Chapter 4
Monitoring Respiratory Mechanics

Not only does the ventilator act therapeutically to support ventilation and gas exchange; it can also provide critical information regarding a patient's respiratory mechanics, which can aid in the diagnosis of the patient's respiratory failure.

Two-Component Model

To understand how the ventilator provides information about respiratory mechanics, it is helpful to break down the respiratory system into two components: the **resistive component** and the **elastic component**. The resistive component is determined by the airways, which are comprised of the endotracheal tube and the patient's own airways. The elastic component is determined by the lung parenchyma and the chest wall. **Elastance**, the inverse of compliance, is a measure of stiffness. The ventilator must provide adequate airway pressure to push air through the resistive component (creating flow), an action analogous to blowing air through a tube. The ventilator must also provide adequate airway pressure to inflate the elastic component (filling with volume), an action analogous to inflating a balloon. Therefore, proximal airway

H. Poor, *Basics of Mechanical Ventilation*, https://doi.org/10.1007/978-3-319-89981-7_4

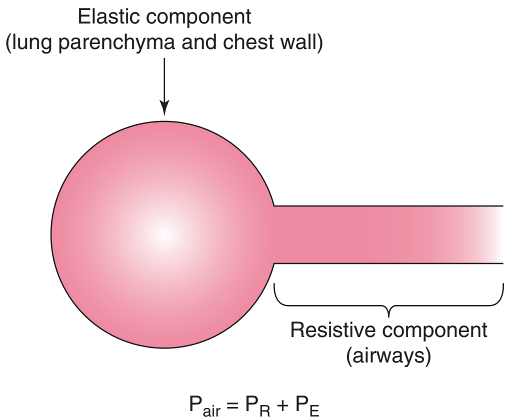


FIGURE 4.1 Two-component model of the respiratory system. The respiratory system is composed of a resistive component (airways) and an elastic component (lung parenchyma and chest wall). P_{air} proximal airway pressure; P_E elastic component of proximal airway pressure; P_R resistive component of proximal airway pressure

pressure is equal to the sum of pressure arising from the resistive component and pressure arising from the elastic component (Fig. 4.1).

Key Concept #1
Two-component model of the respiratory system:

- Resistive component = airways
- Elastic component = lung parenchyma and chest wall

The resistive component of proximal airway pressure (P_R) is equal to the product of flow (Q) and resistance (R), a relationship analogous to Ohm's law, as described in Chap. 1. Increasing either flow through the tube or increasing resistance of the tube will increase airway pressure:

$$P_R = Q \times R$$

The elastic component of proximal airway pressure (P_E) is equal to volume (V) in the lungs divided by compliance (C)

of the respiratory system. Increasing tidal volume or decreasing compliance (increasing stiffness) will increase airway pressure:

$$P_{\mathrm{E}} = \frac{V}{C}$$

Putting these two components together provides the equation for proximal airway pressure:

$$P_{\mathrm{air}} = Q \times R + \frac{V}{C}$$

Note that this equation is merely a rearrangement of the equation from Chap. 1 (P_{alv} = alveolar pressure):

$$Q = \frac{P_{\mathrm{air}} - P_{\mathrm{alv}}}{R}$$

V/C is substituted for P_{alv}:

$$Q = \frac{P_{\mathrm{air}} - \frac{V}{C}}{R}$$

The equation is rearranged:

$$P_{\mathrm{air}} = Q \times R + \frac{V}{C}$$

Key Concept #2

- Compliance is a measure of “stretchiness”
- Elastance is a measure of “stiffness”
- Compliance is the reciprocal of elastance

Airway Pressures

Ventilators have pressure gauges that continuously report proximal airway pressure during mechanical ventilation. Evaluating this proximal airway pressure relative to flow and tidal volume can provide information about a patient's respiratory mechanics, specifically resistance and compliance of the respiratory system.

In the setting of volume-controlled ventilation (VCV), flow (target) and tidal volume (cycle) are set. Therefore, proximal airway pressure will depend on resistance of the airways and compliance of the lung parenchyma and chest wall. **Peak airway pressure** is the maximum proximal airway pressure during the respiratory cycle. For a given flow rate and tidal volume, peak airway pressure will be elevated in the setting of increased resistance or decreased compliance. In order to determine whether increased peak airway pressure is a result of increased resistance or decreased compliance, an **inspiratory pause maneuver** can be performed. With this maneuver, after the set tidal volume is delivered, the expiratory valve of the ventilator closes, preventing air from leaving the respiratory system for a short period of time. Because air cannot leave the respiratory system during this time period, pressure everywhere in the respiratory system equalizes. When pressure across the entire respiratory system has equalized, there is no longer any pressure gradient to drive flow, so flow ceases ($Q = 0$). As noted, $P_R = Q \times R$, and therefore P_R (the resistive component of proximal airway pressure) will also be zero, regardless of airway resistance. Thus, the measured proximal airway pressure consists only of that which arises from the elastic component (P_E), which is equal to V/C.

Proximal airway pressure measured at the end of the inspiratory pause maneuver is known as **plateau pressure**. Plateau pressure will increase with increased tidal volume or decreased respiratory system compliance. Plateau pressure can be viewed as the maximum pressure during the respiratory cycle in the alveolus. At the beginning of a breath, alveolar pressure is at its lowest. During inspiration, as air fills the alveolus, pressure within the alveolus rises, reaching a maximum level

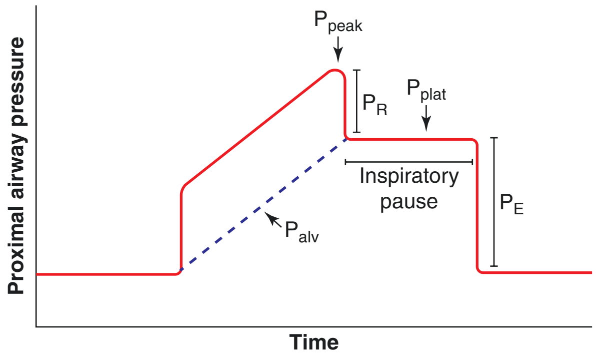


FIGURE 4.2 Pressure waveform with an inspiratory pause maneuver. This pressure waveform is from a volume-controlled ventilation mode with a constant flow waveform. Peak airway pressure is the maximum proximal airway pressure during the respiratory cycle. When an inspiratory pause maneuver is performed, inspiratory flow ceases and exhalation is temporarily prevented. Because flow has ceased, the resistive component of proximal airway pressure (P_R) becomes zero, making the measured proximal airway pressure equal to the elastic component (P_E). P_E at the end of inspiration is equal to plateau pressure. Note that alveolar pressure is at its lowest value at the beginning of inspiration and rises to its maximum level by the end of inspiration, which is equal to plateau pressure.
P_{air} proximal airway pressure; P_{alv} alveolar pressure; P_E elastic component of proximal airway pressure; P_{peak} peak airway pressure; P_{plat} plateau pressure; P_R resistive component of proximal airway pressure

once the entire tidal volume is delivered. That maximum level for alveolar pressure is equal to plateau pressure (Fig. 4.2).

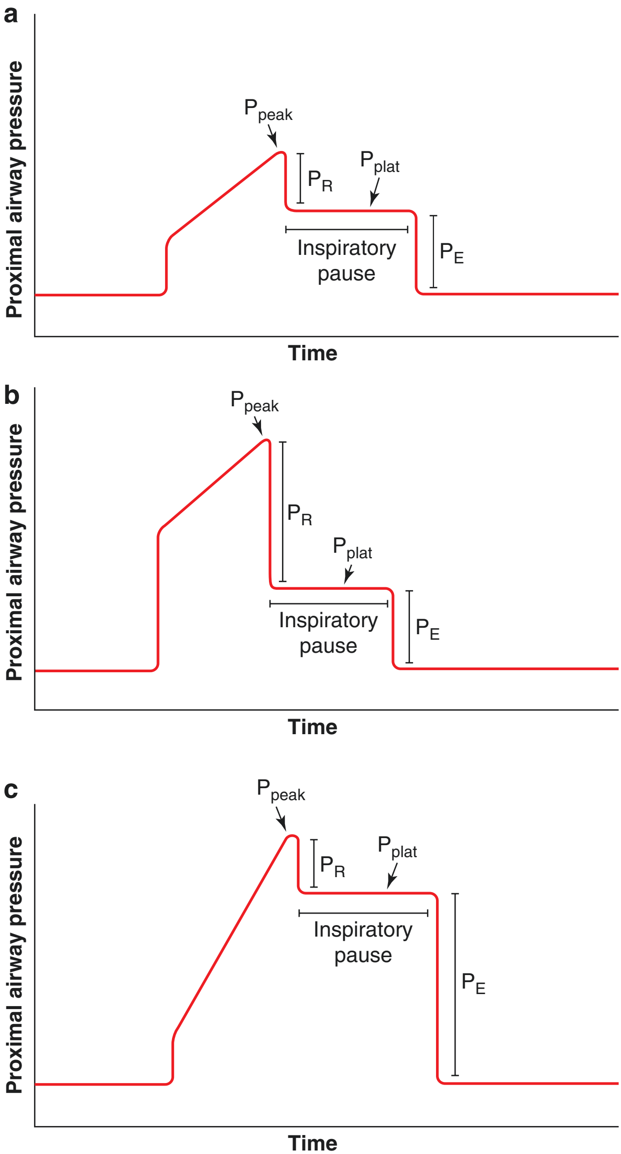
Key Concept #3
Plateau pressure:

- Measure of maximum alveolar pressure during respiratory cycle
- Measured by **inspiratory pause maneuver**
- Higher with increased tidal volume and decreased respiratory system compliance

Diagnostic Algorithm

Peak and plateau pressures, as measured during VCV, can provide information about a patient's respiratory mechanics (Fig. 4.3). Elevated peak pressure is the result of elevated pressure from the resistive component, an elevated pressure from the elastic component, or both. To determine the etiology of elevated peak pressure, an inspiratory pause should be performed to measure plateau pressure. If plateau pressure is normal, the elevated peak pressure is due to increased airway resistance (Fig. 4.3b). Common causes of increased airway resistance include biting of the endotracheal tube, secretions in the airway, and bronchoconstriction. If plateau pressure is elevated, the elevated peak pressure is due to decreased respiratory system compliance or to increased lung volume (Fig. 4.3c). Common causes of decreased respiratory system compliance include pulmonary edema, pulmonary fibrosis, ascites, obesity, and pregnancy. Pneumothorax and atelectasis increase plateau pressure because the set tidal volume from VCV has less lung available to enter. Gas trapping, as explained in Chap. 6, also increases plateau pressure by increasing the end-expiratory lung volume and pressure—the addition of a set tidal volume to an elevated end-expiratory lung volume and pressure will result in elevated plateau pressure.

FIGURE 4.3 Pressure waveforms with inspiratory pause maneuver. (**a**) Normal peak and plateau pressure. (**b**) Elevated peak pressure but normal plateau pressure. The increased peak pressure is due to elevation in the resistive component of proximal airway pressure (P_R). (**c**) Elevated peak pressure and elevated plateau pressure. The increased peak pressure is due to an elevation in the elastic component of proximal airway pressure (P_E).
P_E elastic component of proximal airway pressure; P_{peak} peak airway pressure; P_{plat} plateau pressure; P_R resistive component of proximal airway pressure


a
Proximal airway pressure
Ppeak
PR
Pplat
Inspiratory pause
PE
Time
b
Proximal airway pressure
Ppeak
PR
Pplat
Inspiratory pause
PE
Time
c
Proximal airway pressure
Ppeak
PR
Pplat
Inspiratory pause
PE
Time

Key Concept #4

Causes of increased airway resistance:

- Biting of endotracheal tube
- Airway secretions
- Bronchoconstriction

Key Concept #5

Causes of decreased respiratory system compliance:

- Pulmonary edema
- Pulmonary fibrosis
- Pneumothorax
- Atelectasis
- Gas trapping
- Ascites
- Obesity
- Pregnancy

Decreased peak pressure during VCV can be noted in the setting of patient inspiratory efforts or an endotracheal tube cuff leak. Because flow in VCV is set, patient inspiratory efforts will not alter flow but will reduce proximal airway pressure. Apposition of the endotracheal tube cuff to the trachea seals the upper airway, allowing for pressurization of the respiratory system during inspiration. If the cuff does not form an adequate seal, air can leak outward, reducing peak airway pressure. Cuff leaks can occur because of cuff underinflation, cephalad migration of the endotracheal tube, inadvertent intratracheal placement of a gastric tube, or a defective endotracheal tube cuff (Fig. 4.4).

Key Concept #6
Causes of decreased peak airway pressure:

- Patient inspiratory efforts
- Endotracheal tube cuff leak

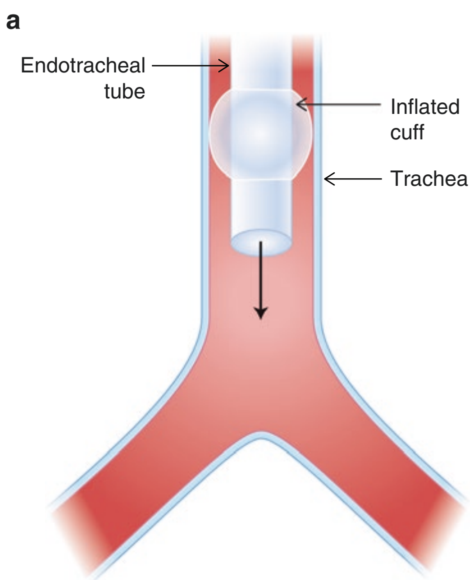


FIGURE 4.4 Endotracheal tube in the trachea. (**a**) The inflated cuff seals the upper airway and allows for pressurization of the respiratory system during inspiration. (**b**) An underinflated cuff results in air leak around the cuff and out of the upper airway, leading to lower proximal airway pressure with volume-controlled ventilation.

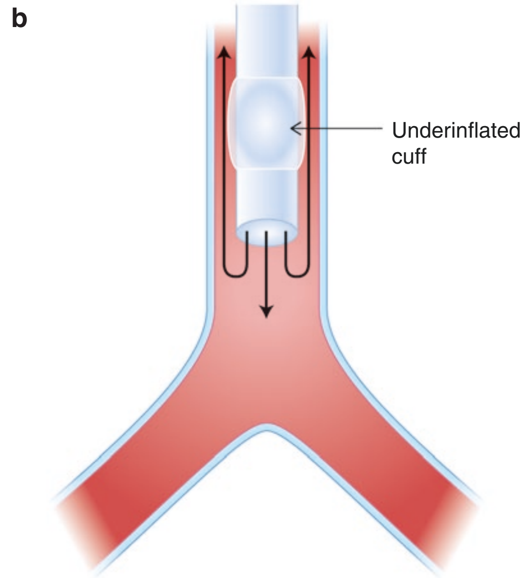


FIGURE 4.4 (continued)

Suggested Readings

1. Cairo J. Pilbeam's mechanical ventilation: physiological and clinical applications. 5th ed. St. Louis: Mosby; 2012.
2. Hess D. Respiratory mechanics in mechanically ventilated patients. Respir Care. 2014;59:1773–94.
3. MacIntyre N, Branson R. Mechanical ventilation. 2nd ed. Philadelphia: Saunders; 2009.
4. Marino P. Marino's the ICU book. 3rd ed. Philadelphia: Lippincott Williams & Wilkins; 2007.
5. Tobin M. Principles and practice of mechanical ventilation. 3rd ed. Beijing: McGraw-Hill; 2013.