INTRODUCTION

The pathophysiology included in this topic is among the most formative and challenging changes to the new education standards. Previously, EMTs had to know only about the air moving in and out of the body—and, quite frankly, in very simple terms and concepts. It was the belief, in creating the standards that include this information, that EMTs would understand the internal processes of perfusion and gas transport that would make assessment and care performed more intuitive and effective.

REGULATION OF VENTILATION

Although breathing can be altered voluntarily, it is primarily controlled involuntarily by the autonomic nervous system. A large part of the regulation is related to maintaining normal gas exchange and normal blood gas levels. Receptors within the body constantly measure the amount of oxygen (O\textsubscript{2}), carbon dioxide (CO\textsubscript{2}), and hydrogen ions (pH) and signal the brain to adjust the rate and depth of respiration (Figure 7-1). Centers responsible for ventilatory control are the chemoreceptors, lung receptors, and specialized centers in the brainstem.

Chemoreceptors

Chemoreceptors are specialized receptors that monitor the number of hydrogen ions (pH) and the carbon dioxide and oxygen levels in the arterial blood. There are two different types of chemoreceptors: central and peripheral.

CENTRAL CHEMORECEPTORS  The central chemoreceptors are located near the respiratory center in the medulla. These receptors are most sensitive to changes in the amount of carbon dioxide in arterial blood and the pH of cerebrospinal fluid (CSF). The pH of CSF is directly related to the amount of carbon dioxide in the arterial blood. Carbon dioxide readily crosses the blood–brain barrier and moves into the CSF. In the CSF, the CO\textsubscript{2} combines with water (H\textsubscript{2}O) to form carbonic acid (H\textsubscript{2}CO\textsubscript{3}). Thus there is an association between CO\textsubscript{2} and the level of acid in the body as follows:

- An increase in the amount of CO\textsubscript{2} in the blood will increase the amount of acid in the blood.
- A decrease in the amount of CO\textsubscript{2} in the blood will decrease the amount of acid in the blood.

The central chemoreceptors are highly sensitive to the amount of hydrogen in the CSF. After the CO\textsubscript{2} and H\textsubscript{2}O molecules combine to form H\textsubscript{2}CO\textsubscript{3}, the hydrogen ions (H\textsuperscript{+}) dissociate from the H\textsubscript{2}CO\textsubscript{3}, enter the CSF, and stimulate the central chemoreceptors. Small changes in the H\textsuperscript{+} level in the CSF will stimulate
a change in respirations. Because CO₂ is needed to produce H₂CO₃, the changes in the breathing rate and depth are geared toward increasing or decreasing the CO₂ level in the arterial blood. The response of ventilation can be summarized as follows:

An increase in arterial CO₂ will increase the number of hydrogen ions in the CSF, stimulating an increase in the rate and depth of respiration to blow off more CO₂.

A decrease in arterial CO₂ will decrease the number of hydrogen ions in the CSF, causing a decrease in the rate and depth of respiration to blow off less CO₂.

**PERIPHERAL CHEMORECEPTORS** The peripheral chemoreceptors are located in the aortic arch and carotid artery bodies in the neck. These chemoreceptors are also sensitive to CO₂ and pH; however, the arterial oxygen level is the strongest stimulus. Thus, a change in the arterial oxygen level is what stimulates the brain to increase or decrease ventilation. It takes a significant decrease in the arterial oxygen content to trigger the peripheral chemoreceptors to stimulate the respiratory center to increase rate and depth of respiration. The activity of the peripheral chemoreceptors can be summarized as follows:

A significant decrease in the arterial oxygen content will result in an increase in the rate and depth of ventilation aimed at increasing the arterial oxygen content.

Stimulation of both the central and peripheral chemoreceptors have a greater influence on changing the rate and depth of ventilation than either alone.

**Hypoxic Drive**

A person’s ventilation is normally controlled by the strong stimulus provided by the amount of CO₂ in the arterial blood. This is referred to as a hypcapnic drive or hypercarbic drive. However, some patients with chronic obstructive pulmonary disease (COPD), such as emphysema or chronic bronchitis, have a tendency
to retain carbon dioxide in their arterial blood from poor gas exchange. Because the \( \text{CO}_2 \) level is chronically elevated, the central chemoreceptors become desensitized to fluctuations that typically would stimulate a change in the rate or depth of ventilation. Because of the desensitization of the central chemoreceptors, the peripheral chemoreceptors become the primary stimulus to control ventilation. Thus, hypoxia, rather than \( \text{CO}_2 \), becomes the stimulus for the person to breathe; this is referred to as a hypoxic drive.

**Lung Receptors**

Three different types of receptors are found within the lungs: irritant receptors, stretch receptors, and J-receptors. The irritant receptors are found in the airways and are sensitive to irritating gases, aerosols, and particles. Irritant receptors will cause a cough, bronchoconstriction, and an increase in the rate of ventilation.

The stretch receptors are located within the smooth muscle of the airways. These are responsible for measuring the size and volume of the lungs. To prevent overinflation when stimulated by high tidal volumes, these receptors decrease the rate and volume of ventilation when stretched.

J-receptors are located in the capillaries surrounding the alveoli and are sensitive to increases in pressure within the capillary. When activated, these receptors stimulate rapid, shallow respiration.

**SPECIALIZED RESPIRATORY CENTERS IN THE BRAIN**

The brainstem contains four respiratory control centers: the dorsal respiratory group, the ventral respiratory group, the apneustic center, and the pneumotaxic center. These centers stimulate the respiratory muscles to either contract or relax, depending on the impulse.

The dorsal respiratory group (DRG) is responsible for setting the basic rhythm of respiration. It consists of inspiratory neurons that send nerve impulses to the external intercostal muscles and diaphragm, stimulating them to contract, which results in inspiration. The DRG is active in every respiratory cycle, whether breathing is quiet or forced. In a typical respiratory cycle, the DRG stimulates the respiratory muscles to contract for 2 seconds, followed by 3 seconds with no stimulation, resulting in respiratory muscle relaxation.

The ventral respiratory group (VRG) has both inspiratory and expiratory neurons. However, the VRG is basically inactive during normal quiet breathing. The VRG becomes active when accessory muscles are needed to assist in inspiration or expiration. The VRG, in which the \( I \) subscript indicates inspiratory VRG neurons, stimulates the pectoralis minor, scalene, and sternocleidomastoid muscles to force inspiration. The VRG, in which the \( E \) subscript indicates expiratory VRG neurons, stimulates the internal intercostal and abdominal muscles to force exhalation.

The apneustic center does not control the rhythm of respiration; however, it provides stimulation to the DRG and VRG to intensify the inhalation effort. The apneustic center may prolong inspiration, increasing the ventilatory volume.

The pneumotaxic center sends inhibitory impulses to the apneustic center to cease inhalation before the lungs become overinflated. It can promote passive exhalation both by shutting off the DRG and VRG and by activating the VRG.

**VENTILATION/PERFUSION RATIO**

The ventilation/perfusion (V/Q) ratio describes the dynamic relationship between the amount of ventilation in the alveoli and the amount of perfusion through the alveolar capillaries. This relationship determines the quality of gas exchange across the alveolar–capillary membrane, which in turn determines the amount of oxygen entering the blood and \( \text{CO}_2 \) offloading from the blood. This relationship can be used to explain the etiology of hypoxemia.

In the ideal lung, each alveolus would receive an adequate amount of ventilation and a matching amount of blood flow through the surrounding capillary, resulting in a V/Q ratio of 1—that is, ventilation and perfusion are equal. This ideal condition never exists, though, because of the effects of gravity on blood flow, the structure of the lungs, and shunting of blood.

When a person is in a standing position, gravity pulls the lungs downward toward the diaphragm, compressing the lower lobes. As the lower lobes are compressed and blood is pulled down to the bases of the lungs, air travels upward to the apexes (tops) of the lungs and increases the residual volume. Interestingly, the alveoli in the apexes of the lungs have a greater residual volume of air, are larger, and have a higher surface tension, but they are fewer in number compared with other areas of the lungs. These larger alveoli in the apexes have a higher surface tension, which makes them less compliant and harder to inflate during ventilation. Thus, the tidal volume is shifted to the lower lobes, where the lung is more compliant and there is less surface tension.

Because gravity pulls the blood downward, less pressure is required to perfuse the lower lobes of the lungs, as compared with the apexes, which are above the level of the heart. As a result, the bases of the lungs receive a greater amount of blood and are much better perfused than the apexes. This is a desirable condition, as the greatest amount of ventilation also exists in the base of the lungs.

The V/Q ratio is never at an ideal state in any zones of the lungs. In the apexes, the amount of available ventilation in the alveoli exceeds the amount of perfusion through the pulmonary capillaries; that is, more oxygen is available in the alveoli than the supply of blood is able to pick up and transport. This is considered to be wasted ventilation. In the bases, the amount of perfusion exceeds the amount of ventilation; this means more blood is moving through the pulmonary capillaries than there is alveolar oxygen available for it to pick up. This is considered to be wasted perfusion. Overall, under normal conditions, perfusion exceeds the amount of available ventilation.

**Pressure Imbalances**

The perfusion of blood through the pulmonary...
Capillaries is affected by the amount of air and pressure inside the alveoli and the pressure of the blood flowing through the capillary bed (Figure 7.2). If the pressure in an alveolus exceeds the hydrostatic pressure of blood in the capillary bed, blood flow through the capillary stops. This is most likely to occur in the apexes of the lungs, where the pressure inside the alveoli is highest and the blood flow is lowest. However, it may also occur in the patient who is losing blood from an injury and has a decreasing blood pressure.

A decrease in the systemic blood pressure will also cause the pressure in the pulmonary capillaries to decrease. If the patient does not have a chest or lung injury, the lungs will continue to receive adequate volumes of air, creating adequate pressure in the alveoli. However, the reduction in blood pressure may allow the alveolar pressure to exceed the pulmonary capillary pressure and impede blood flow. This will result in poor alveolar perfusion, hypoxemia (reduced oxygen concentrations in the blood), and cellular hypoxia (oxygen deficiency in the cells).

**Hypoxia generally results from a ventilation or perfusion disturbance.**

**Ventilatory Disturbances**

A disturbance on the ventilation side of the ventilation/perfusion ratio can lead to hypoxia. If a condition or injury causes less oxygenated air to be available in the alveoli for the amount of blood flowing through the pulmonary capillaries, the end result will be less oxygen saturating the blood and less oxygen delivered to the cells, creating hypoxemia and cellular hypoxia.

For example, if a patient is having an asthma attack and the bronchioles are inflamed and constricted, the restricted airways reduce airflow and provide less oxygenated air to the alveoli for gas exchange. The blood pressure is not affected; therefore, the amount of blood passing through the pulmonary capillaries remains normal. A ventilation disturbance has been created by making less oxygen available to the blood passing through the capillaries. In this condition, there is wasted perfusion, as the blood is available but there is an inadequate amount of oxygen to be picked up. This disturbance in ventilation leads to hypoxemia and cellular hypoxia.

In the situation just described, in which an asthma attack has caused a ventilatory disturbance, the ventilation side of the ventilation/perfusion ratio must be improved by relieving the bronchiole airway restriction and increasing the amount of oxygenated air entering the alveoli. An EMT would achieve this by placing the patient on oxygen and administering a medication to dilate the bronchioles to improve airflow. This treatment would not only increase the amount of air in the alveoli, but it would also increase the concentration of oxygen in the alveolar air, making more oxygen available for the blood moving through the pulmonary capillaries. This would reduce or eliminate the hypoxemia and cellular hypoxia.

**Perfusion Disturbances**

A perfusion disturbance may also lead to severe cellular hypoxia. Consider a patient you encounter who has cut his radial artery on a saw and suffered severe blood loss. The patient has no chest or lung injury and has an increased rate and depth of ventilation. His minute ventilation and alveolar ventilation are increased; however, his cells are becoming hypoxic. Although he is moving more oxygenated air into the alveoli, his blood loss has significantly reduced the amount of blood flow through the pulmonary capillaries. This represents a perfusion disturbance because there is not enough blood to pick up the oxygen available in the alveoli. This would create a state of wasted ventilation, hypoxemia, and cellular hypoxia.

By placing the patient on oxygen, you might reduce some of the cellular hypoxia; however, it will not be eliminated until the perfusion disturbance is fixed. The bleeding must be stopped, and this patient needs to receive fluid and blood to increase the flow and pressure in the pulmonary capillaries so enough hemoglobin is available for oxygen in the alveoli to attach to and be transported to the cells.

Hypoxia generally results from a ventilation or perfusion disturbance. Myriad conditions can cause one of these disturbances to occur. The management of hypoxia resulting from a ventilatory disturbance should focus on improving ventilation and oxygenation. Managing a disturbance in perfusion must focus on increasing blood flow through the pulmonary capillaries, the availability of hemoglobin, and delivery of oxygen to the cells.

---

*Figure 7.2 Perfusion of the pulmonary capillaries is affected by pressure within the alveoli and pressure within the capillaries.*
TRANSPORT OF OXYGEN AND CARBON DIOXIDE IN THE BLOOD

Oxygen must be continuously delivered by the blood to the cells for normal cellular metabolism to occur. Carbon dioxide, a byproduct of aerobic metabolism, must be carried back to the lungs to be eliminated during exhalation. A disturbance in the transport system may lead to both cellular hypoxia (a lack of oxygen available to the cells) and hypercarbia (a buildup of carbon dioxide in the blood). Both hypoxia and hypercarbia pose problems for normal cellular function and stability.

Both oxygen and carbon dioxide are transported by the blood but in different ways (Figure 7-3). It is important to remember that oxygen and carbon dioxide move from areas of higher concentration to areas of lower concentration. This helps to explain the movement of gas molecules between alveoli and capillaries and between capillaries and cells.

A pulmonary embolus is another example of a common perfusion disturbance in which blood flow to a portion of the lung is physically blocked.

Oxygen Transport

Approximately 1000 mL of oxygen is delivered to the cells every minute. Oxygen is transported by the blood in two ways: dissolved in plasma and attached to hemoglobin. A small amount, only 1.5 percent to 3 percent, is dissolved in plasma. The majority of oxygen, approximately 97 percent to 98.5 percent, is attached to hemoglobin molecules.

Hemoglobin is a protein molecule that has four iron sites to which oxygen can bind. Thus, one hemoglobin molecule could carry up to four oxygen molecules. If one oxygen molecule is attached to the hemoglobin molecule, it is considered to have 25 percent saturation. Attachment of two oxygen molecules would be considered 50 percent saturation, three molecules 75 percent saturation, and four molecules 100 percent saturation. The attachment of one oxygen molecule to a hemoglobin iron-binding site will increase the affinity for the other sites to also bind with oxygen.

Once an oxygen molecule binds with hemoglobin, the hemoglobin molecule is referred to as oxyhemoglobin. A hemoglobin molecule that has no oxygen attached is referred to as deoxyhemoglobin. Without hemoglobin, the negligible amount of oxygen that can be transported by plasma would not be enough to sustain normal cellular function or life. A loss of hemoglobin, which commonly occurs as a result of bleeding, can easily lead to severe cellular hypoxia, even though an adequate amount of oxygen is available in the alveoli.

Carbon Dioxide Transport

Carbon dioxide is transported in the blood in three ways: Approximately 7 percent is dissolved in plasma, 23 percent is attached to hemoglobin, and 70 percent is in the form of bicarbonate.

As CO₂ leaves the cells, it crosses over into the capillaries, where a small amount dissolves into the plasma. A larger amount of CO₂ attaches to hemoglobin. The largest amount of CO₂ diffuses into the red blood cells and combines with water to form H₂CO₃, which then dissociates into hydrogen and bicarbonate. The bicarbonate exits the cell and is transported in the blood plasma. When the blood reaches the pulmonary circulation, the bicarbonate diffuses back into the red blood cell, where it combines with hydrogen and splits back into water and carbon dioxide. Regardless of the transport mechanism, the carbon dioxide diffuses into the alveoli, which are low in CO₂ concentration, and is eliminated during exhalation.

Alveolar/Capillary Gas Exchange

After inhalation, the alveoli are filled with oxygen-rich air that contains very little carbon dioxide. Conversely, the venous blood that flows through the capillaries surrounding the alveoli contains low levels of oxygen and higher amounts of carbon dioxide.

Because gas molecules naturally move from an area of high concentration to an area of low concentration, the high oxygen content in the alveoli moves across...
the membranes and into the capillaries, where the oxygen content is very low (Figure 7-4). There, as described earlier, a small amount of oxygen dissolves in the plasma and a larger amount attaches to the hemoglobin. Simultaneously, CO₂ moves in the opposite direction, from the high levels contained in the capillaries into the alveoli, where the CO₂ content is low. It happens this way: The bicarbonate ions in the blood convert to water and CO₂; additional CO₂ diffuses out of the plasma and offloads from the hemoglobin; and all this CO₂ crosses from the capillaries into the alveoli.

After these exchanges—from alveoli to capillaries and from capillaries to alveoli—the alveoli contain low levels of oxygen and high levels of CO₂, whereas the blood in the capillaries contains high levels of oxygen and low levels of CO₂. Basically, the gases have switched concentrations. The CO₂-rich air in the alveoli is exhaled from the lungs. The oxygen-rich blood in the capillaries is transported from the pulmonary circulation to the left atrium and then to the left ventricle of the heart, from which it is ejected into the aorta and to the arteries throughout the body. This blood that is circulating throughout the body will be used in the cell/capillary gas exchange described next.

**Cell/Capillary Gas Exchange**

The blood that was ejected from the left ventricle into the arteries contains high concentrations of oxygen and low concentrations of CO₂. This blood travels through an artery and then enters a smaller arteriole that leads to a capillary bed that is surrounded by cells. During cell metabolism, the cells have used oxygen and produced carbon dioxide as a byproduct. Thus, whereas the capillary beds contain blood that is high in oxygen and low in CO₂, the cells contain low levels of oxygen and high levels of CO₂.

As the blood enters the capillary, oxygen breaks free of the hemoglobin and diffuses out of the plasma, crosses the capillary membrane, and enters the cell. Simultaneously, CO₂ leaves the cell and crosses over into the capillary, where it dissolves in the plasma, attaches to hemoglobin, or enters the red blood cell to be converted to bicarbonate (Figure 7-4).

As the blood leaves the capillary, it enters a small venule, from which it is eventually dumped into a larger vein. The blood in the venules and veins contains low concentrations of oxygen and high concentrations of CO₂. This CO₂-carrying blood is transported to the right atrium of the heart, from which it enters the right ventricle and is pumped to the lungs. There, the blood enters the pulmonary capillaries to give off CO₂ and pick up oxygen in the alveolar/capillary gas exchange, as described earlier.

For the cells to receive an adequate amount of oxygen and eliminate CO₂, both the alveolar/capillary gas exchange and cell/capillary gas exchange must be functioning properly. A disturbance in either will result in either inadequate amounts of oxygen being delivered to the cells or the accumulation of CO₂.
REVIEW ITEMS

Circle the correct answer.

1. An increase in the level of carbon dioxide in the arterial blood will result in ______.
   a. a decrease in the respiratory tidal volume
   b. a decrease in the number of hydrogen ions
   c. an increase in the respiratory rate
   d. an increase in bicarbonate

2. Increasing the oxygen content in the arterial blood in a patient breathing on a hypoxic drive will possibly lead to ______.
   a. stimulation of the central chemoreceptors
   b. a decrease in the rate and depth of respiration
   c. an increase in the amount of carbonic acid
   d. collection of hydrogen ions in the CSF

3. A patient presents with use of the sternocleidomastoid muscle and retractions during respiration. You would suspect that which of the following respiratory centers is providing respiratory muscle stimulation?
   a. DRG
   b. VRG

4. Hypoxia associated with an acute asthma attack would likely result from ______.
   a. a ventilation disturbance
   b. an upper airway occlusion
   c. a perfusion disturbance
   d. chemoreceptor dysfunction

5. The primary method of transport of carbon dioxide in the blood is ______.
   a. dissolved in plasma
   b. attached to hemoglobin
   c. as carbonic acid
   d. in the form of bicarbonate

APPLIED PATHOPHYSIOLOGY

Write your answers in the spaces provided.

1. Explain how the central chemoreceptors regulate the rate and depth of respiration.

2. Explain how the peripheral chemoreceptors regulate the rate and depth of respiration.

3. Describe how admonition of a high concentration of oxygen in a patient with a hypoxic drive may lead to respiratory depression and failure.

4. Explain a normal respiratory cycle based on activity of the DRG.

5. Explain the respiratory cycle in forced breathing based on activity of the VRG.

6. Explain hypoxia based on the ventilation/perfusion ratio.
7. Explain how a ventilation disturbance would lead to hypoxia.

8. Explain how a perfusion disturbance would lead to hypoxia.

9. Explain two ways oxygen is transported in the blood.

10. Explain three ways carbon dioxide is transported in the blood.

11. Explain gas exchange at the alveolar/capillary level.

12. Explain gas exchange at the tissue/capillary level.

CLINICAL DECISION MAKING

Write your answers in the spaces provided.

You arrive on the scene and find a 28-year-old female patient who was shot in the chest. The patient complains that he is struggling to breathe. His airway is open, and his respirations are rapid. His skin is pale, cool, and clammy, and he is exhibiting circumoral cyanosis. His SpO₂ reading is 76 percent on room air.

1. Following scene safety, what is your first immediate action after approaching this patient?

2. What are the life threats to this patient?

3. What do you suspect is causing the cyanosis and poor SpO₂ reading?

4. Would the hypoxia be related to a ventilation or perfusion disturbance?

5. Based on stimulation of the chemoreceptors, what is causing an increase in the respiratory rate?