Mechanical Ventilation for COVID-19

Physiology of Mechanical Ventilation

Readings adapted from Wilcox, Susan R., et al. *Mechanical Ventilation in Emergency Medicine.* Springer, 2019

Introduction

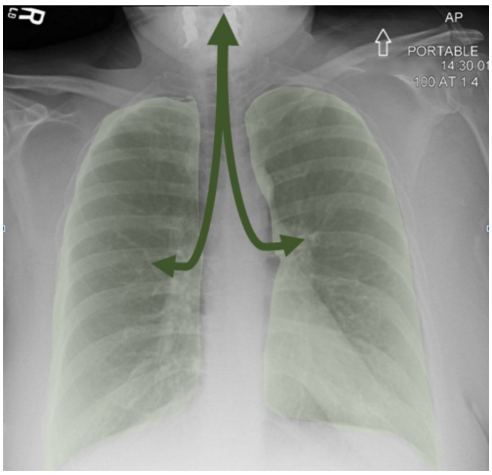
A discussion of the principles of mechanical ventilation must begin with a review of important physiologic concepts. We will begin with a review of gas exchange, and the concepts of shunt and dead space ventilation.

GAS EXCHANGE

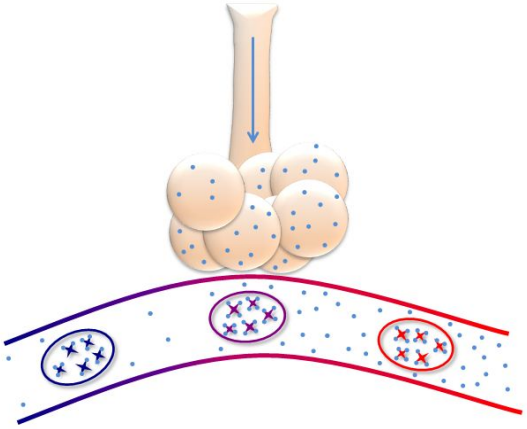
This diagram represents a normal cluster of alveoli with a normal capillary, delivering carbon dioxide (CO_2), shown in green on the left and picking up oxygen (O_2), illustrated by the change in the color of the capillary on the right. The diagrams are highly simplified for conceptual emphasis.

Carbon dioxide travels dissolved in the blood. Approaching the alveolus, the CO_2 easily crosses through the blood, across the capillary wall, and into the alveolus.

Because CO_2 crosses so readily into the alveolus from the serum, ventilation occurs readily. This means that the major determinants of CO_2 in the blood are the rate of production (increased with elevated metabolic demand, such as in sepsis or exercise) and the rate of elimination, largely determined by the minute ventilation. The minute ventilation is the amount of air moving through the lungs in one minute, quantified as the tidal volume (green arrows in the image below) and the respiratory rate (represented by the back and forth arrows.) The higher the minute ventilation, the lower the CO_2. Normal minute ventilation is about 6-8 L/min. In times of stress, with increased CO_2 production, minute ventilation may increase to 10-15 L/min.



Conversely, the path for oxygen is less simple. Oxygen is transported largely bound to hemoglobin inside the red blood cells. The hemoglobin in the schematic below demonstrates the four binding sites per hemoglobin molecule inside the red blood cells. Oxygen is represented by small blue dots. The concentration of oxygen is high in the alveoli, and it diffuses down the concentration gradient, into the capillary, into the RBC, and binds with hemoglobin.



While this binding allows for great efficiency in carrying oxygen, the multiple steps for oxygen transport, as compared to the simplicity of CO_2, explains some of the differential clinical effects seen with ventilation and oxygenation.

A small amount of oxygen is carried dissolved in the plasma, but compared to the amount bound to hemoglobin, this amount is trivial. The oxygen-carrying capacity of the blood is described by the equation:

Oxygen Delivery = Cardiac Output x (Hgb x 1.39 x Oxygen Saturation) + (PaO_2 x 0.003)

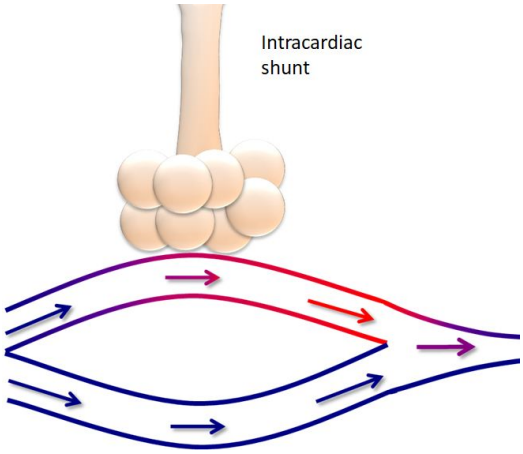
This equation intuitively makes sense, as the more Hgb available to carry oxygen, the more oxygen that can be delivered.

ISSUES WITH OXYGENATION

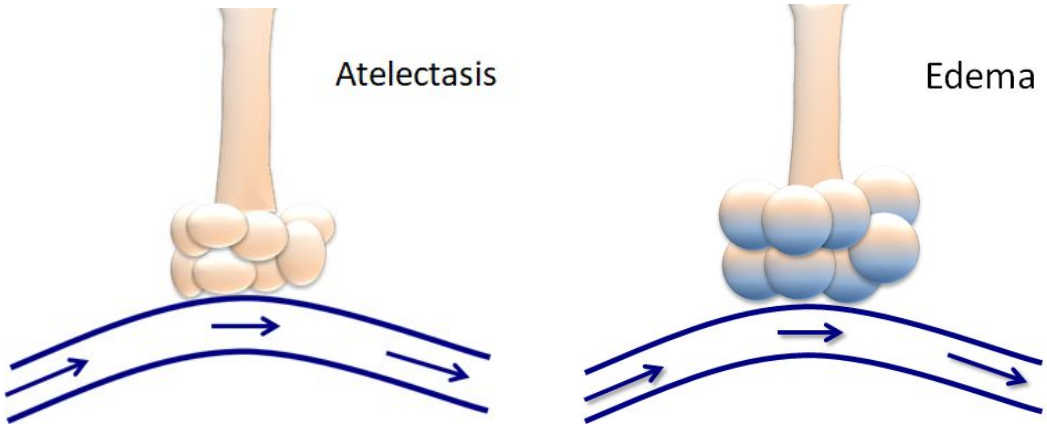
HYPOXEMIA

There are five broad physiologic causes of hypoxemia: shunting, VQ mismatch, alveolar hypoventilation, and decreased partial pressure of oxygen. Understanding these mechanisms allows a clinician at the bedside to quickly develop a differential diagnosis for hypoxemia and target diagnostics to assess for the precise etiology. We will review each mechanism in detail.

Shunts, or blood bypassing normal gas exchange, is one of the most common causes of hypoxemia. A classic example of a shunt is an intracardiac shunt. In this example, much of the blood passes by the alveoli, participating in normal gas exchange. However, a small amount is diverted through the heart, bypassing the lungs. This deoxygenated blood mixes with the oxygenated blood, leading to hypoxemia.

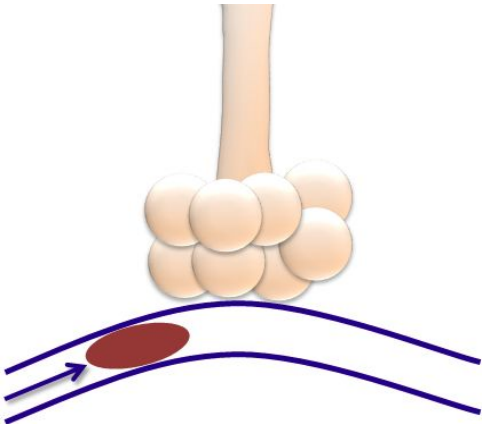


When an area of the lung is perfused, but not ventilated, that results in an intra-pulmonary shunt. In other words, the inspired oxygen cannot reach the alveoli for gas exchange. There are several different causes of intra-pulmonary shunts, including **atelectasis**, **pneumonia**, **pulmonary edema**, **acute respiratory distress syndrome (ARDS)**, **hemothorax** or **pneumothorax**, **hyperinflation** or **auto-PEEPing**. All of these pathological processes prevent effective gas exchange at the alveoli.



When an area has ventilation, but no perfusion, this is dead space. In other words, the airways are functioning normally, but there is a disease process in the vasculature. The best example would be a patient in cardiac arrest who is intubated and ventilated, but there is an interruption of chest compressions. Dead space can be anatomic and physiologic, such as oxygenation but lack of gas exchange that occurs in the upper airways,

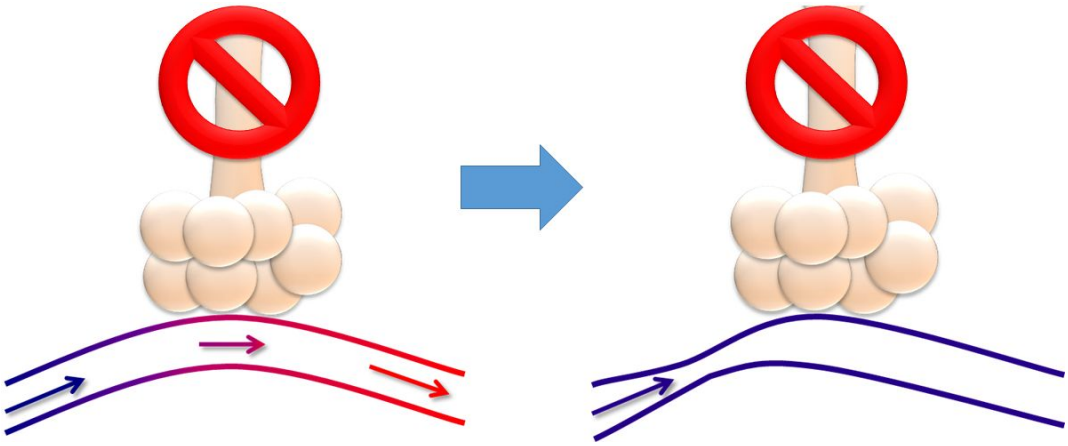
like the trachea. There can also be pathological causes of dead space, such as this diagram of microthrombi blocking a capillary.



Other examples of dead space include low cardiac output and hyperinflation, as occurs in obstructive lung disease. In diseases such as chronic obstructive lung disease (COPD), there can be a significant level of hyperinflation or auto-PEEP, which can lead to vasoconstriction of the capillaries involved in gas exchanged, thereby leading to impaired gas exchanged. Dead space ventilation can lead to both hypoxia and hypercapnia, due to CO_2 retention.

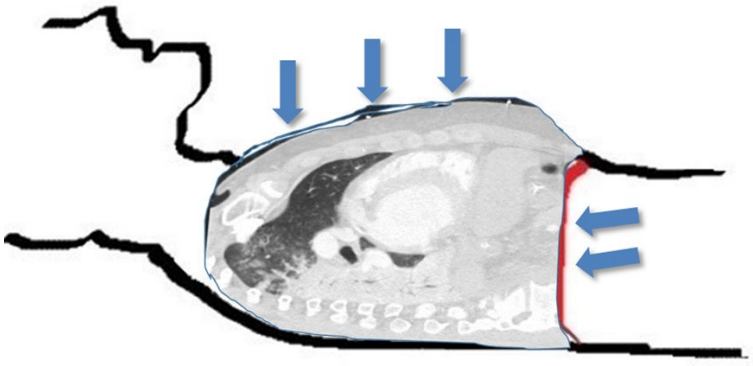
HYPOXIC VASOCONSTRICTION

When an area of the lung is hypoxic, or there is impairment in the oxygen delivery, the lung tries to optimize ventilation and perfusion ratio (V/Q matching) by means of hypoxic vasoconstriction. In this schematic below, the cluster of alveoli is not receiving oxygen. Therefore, the arterioles leading to the alveoli constrict, diverting blood away from this under-ventilated area, in an effort to improve oxygenation.



ATELECTASIS and DERECRUITMENT

Maximizing V/Q matching, by preventing atelectasis, is a key principle in the management of respiratory failure. Alveolar derecruitment, or atelectasis, leads to the creation of shunts. Atelectasis has multiple detrimental effects in ventilated patients. First, atelectasis decreases the surface area for gas exchange. Atelectasis on a large scale is derecruitment. Derecuitement is compounded by excessive lung weight (such as with pulmonary edema), chest wall weight (as with morbid obesity), abdominal contents and distention (as with small bowel obstructions), and even cardiac compresses (as with pericardial effusion). The addition of sedation and paralysis to positive pressure ventilation can further augment this derecruitment. This diagram reflects the pressures leading to compression of the lungs when lying a patient supine – the weight of the heart, the weight of the chest wall, the weight of the abdominal contents, and the weight of the lungs themselves.



Atelectasis also worsens lung mechanics. Consider blowing up a small party balloon. To start to open the balloon, a large amount of pressure is required. Once the balloon starts to inflate, blowing it up further is easy, until it reaches the point of overdistention.

COMPLIANCE and RESISTANCE

Two other important physiologic concepts to review are compliance and resistance.

Resistance is the impedance of flow in the tubing and airways and therefore can only occur when there is airflow.

According to Ohm's Law:

Resistance (R) = Δ pressure /Δ volume
R = (Peak inspiratory pressure – Plateau pressure) / Tidal volume
R = (PIP- Pplat) / (TV)

Assuming a constant tidal volume, the resistance equation can be simplified to:

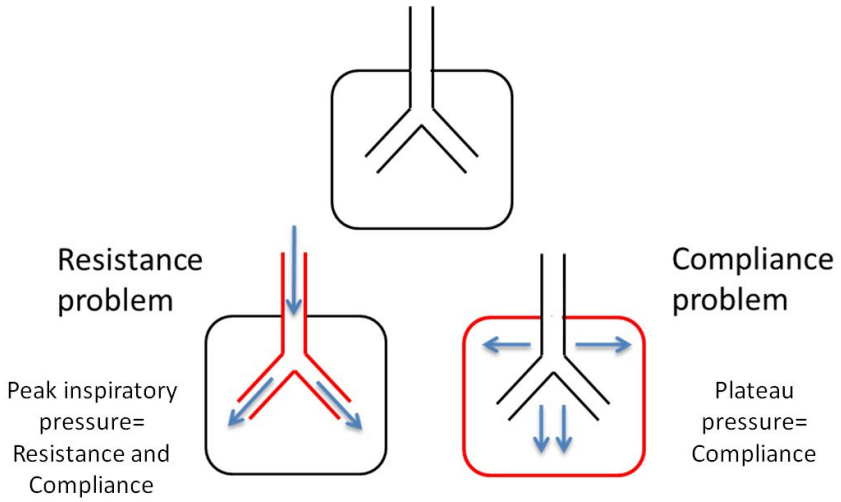
R ≈ (PIP- Pplat)

Normal airway resistance should be ≤ 5 cm H_20. Resistance is a factor in ventilating all patients but can become particularly important when ventilating patients with COPD or asthma. The resistance in a system increases with decreasing diameter. While common examples include a very small endotracheal tube (ETT) or bronchospasm leading to narrowing of the airways, recall that a "decrease in the diameter" can also occur at just one point, such as with kinking or biting of the ETT, or a mucous plug in a large airway.

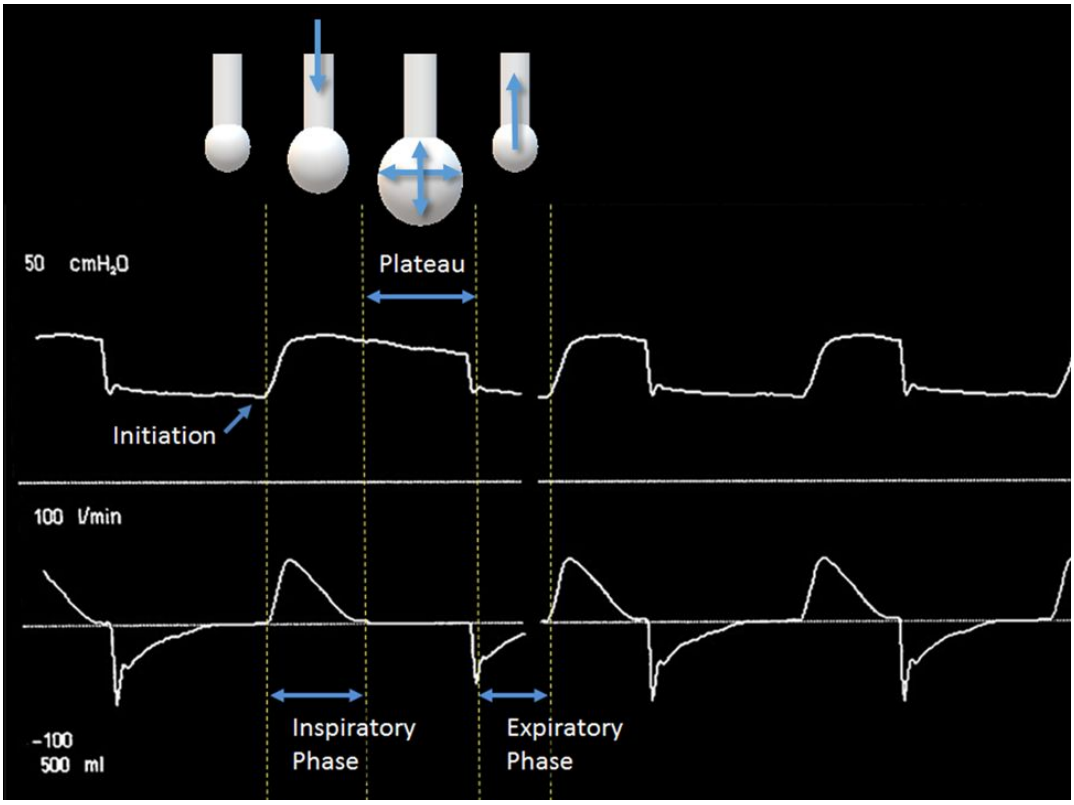
Compliance refers to the distensibility of the system and is the inverse of elastance. In other words, it is a measure of the lung's ability to stretch and expand. The more elastic a system, or higher the "recoil," the lower the compliance. A common analogy to understand the concepts of elastance is to analyze the recoil of springs. Imagine a very tightly wound and stiff spring. This spring is difficult to stretch and wants to stay in the coiled position. This spring would have high elastance and low compliance. Envision a second, loosely coiled spring. Very little force is required to stretch out this spring, and therefore, it has low elastance but high compliance.

Although compliance is commonly used to describe the lung parenchyma, remember that compliance actually involves all components of the system. In other words, a patient with pulmonary edema may have low compliance due to an issue with the lung parenchyma, but another patient may have similarly low compliance due to severe chest wall stiffness after a third-degree burn. Clinically, knowing the exact cause of decreased compliance in a given patient can be challenging. Physicians should not, therefore, always assume that it is always related to "stiff lungs."

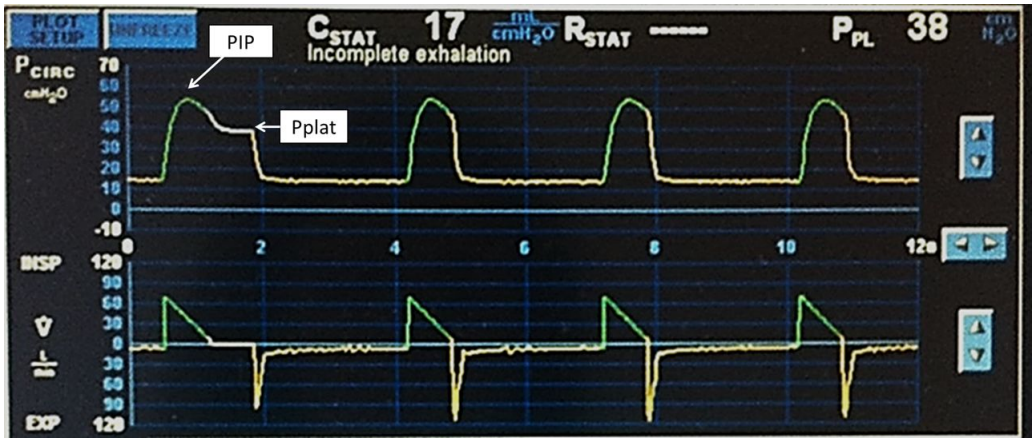
In the schematic below, the top "lungs" are healthy. The lungs on the left have a resistance problem or impairment in airflow. The lungs on the right have a compliance problem or impairment in stretch and recoil. In this diagram, both figures could have elevated peak inspiratory pressures (PIP), due to the excess pressure generated in the system. However, only the right-hand figure would have an elevated plateau pressure (Pplat), since this process occurs when there is an absence of airflow.



Therefore, when troubleshooting high pressures on a ventilator, two values are needed. The peak inspiratory pressure (PIP) is the maximum pressure in the system and includes both resistance and compliance. An inspiratory pause stops all airflow, thereby removing resistance, and only leaving compliance, as illustrated in this diagram below. The plateau pressure, or Pplat, is, therefore, a measure of compliance.



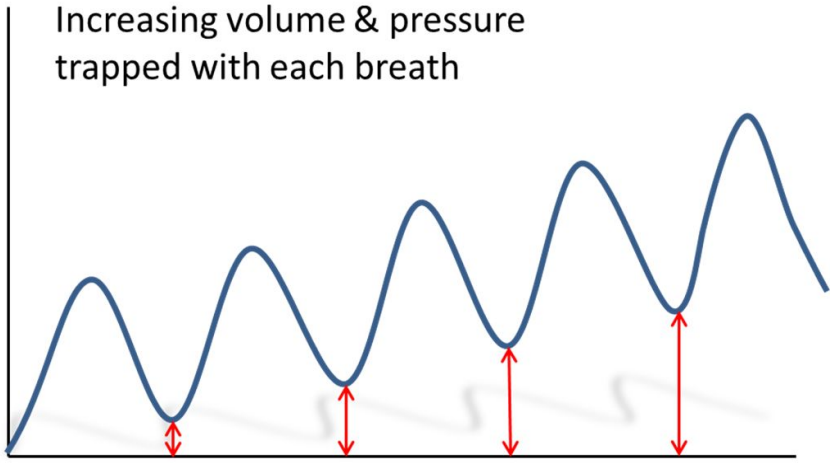
These values can be displayed on the ventilator screen. On most ventilators, the PIP is always seen, while the Pplat is seen by pushing the “inspiratory hold” or “inspiratory pause” button on the ventilator. An elevated PIP and normal Pplat is indicative of increased airway resistance. An elevated PIP and elevated Pplat is indicative of abnormal compliance.



Determining whether the patient has a resistance problem or a compliance problem can assist in the differential diagnosis of respiratory failure, as outlined in the table below.

High Resistance High PIP, Low/Normal P_{plat}	**Low Compliance** High PIP, High P_{plat}
Kinked/obstructed ETT	Mainstem intubation
Mucus plugging	Atelectasis
Bronchospasm	Pulmonary edema
ETT too narrow (small)	ARDS
Coughing	Hemo/pneumothorax
Bronchospasm (obstructive lung disease)	Pneumonia
	Pulmonary fibrosis (restrictive lung disease)
	Air-trapping with accumulated autoPEEP
	Obesity
	Abdominal compartment syndrome
	Circumferential burns of the chest
	Scoliosis
	Supine position

Air trapping, also referred to as breath-stacking, can lead to the development of auto-PEEP, or intrinsic PEEP (iPEEP). These pressures should be differentiated from the set PEEP, or extrinsic PEEP (ePEEP). ePEEP refers to the additional end-expiratory positive pressure set during mechanical ventilation to prevent alveolar collapse and recruitment. In contrast, auto-PEEP, or iPEEP, is a pathophysiological process that can occur when the ventilator initiates the next breath prior to complete exhalation. While this is most common in patients with prolonged expiratory phases, such as asthma or COPD, it can also occur in patients who have a fast respiratory rate or those who are being ventilated with large tidal volumes. The amount of auto-PEEP can be measured by pressing the “expiratory hold” or “expiratory pause” button on the ventilator. When this button is pressed, the ventilator will display the total PEEP. The auto-PEEP is the difference between the total PEEP and the set PEEP: **Auto-PEEP (iPEEP) = Total PEEP – ePEEP**

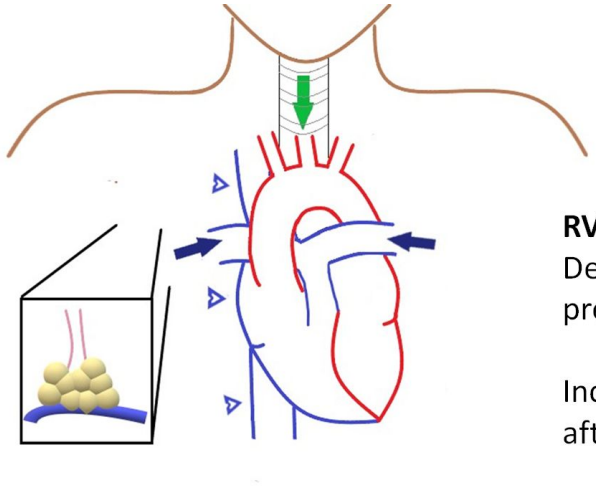


The schematic above represents the effects of air trapping. Please note that this diagram is for illustration purposes only and does not represent the expected tracings on actual ventilator screens.

Air trapping, or autoPEEP, can lead to significant adverse cardiopulmonary effects. The increased intrathoracic pressure from autoPEEP can decrease venous return and lead to hemodynamic instability, even cardiac arrest in severe cases. The increased pressures may also result in a pneumothorax or pneumomediastium. Additionally, air trapping can lead to ineffective ventilation due to collapse of the capillaries responsible for gas exchange, with worsening hypercarbia and hypoxemia. While this may seem like a paradox, as one may assume that increasing the minute ventilation, or moving more air, will improve ventilation, there is a limit to the beneficial effects. Once the lungs are overdistended, gas exchange is ineffective. In these circumstances, allowing the patient sufficient time to exhale can decrease CO2 retention.

Anticipating Physiologic Changes

Critically ill patients are at high risk of deterioration with intubation and initiation of mechanical ventilation. Much of this text is devoted to reviewing the effects of positive pressure ventilation (PPV) can have on pulmonary physiology. However, mechanical ventilation can also have extra-pulmonary effects that warrant review. Specifically, PPV leads to an increase in the intrathoracic pressure, which has different effects on the right and left ventricles. For the right ventricle, the PPV will lead to decreased preload via decreased venous return. This is shown by the blue and white arrowheads indicating increased pressure. The distention of the alveoli can also lead to increased afterload on the right ventricle. The inset illustrates the compression of small capillaries by distended alveoli, leading to an increase in pulmonary vascular resistance.



RV:
Decreased preload

Increased afterload

Note, however, that there is a U-shaped curve for changes in the pulmonary vascular resistance. Both atelectasis and overdistention can increase the afterload on the right ventricle.

The effects on the left ventricle are slightly different. PPV also decreases the left ventricular preload, given the impact on the right ventricle. However, the increased intrathoracic pressure also decreases the transmural pressure, or the afterload, on the left ventricle. While we use this principle to care for those with congestive heart failure (CHF), can lead to an increase in stroke volume and cardiac output.

However, in excess, these impacts on the cardiovascular system can lead to a decrease in the cardiac output and hypotension, especially in the intravascularly depleted patient, those with shock physiology, or with air trapping. Additionally, PPV leads to a decrease in the left ventricular afterload.

When intubating and placing the patient on the ventilator, the clinician should anticipate these effects. A volume-depleted patient, such as a patient with a GI bleed, may have hemodynamic collapse with initiation of positive pressure ventilation.

When initiating mechanical ventilation, the practitioner must be conscientious to ensure adequate gas exchange to meet the metabolic demands of the patient. For example, a patient in severe metabolic acidosis with respiratory compensation might be very tachypneic. One must be cognizant to increase the respiratory rate on the ventilator to help meet the patient's metabolic demands. Failure to do so can be detrimental for the patient, and lead to rapid decompensation.

Along the same lines, the practitioner must be careful to set and then adjust the ventilator settings to prevent further decompensation or injury. For example, excessive volumes on the ventilator can lead to volutrauma and impaired gas exchange. Excess pressure can lead to hemodynamic instability or barotrauma. These concepts will be explored further in the content on Ventilator Management in ARDS.