases due to the zeroing of the resistive pressure component. P_{aw} , airway pressure; P_{plat} , plateau pressure; PEEP, total peep; DP, driving pressure.

example of measurement of compliance during pressure-controlled ventilation.

However, when assessing respiratory mechanics, we recommend to set the ventilator in volume-controlled ventilation in order to visualize all pressures at a glance and to measure both R_{rs} and Cpl_{rs} with just one inspiratory and one expiratory hold.

Figure 5 provides some examples of how to interpret a modification of airway pressures during volume-controlled ventilation. An increase of resistance is evident when P_{peak} increases without modification of P_{plat} (Patient A). A reduction of compliance is suggested in the case of similar increase of P_{peak} and P_{plat} (Patient B). The last example shows a patient with both increased R_{rs} and decreased Cpl_{rs} : the peak to plateau pressure drop is high but P_{plat} is also increased (Patient C). This visual approach to pressure curve can be particularly useful in case of critical events.

Conclusion

Measuring respiratory mechanics is essential in critical care patients in order to avoid complication and to face any

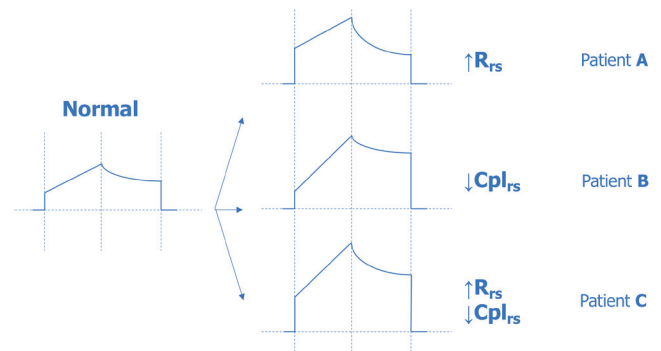


Fig. 5 - Modification of the pressure curve at the ventilator in case of increase of resistance (R_{rs} , Patient A), decrease of compliance (Cpl_{rs} , Patient B) or both (Patient C).

ventilation problem. Intensivists should perform inspiratory and expiratory holds at the ventilator during every clinical assessment of a ventilated patient. Measuring respiratory mechanics should be considered as important as assessing fluid balance, deciding antibiotic therapy or choosing sedation.

Disclosures

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