Chapter 8 –Respiratory System

Objectives

Given the synopsis in this chapter, competence in each objective will be demonstrated by responding to multiple choices or matching questions, completing fill-in questions, or writing short answers, at the level of 75% or greater proficiency for each student.

A. To describe the organization and general function of respiratory system.
B. To explain the relationship of the pleural cavities and the lungs, and the function of the pleural fluid.
C. To compare and contrast the processes of exhalation and inhalation, including the roles of the respiratory pressures and the elastic connective tissues of the lungs.
D. To describe ventilatory volumes commonly measured and explain their significance in respiratory evaluation.
E. To explain the process of gas exchange between the alveoli and blood in the lungs, and gas exchange between muscle cells and blood in a muscle.
F. To explain the process of oxygen and carbon dioxide transport through the blood.
G. To explain how the respiratory system regulates acid-base balance.

The respiratory system in humans includes the nasal and oral cavities, the respiratory airways leading to the lungs, the lungs and pleural cavities, and the muscles of the chest and abdomen responsible for moving air into and out of the lungs during breathing. The primary purpose of the respiratory system is to obtain oxygen from the air and transfer it to the blood, and to transfer carbon dioxide from the blood and move it to the air. Additionally, the amount of carbon dioxide in the blood affects pH and the respiratory system plays a critical role in controlling acid-base balance.

Organization of the Respiratory System

Air passes through the nose, mouth, larynx, trachea and bronchi in order to reach the lungs, as shown in Figure 8.1 and 8.2. The lungs are located within the pleural cavities of the chest. The diaphragm is located below the pleural cavities, and forms a partition between the thoracic cavity and the abdominal cavity

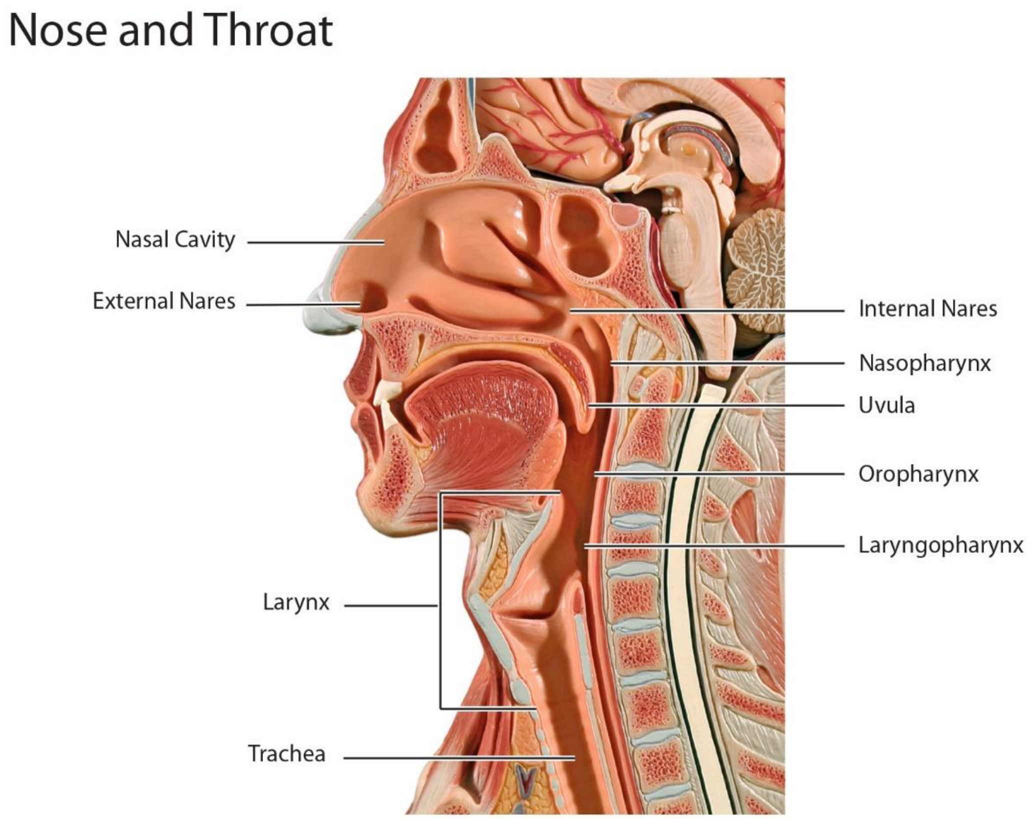
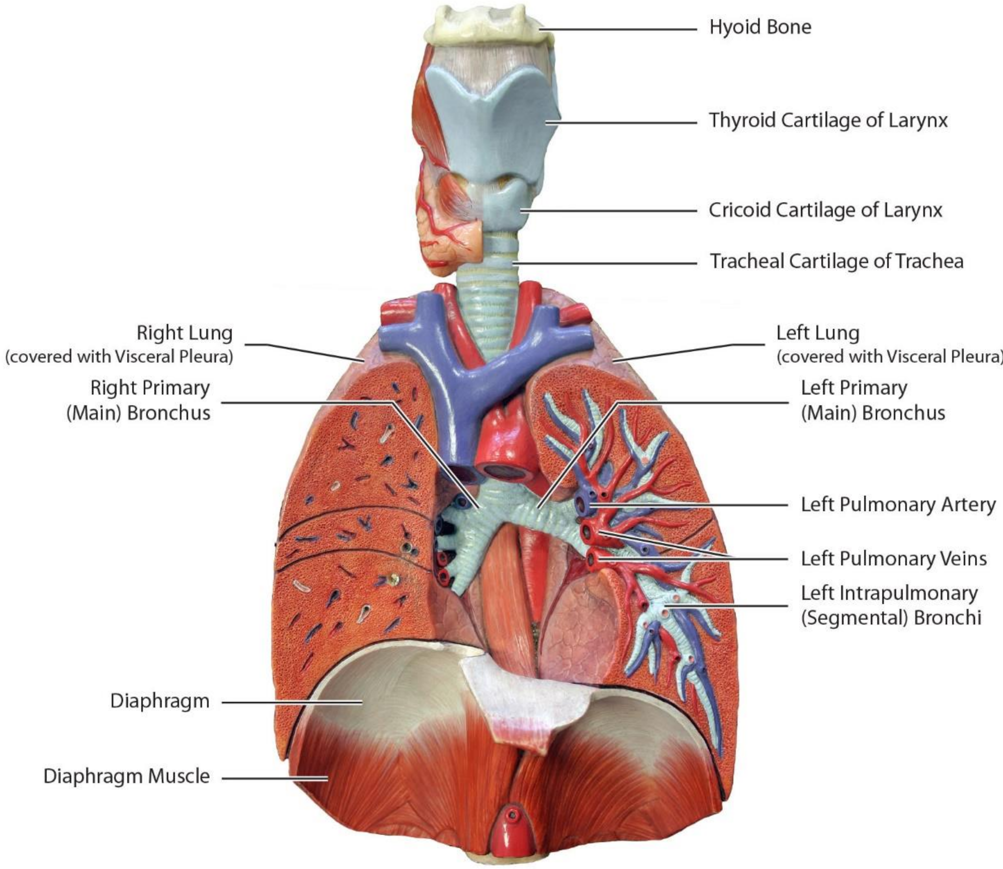


Figure 8.1 © 2014 David G. Ward, Ph.D., Atlas of Anatomy for Allied Health.

Neck and Thoracic Cavity

Larynx, Trachea, and Lungs



Larynx - midsagittal

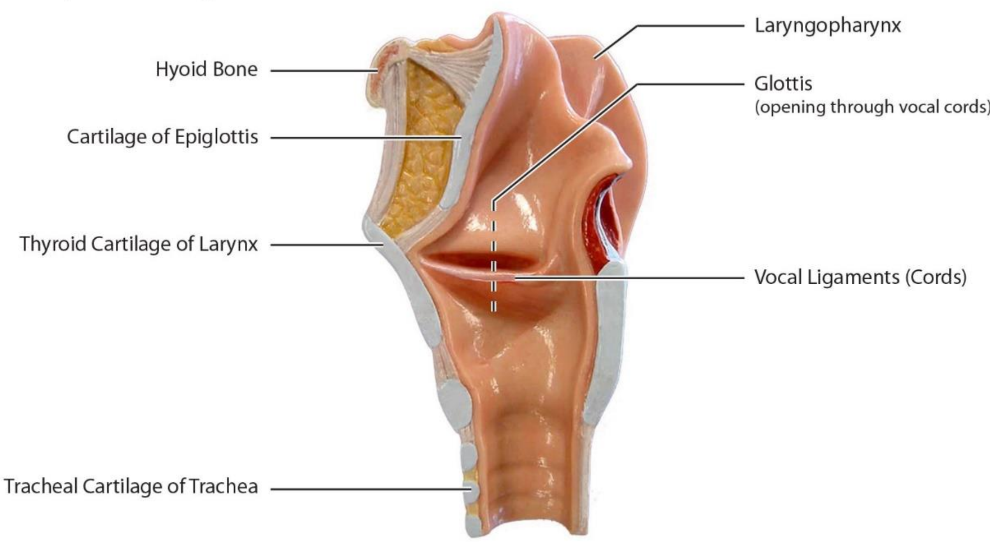


Figure 8.2 © 2014 David G. Ward, Ph.D., Atlas of Anatomy for Allied Health.

The respiratory airways are lined with a respiratory epithelium that separates the air from the body. In the nose, trachea, and bronchi the epithelium is ciliated and plays a major role in removing dust and debris from the airways. The Pseudostratified ciliated columnar epithelium (PCCE) of the trachea is shown in Figure 8.3

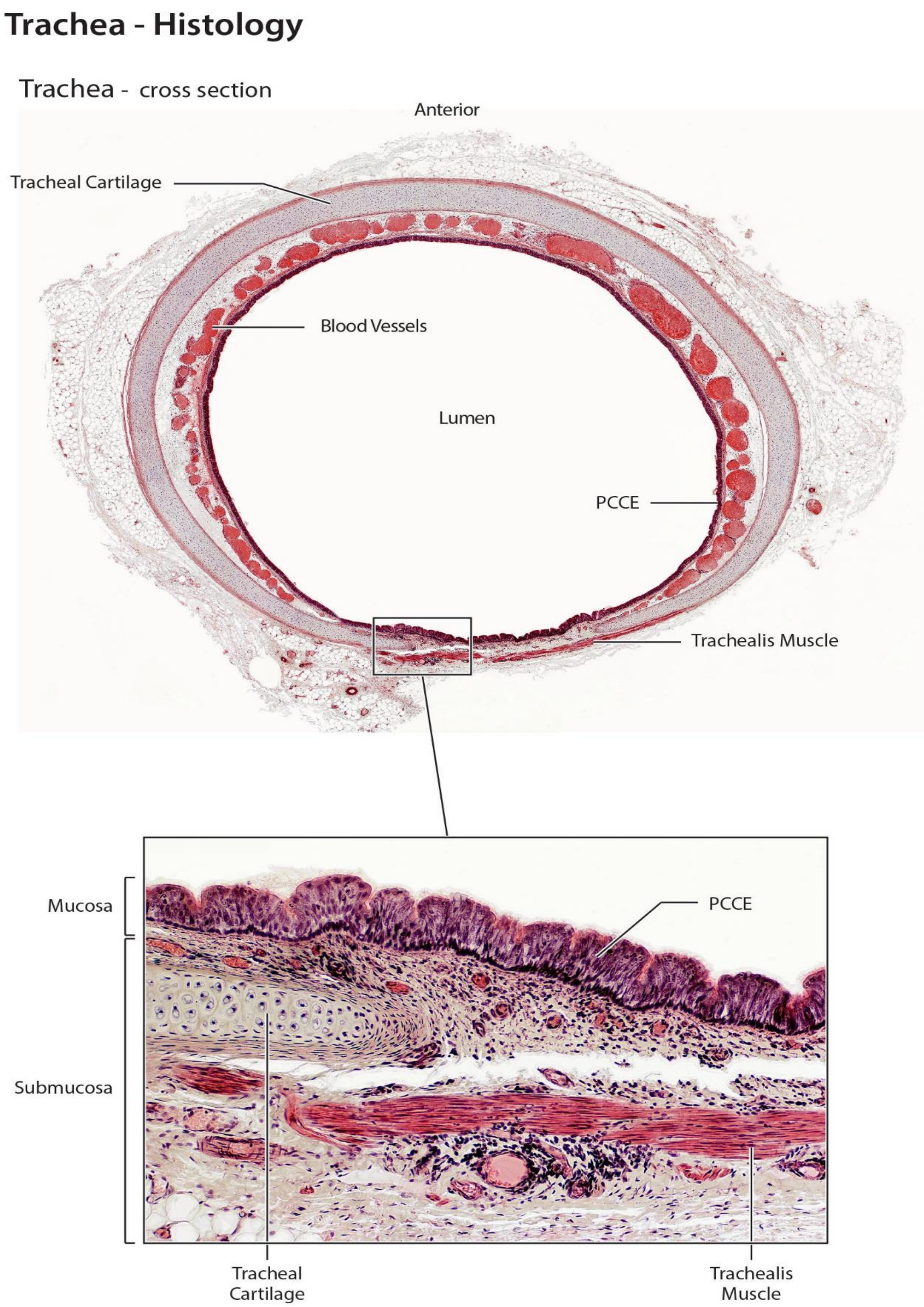


Figure 8.3 © 2014 David G. Ward, Ph.D., Atlas of Anatomy for Allied Health.

The respiratory airways carry air into and out of the alveoli which make up the major portion of the lungs, as shown in Figure 8.4. The alveoli are spherical structures made largely of simple squamous epithelium that are clustered together to form alveolar sacs. The alveolar sacs in turn connect to bronchioles that in turn connect to intrapulmonary bronchi (segmental bronchi). The epithelium of the alveoli is surrounded by elastic connective tissue and by the pulmonary capillaries. The elastic connective tissue places a constant pressure on the alveoli and causes them to recoil after being stretched. Elastic connective tissue is also found under the visceral pleura of the lungs. The pulmonary capillaries provide for the exchange of gasses between the blood and the air in the alveoli. Pulmonary arterioles and venules connect the capillaries to the pulmonary arteries and veins.

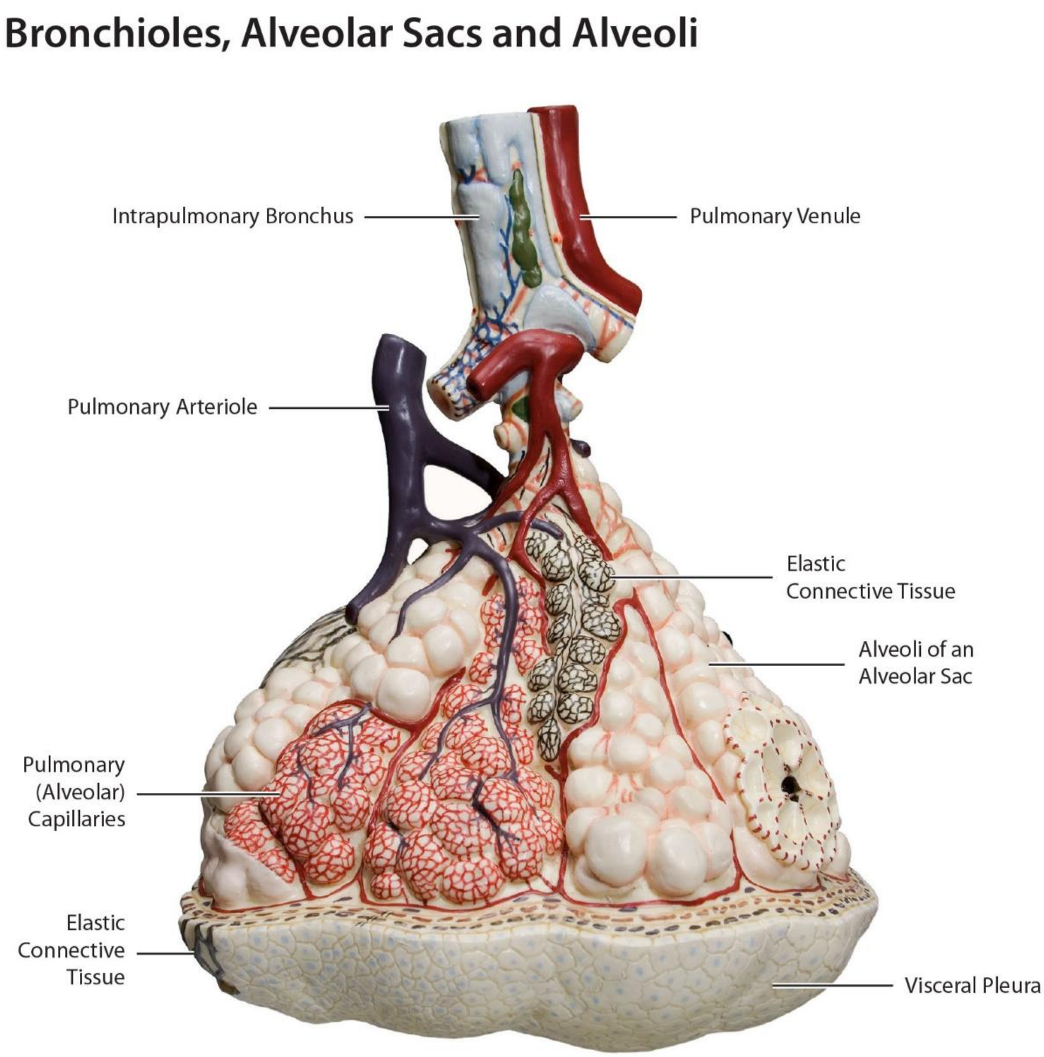


Figure 8.4 © 2014 David G. Ward, Ph.D., Atlas of Anatomy for Allied Health.

Pleural membranes and pleural fluid

The pleural membranes are composed of simple squamous epithelia and are located in the pleural cavities of the chest, as shown in Figure 8.5. The parietal pleura line each of the pleural cavities. The visceral pleura cover each of the lungs. Pleural fluid is secreted by the pleural membranes and fills the spaces between the pleural membranes. The pleural fluid creates a fluid bond (and an associated negative intrapleural pressure) that pulls the pleural membranes against each other. Without this fluid bond, expansion of the chest does not cause the lungs to expand and inhalation does not occur. This is seen following chest trauma that causes a pneumothorax.

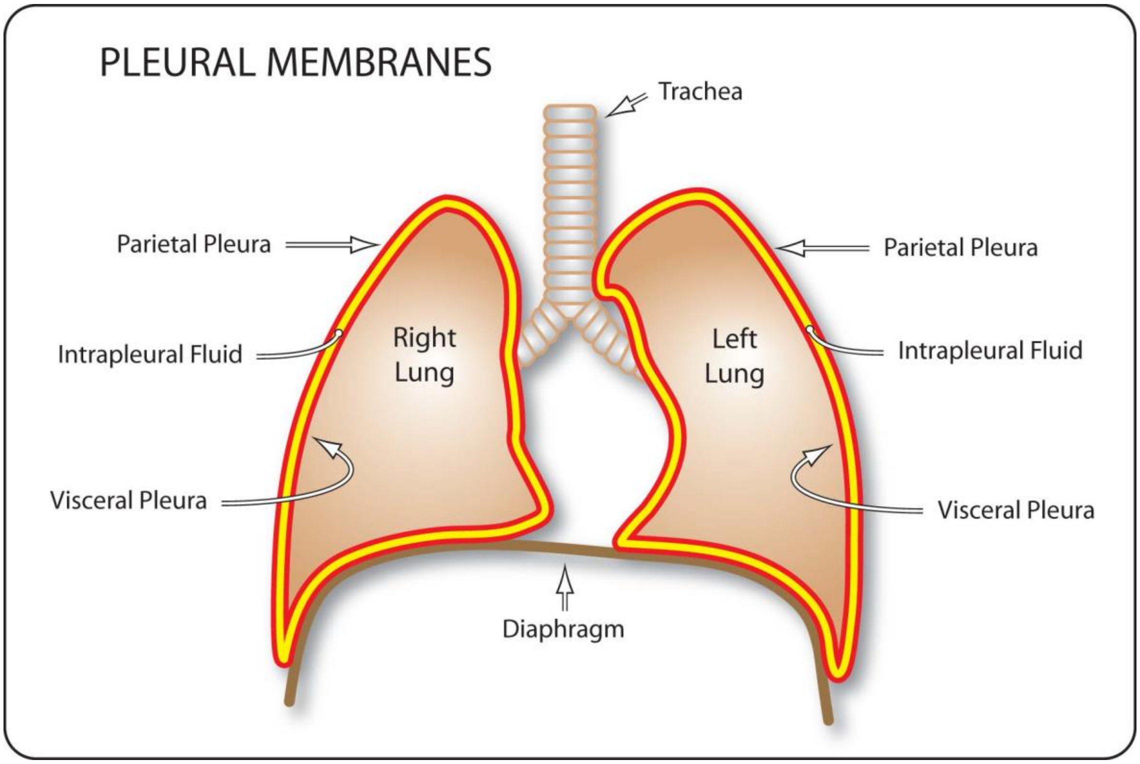


Figure 8.5 © 2010 David G. Ward, Ph.D.

Pulmonary Ventilation and Lung Mechanics

Pulmonary ventilation is the process of moving air between the atmosphere and the alveoli of the lungs. Movement of air depends on changing the size of the lungs and is critically dependent on the elastic connective tissue of the lungs, the pleural membranes and pleural fluid, and the muscles of the chest and abdomen.

As the volume of the lungs increases the pressure decreases; as the volume of the lungs decreases the pressure increases.

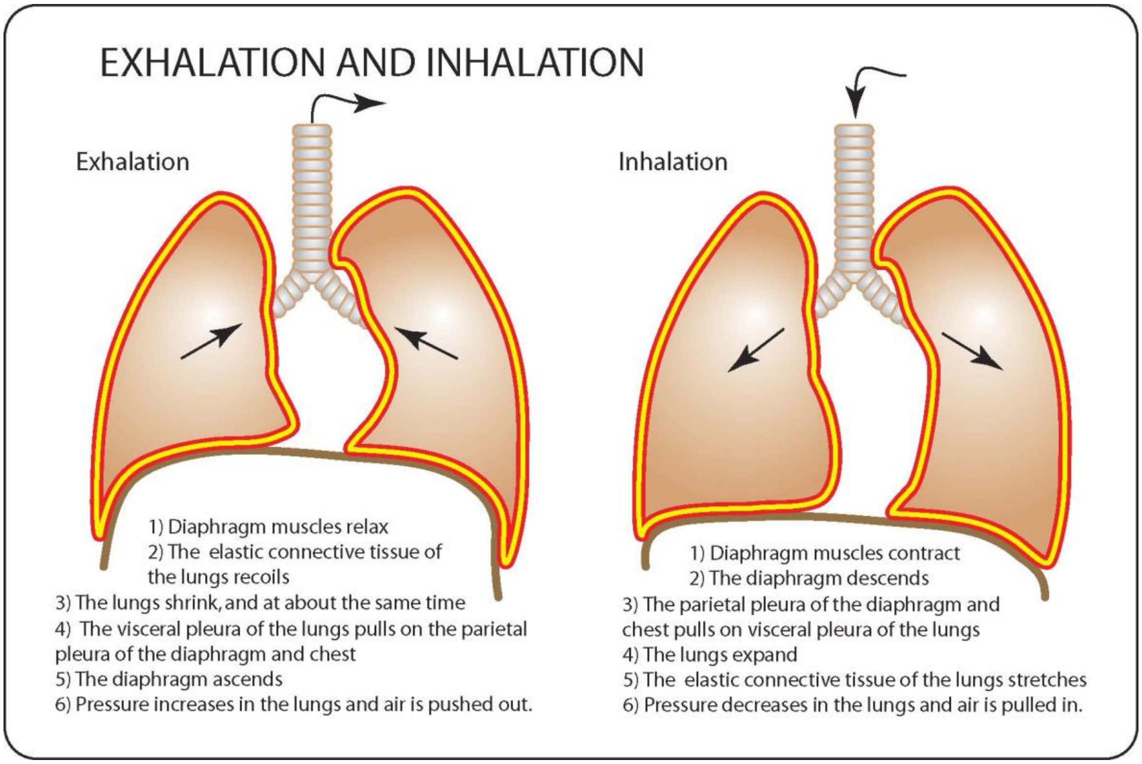


Figure 8.6 © 2007 David G. Ward, Ph.D.

Inhalation and Exhalation

The processes of inhalation and exhalation are illustrated in Figure 8.6.

During quiet inhalation, the diaphragm and external intercostal muscles contract, and:

1. The diaphragm descends and the ribcage expands
2. The parietal pleura of the diaphragm and chest pull on the visceral pleura of the lungs, and at about the same time:
3. The lungs expand
4. The elastic connective tissue of the lungs stretches
5. Pressure decreases in the lungs and air is drawn in.

During forced inhalation contraction of the external intercostal muscles, the serratus anterior and posterior muscles, and the sternocleidomastoid and scalene muscles, increase the size of the thoracic cavity by expanding the ribcage.
During quiet exhalation, the diaphragm and external intercostal muscles relax and:

1. The elastic connective tissue of the lungs recoils
2. The lungs shrink, and at about the same time :
3. The visceral pleura of the lungs pull on the parietal pleura of the diaphragm and chest
4. The diaphragm ascends, and the ribcage contracts
5. Pressure increases in the lungs and air is expelled.

During forced exhalation contraction of the internal intercostal muscles, the rectus abdominus and the oblique muscles assist in decreasing the size of the thoracic cavity by compressing the ribcage and compressing the abdominal contents.

Airway flow and resistance

As airway resistance increases, a greater change in respiratory system pressure is needed to produce the same change in air flow. Airway resistance is commonly affected by mechanical manipulation, and by contraction of the smooth muscle of the airways. **Obstructive pulmonary diseases** are caused by increases in airway resistance. Common obstructive pulmonary diseases include:

- COPD caused by chronic bronchitis and emphysema
- Emphysema caused by fracturing or bursting of the alveoli
- Asthma caused by airway constriction
- Bronchiectasis caused by mucus buildup in the airways

Lung compliance

As lung compliance increases a smaller change in transpulmonary pressure is necessary for a given change in lung volume. Conversely, as lung compliance decreases a larger change in transpulmonary pressure is necessary for a given change in lung volume. Lung compliance depends on the elasticity of the lungs and the surface tension in the alveoli. **Restrictive pulmonary diseases** are caused by decreases in lung compliance. Common restrictive pulmonary diseases include:

- Pulmonary fibrosis caused by overgrowth of the connective tissues of the lungs
- Sarcoidosis caused by inflammation of tissues producing small nodules or granulomas.
- Lungs cancers caused by abnormal reproduction of cells.
- Pneumonia caused by inflammation of the lung caused by an infection.

Ventilatory volumes

Ventilatory volumes refer to the volumes of air that can be found in the lungs with different levels of breathing, as shown in Figure 8.67. Even after maximum exhalation, air remains in the lungs. This volume of air is called the residual volume (RV). Usually we do not exhale maximally with each exhalation, and the difference in lung volume between maximum inhalation and normal inhalation is called the expiratory reserve volume (ERV). The sum of the residual volume (RV) and the expiratory reserve volume (ERV) is called the functional residual volume (FRV) because it represents the volume of air that is commonly left in the lungs. The difference in lung volume between normal inhalation and exhalation is called the tidal volume (TV). Even after a normal inhalation, we can inhale considerably more, and the difference in lung volume between maximum inhalation and a normal inhalation is called the inspiratory reserve volume (IRV). Vital capacity (VC) is the maximum volume of air we can exhale from the lungs, and is the sum of ERV, TV and IRV.

$$VC = IRV + TV + ERV$$

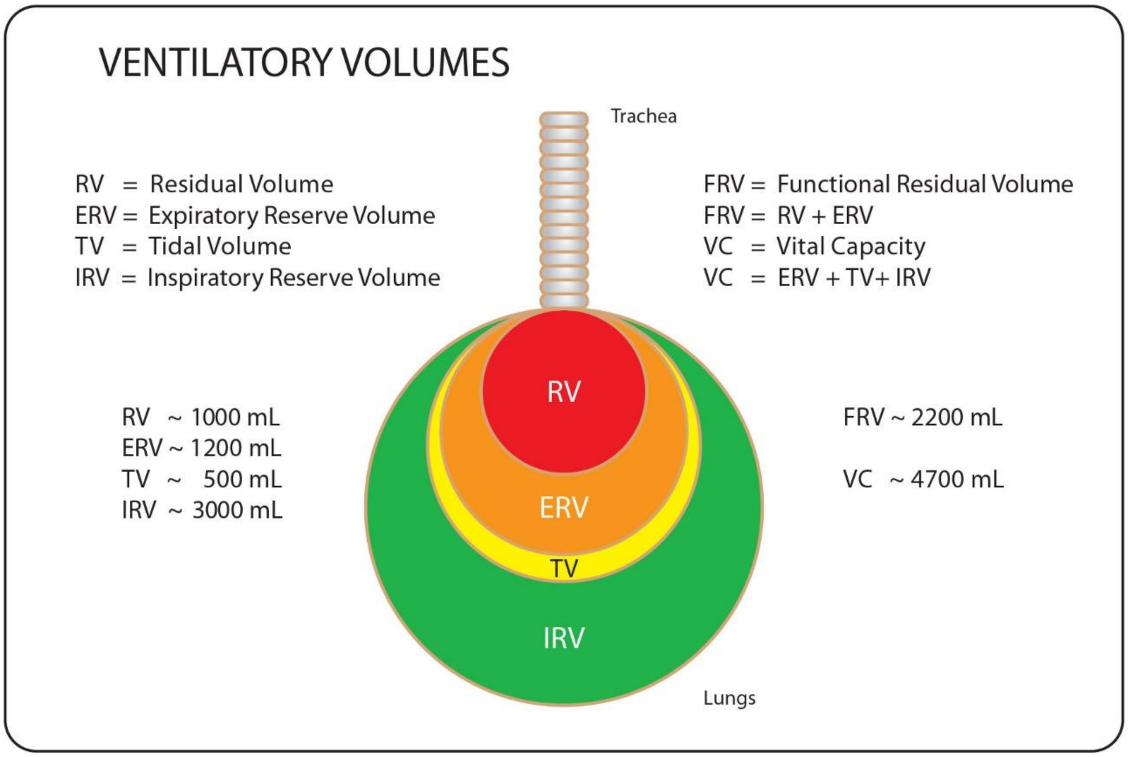


Figure 8.7 © 2007 David G. Ward, Ph.D.

- Vital Capacity (VC) = volume of air moved by the lungs between maximum inhalation and maximum exhalation
- Inspiratory Reserve Volume (IRV) = volume of air that can be moved into the lungs between normal inhalation and maximum inhalation
- Tidal Volume (TV) = volume of air moved by the lungs between normal inhalation and normal exhalation
- Functional Residual Volume (FRV) = RV + ERV
- Expiratory Reserve Volume (ERV) = volume of air that can be expelled from the lungs between normal expiration and maximum exhalation
- Residual volume (RV) = volume of air remaining in the lungs after maximum exhalation (about 25% of VC)

Gas Exchange and Transport

Gas exchange

The partial pressures of oxygen and carbon dioxide in the alveoli, blood vessels and systemic tissues are summarized in Table 8.1. Please refer to chapter 4 for a clarification of why the blood gases of the systemic venous blood and pulmonary arterial blood will be about the same, and why the blood gases of systemic arterial blood and pulmonary venous blood will be about the same.

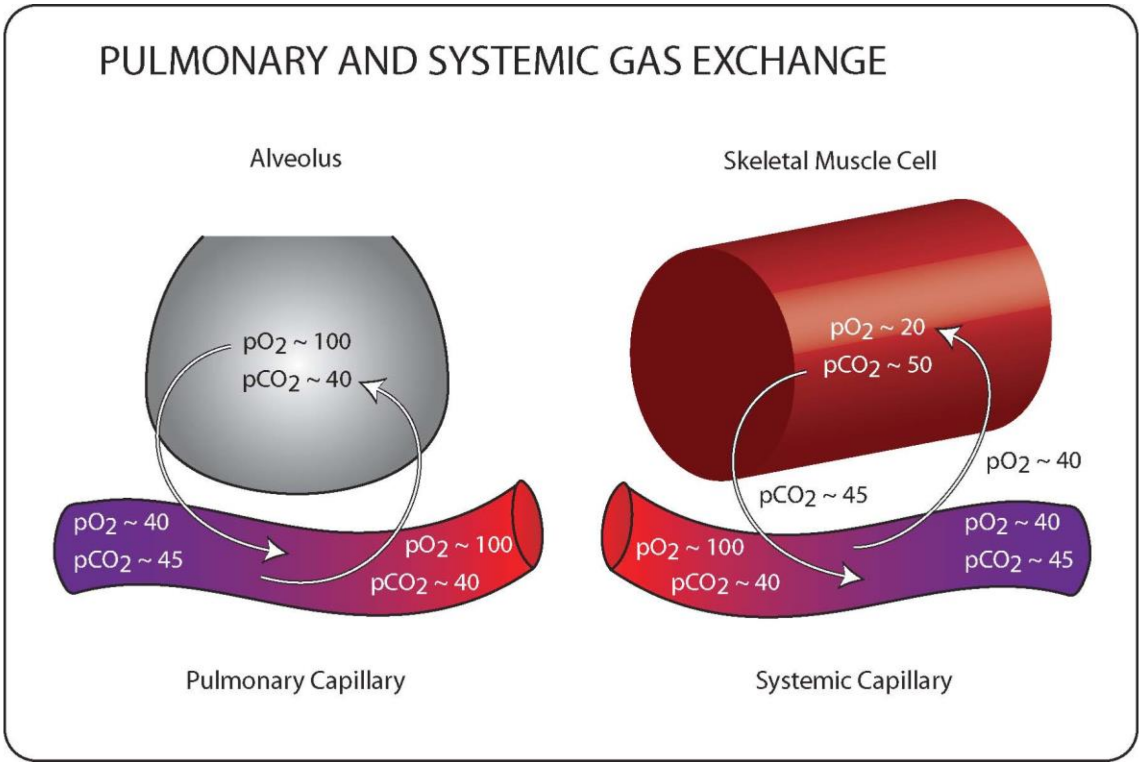
Table 8.1. Alveolar, and vascular blood gasses.

region	*pO_2 T*	*pCO_2 T*
Alveoli	~100	~40
Systemic venous blood and Pulmonary arterial blood	~40	~45
Systemic arterial blood and Pulmonary venous blood	~100	~40
Tissue Cytoplasm	~20	~50

Oxygen will diffuse from an area of higher partial pressure to an area of lower partial pressure. Similarly, carbon dioxide will diffuse from an area of higher partial pressure to an area of lower partial pressure. Figure 8.8 illustrates the diffusion of gases in the lungs between the alveoli and pulmonary capillaries, and the diffusion of gases in muscle between muscle cells and systemic capillaries.

In the lungs, O_2 in the alveoli diffuses into the pulmonary capillary blood, and CO_2 in the pulmonary blood diffuses into the alveoli. Blood that enters the pulmonary capillaries has a pO_2 of 40T and a pCO_2 of 46T. After leaving the pulmonary capillaries the pO_2 is about 100T and the pCO_2 is about 40T.

In the systemic organs, O_2 in the systemic capillary blood diffuses into systemic tissues, and CO_2 in the systemic tissues diffuse into the systemic capillary blood. Blood that enters the systemic capillaries has a pO_2 of about 100T and a pCO_2 of about 40T. After leaving the systemic capillaries the pO_2 is about 40T and the pCO_2 is about 46T.



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Oxygen Transport

Only about 1.5% of O_2 is transported in the blood dissolved in plasma, the remainder is transported bound to hemoglobin. Oxygen combines with hemoglobin in the blood in a reversible reaction. Hemoglobin has a very high affinity for oxygen. At a pO_2 of 40T hemoglobin is 80% saturated (80% of the binding sites for O_2 are occupied by O_2).

$$O_2 + HbH \longleftrightarrow Hb\text{-}O_2 + H^+$$

- As oxygen concentration in the blood increases, more oxygen combines with hemoglobin
- As oxygen concentration in the blood decreases, less oxygen combines with hemoglobin
- Both H^+ and CO_2 compete with O_2 for binding sites on hemoglobin, although with a lower affinity than O_2.

Oxygen gas transport is illustrated in Figure 8.9. In the alveolar capillaries, where the oxygen concentration within the alveoli is greater than the oxygen concentration of the blood, oxygen moves into the blood and combines with hemoglobin.

$$O_2 + HbH \rightarrow Hb\text{-}O_2 + H^+$$

In the tissue capillaries, where the oxygen concentration of the tissues is less than the oxygen concentration of the blood, oxygen dissociates from hemoglobin and moves out of the blood.

$$Hb\text{-}O_2 + H^+ \rightarrow HbH + O_2$$

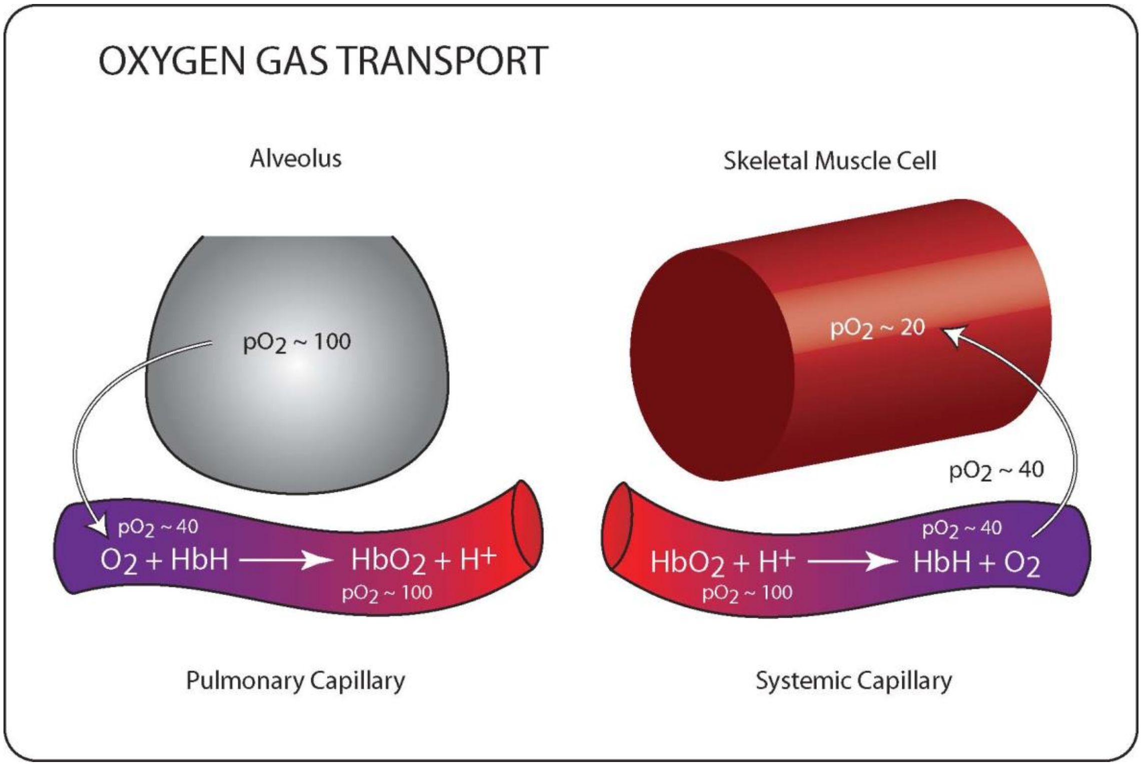

Figure 8.9 © 2007 David G. Ward, Ph.D.

Carbon Dioxide Transport

Carbon dioxide combines only to a limited extent with hemoglobin in the blood in a reversible reaction. Although hemoglobin plays a small role in the transport of CO_2, the binding of O_2 to hemoglobin decreases the affinity of hemoglobin for CO_2 (Haldane effect) and further reduces the transport of CO2 by hemoglobin.

$$Hb + CO_2 \longleftrightarrow Hb\text{-}CO_2$$

Most carbon dioxide combines with water in the erythrocytes in a reversible reaction to form carbonic acid that in turn dissociates in a reversible reaction to form hydrogen ions and bicarbonate ions.

$$CO_2 + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow HCO_3^- + H^+$$

- As carbon dioxide concentration in the blood increases, more hydrogen ions and bicarbonate ions are formed
- As carbon dioxide concentration in the blood decreases, fewer hydrogen ions and bicarbonate ions are formed

Added bicarbonate ions (such as from sodium bicarbonate) will decrease the dissociation of the carbonic acid and thus, decrease the production of hydrogen ions and raise the pH (refer to ‘Acid-Base Balance’). Bicarbonate ions (HCO_3^-) are transported out of the erythrocytes and into the plasma in exchange for Cl^- (chloride shift).

Carbon dioxide transport is illustrated in Figure 8.10. In the alveolar capillaries, where the carbon dioxide concentration within the alveoli is less than the carbon dioxide concentration of the blood, hydrogen ions combine with bicarbonate ions to form carbonic acid. The carbonic acid dissociates into water and carbon dioxide, and the carbon dioxide moves out of the blood.

$$HCO_3- + H^+ \rightarrow H_2CO_3 \rightarrow H_2O + CO_2$$

In the tissue capillaries, where the carbon dioxide concentration of the tissues is greater than the carbon dioxide concentration of the blood, carbon dioxide moves into the blood and combines with water to form carbonic acid. The carbonic acid dissociates into bicarbonate ions and hydrogen ions.

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO_3- + H^+$$

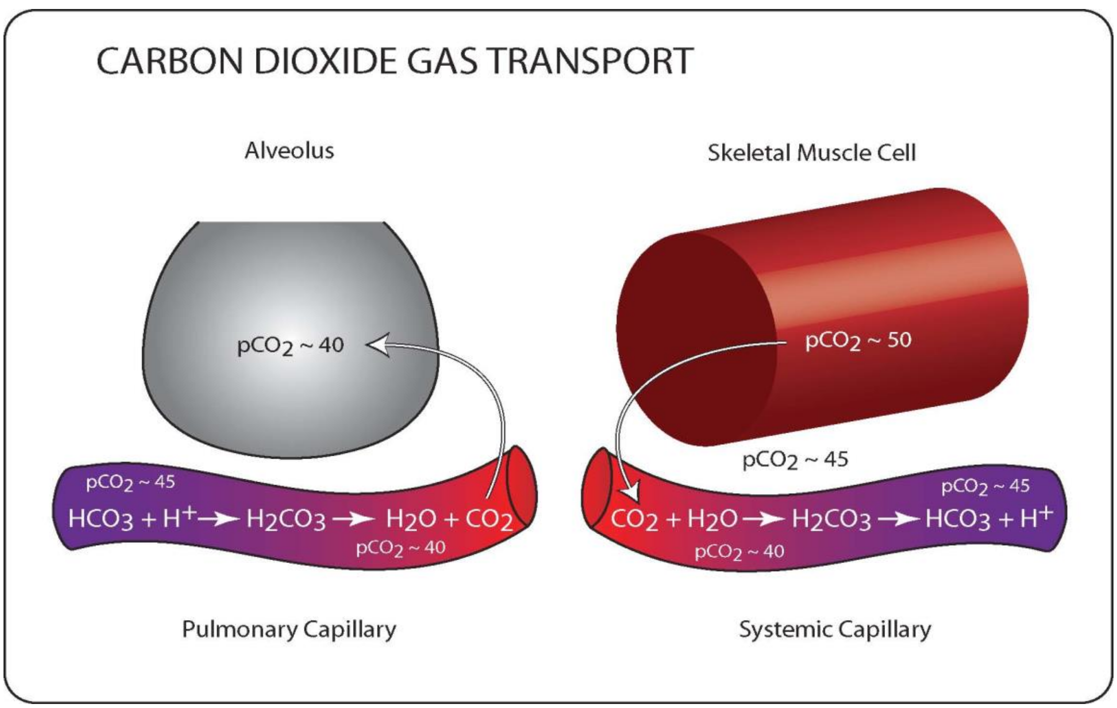

Figure 8.10 © 2007 David G. Ward, Ph.D.

Respiratory Control and Acid-Base Balance

Control of acid – base balance

As we just saw the transport of carbon dioxide in blood is through carbonic acid, and bicarbonate and hydrogen ion formation.

$$CO_2 + H2O \longleftrightarrow H_2CO_3 \longleftrightarrow HCO_3^- + H^+$$

- Excess carbon dioxide in the blood will increase the hydrogen ion concentration and lower the pH.

By way of the chemoreceptor reflexes, excess CO_2 (and excess H^+) will stimulate increases in rate and depth of respiration. The excess H^+ in the blood combines with HCO_3- to form H_2CO_3. The H_2CO_3 will produce H_2O and CO_2 in the blood of the lungs. Removal of the CO_2 by the lungs will thus decrease the H^+ concentration and raise the pH.

$$HCO_3- + H^+ \rightarrow H_2CO_3 \rightarrow H_2O + CO_2$$

$$CO_2 \rightarrow \text{into alveoli of lungs}$$

Furthermore, excess H^+ (from any source) can combine with HCO_3- to produce H_2CO_3 and thus H_2O and CO_2 that can be removed by the lungs. The critical role of CO_2 and HCO_3- in determining pH is seen by the following relationship.

$$pH = 6.1 + \log \frac{[HCO_3^-]}{[CO_2]}$$

Acidosis and Alkalosis

pH can be low (acidosis) or high (alkalosis) due to ventilatory or metabolic causes, as shown in Table 8.2.

- Inadequate removal of carbon dioxide by the lungs leads to respiratory acidosis.
- Excess removal of carbon dioxide leads to respiratory alkalosis.
- High levels of hydrogen ions from metabolic activity lead to metabolic acidosis.
- Low levels of hydrogen ions lead to metabolic alkalosis.

Table 8.2 Acidosis and alkalosis

pH status	*pCO_2*	*HCO_3*	*cause*
Respiratory Acidosis	high	high	hypoventilation
Respiratory alkalosis	low	low	hyperventilation
Metabolic Acidosis	normal	low	increased lactic acid, ketone bodies, diarrhea
Metabolic Alkalosis	normal	high	vomiting, hypokalemia, excess steroids