Chapter 19 –Ventilation, Gas Exchange and Transport

Objectives

Given the synopsis in this chapter, competence in each objective will be demonstrated by writing short essays, drawing diagrams, and responding to multiple choices or matching questions, at the level of 85% 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 membranes to the pleural cavities and the lungs, and the function of the pleural fluid.
C. To explain respiratory system pressure and transpulmonary pressure and their roles in lung function.
D. 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.
E. To define airway flow and explain the calculation of airflow.
F. To define airway resistance, explain how airway size influences airway resistance, and describe the calculation of airway resistance.
G. To explain how changes in lung compliance affect lung volume and transpulmonary pressure.
H. To explain the role of respiratory rate and tidal volume in determining minute volume.
I. To describe ventilatory volumes commonly measured and explain their significance in respiratory evaluation.
J. To explain how local-factors control the size of the respiratory airways.
K. To explain how the parasympathetic and sympathetic nervous systems control the size of the respiratory airways.
L. To explain the concept of partial pressures of gasses.
M. 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.
N. To explain the process of oxygen transport through the blood.
O. To explain the process of carbon dioxide transport through the blood.
P. To describe the control of respiration by neural circuits in the brainstem.
Q. To explain how mechanoreceptor and chemoreceptor reflexes control the rate and depth of respiration.
R. 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

The lungs are located within the pleural cavities of the chest, as shown in Figure 19.1. The diaphragm is located below the pleural cavities, and forms a partition between the thoracic cavity and the abdominal cavity

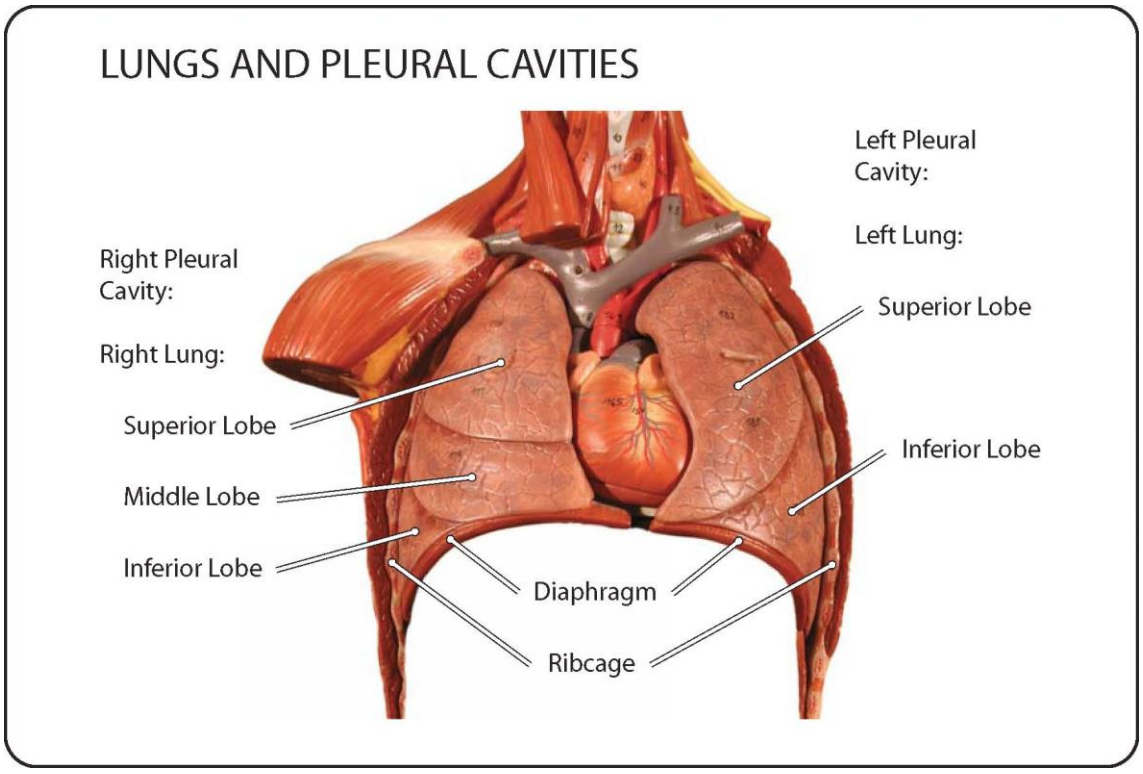

Figure 19.1 © 2007 David G. Ward, Ph.D.

The respiratory airways carry air into and out of the alveoli which make up the major portion of the lungs, as shown in Figure 19.2. The alveoli are spherical structures made largely of simple squamous epithelium that are clustered together to form alveolar sacs. The alveolar sacs connect to bronchioles that in turn connect to intrapulmonary (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. Arterioles and venules connect the capillaries to the pulmonary arteries and veins

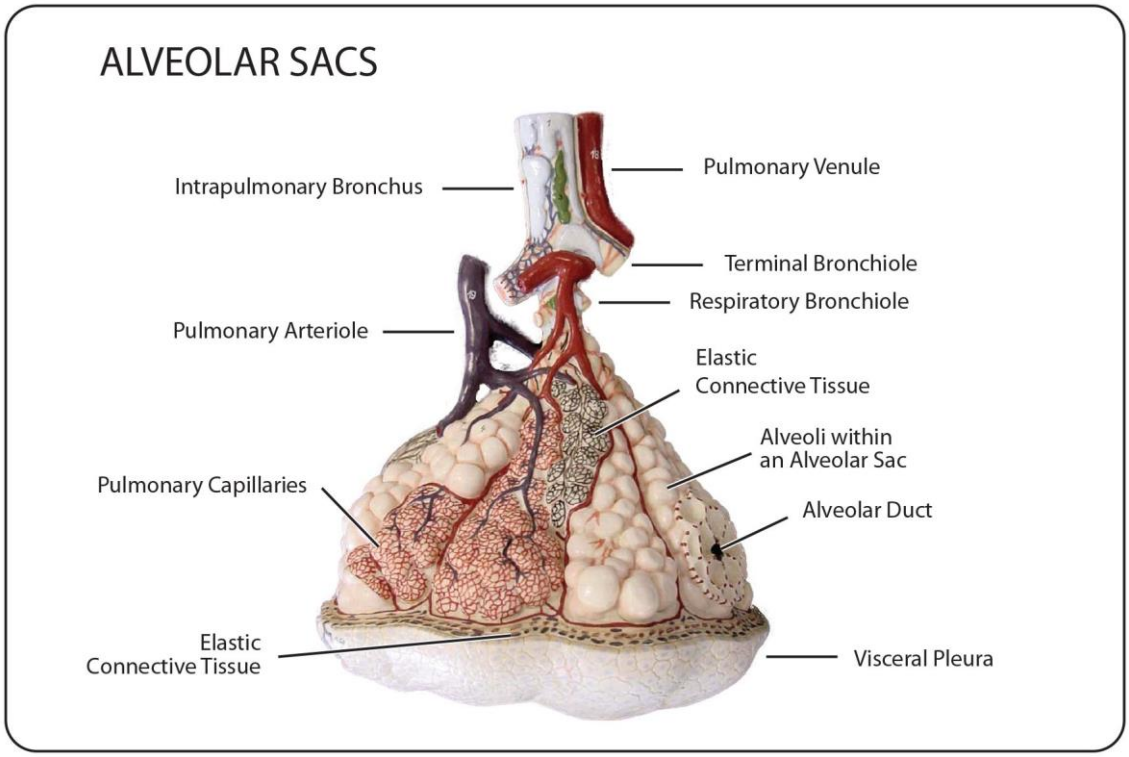

Figure 19.2 © 2015 David G. Ward, Ph.D.

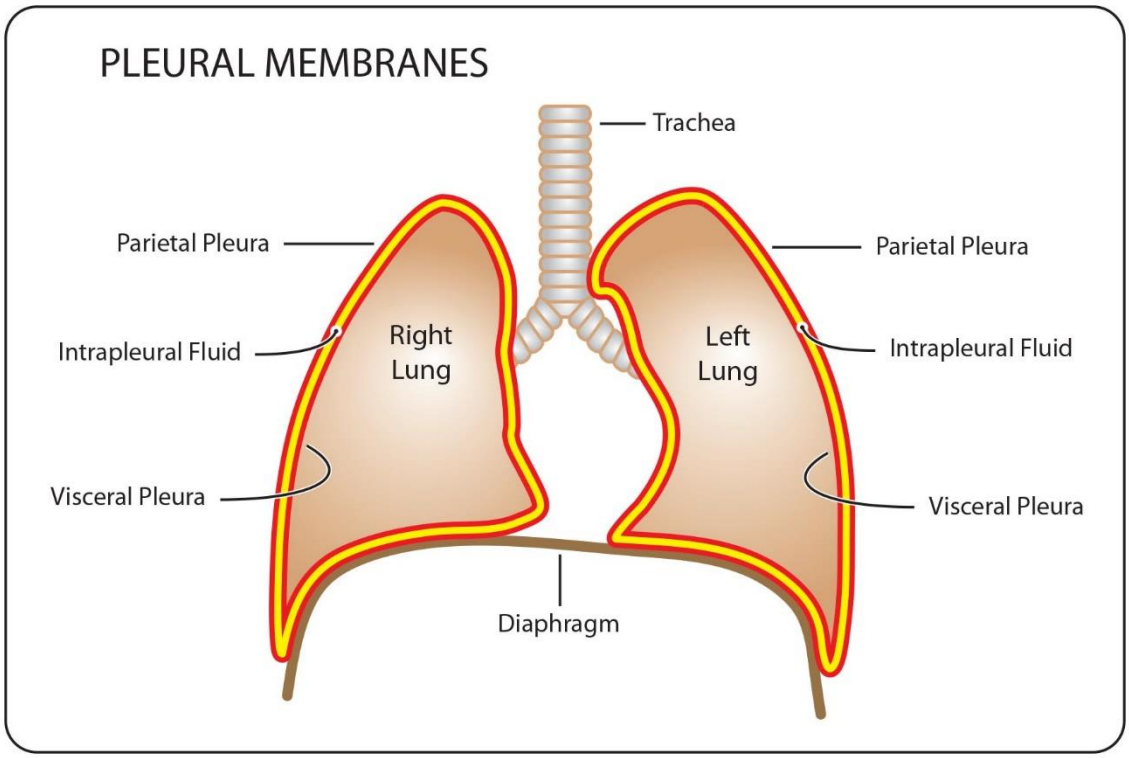

Figure 19.3 © 2015 David G. Ward, Ph.D.

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 19.3. 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.

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.

Respiratory pressures

The role of atmospheric pressure (P_{atm}), alveolar pressure (P_{alv}) and intrapleural pressure (P_{ip}) in ventilation are illustrated in Figure 19.4.

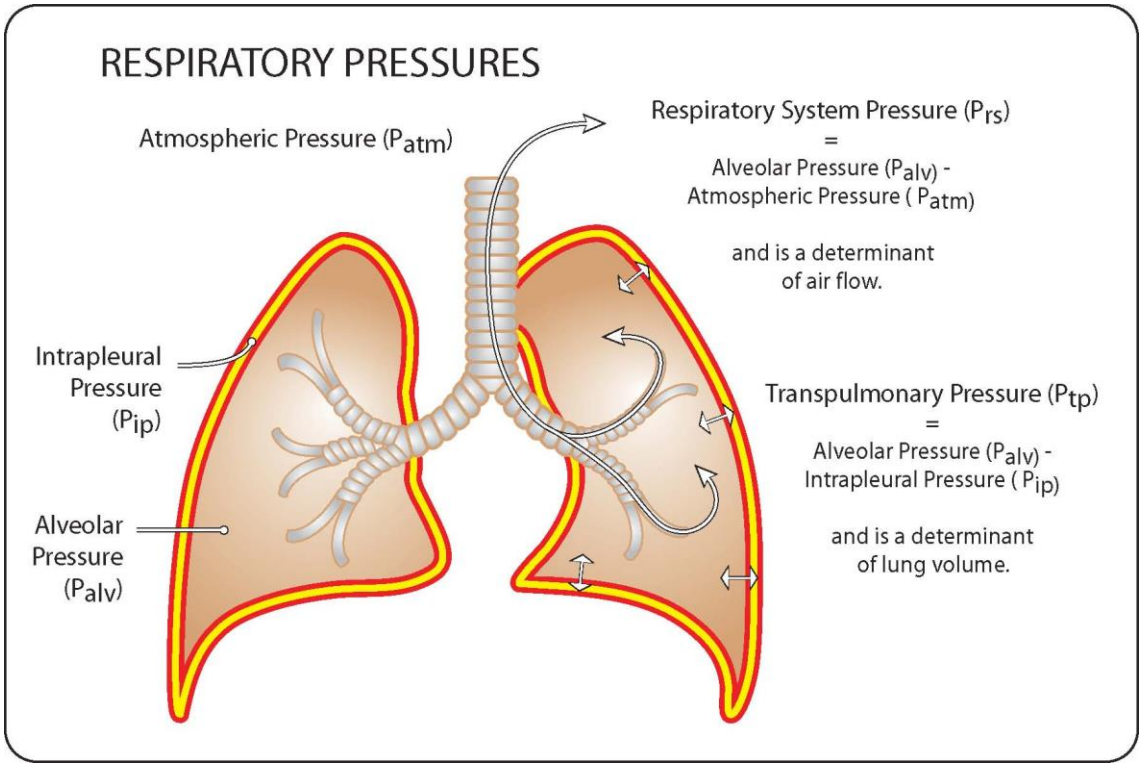

Figure 19.4 © 2007 David G. Ward, Ph.D.

Respiratory System Pressure (P_{rs})

Atmospheric pressure at sea level is 760 mmHg. Alveolar pressure (P_{alv}) ranges from slightly higher than this during exhalation to slightly less than this during inhalation. The difference between alveolar pressure (P_{alv}) and atmospheric pressure (P_{atm}) is called **respiratory system pressure (P_{rs})** and is a major determinant of air flow into and out of the lungs.

- Atmospheric pressure (P_{atm}) (absolute measurement)
  - ~ 760 mmHg
- Alveolar pressure (P_{alv}) (absolute measurement)
  - During quiet inspiration = ~ 757 mmHg
  - During quiet expiration = ~ 763 mmHg
- Respiratory system pressure (P_{rs}) is the difference between alveolar pressure (P_{alv}) and atmospheric pressure (P_{atm}) and is a major determinant of air flow
  - During quiet inspiration = ~ –3 mmHg
  - During quiet expiration = ~ +3 mmHg

Transpulmonary Pressure (P_{tp})

Intrapleural pressure (P_{ip}) is almost always negative and ranges from slightly less than atmospheric pressure (P_{atm}) during exhalation to much less than atmospheric pressure (P_{atm}) during inhalation. The difference between alveolar pressure (P_{alv}) and intrapleural pressure (P_{ip}) is called transpulmonary pressure (P_{tp}) and is a major determinant of lung volume.

- Intrapleural pressure (P_{ip}) (absolute measurement)
  - During quiet inspiration = ~ 754 mmHg
  - During quiet expiration = ~ 757 mmHg
- Transpulmonary pressure (P_{tp}) is the difference between alveolar pressure (P_{alv}) and intrapleural pressure (P_{ip}) and is a major determinant of lung volume
  - During quiet inspiration = ~ +3 mmHg
  - During quiet expiration = ~ +6 mmHg

Boyle's Law

Boyle's law establishes the relationship between the pressure (P) and the volume (V) of gases.

$$P \propto \frac{1}{V}$$

The pressure (P) of a gas in inversely proportional ($\propto$) to its volume (V) at a constant temperature. For the respiratory system, as the volume of the lungs increases the pressure decreases; as the volume of the lungs decreases the pressure increases.

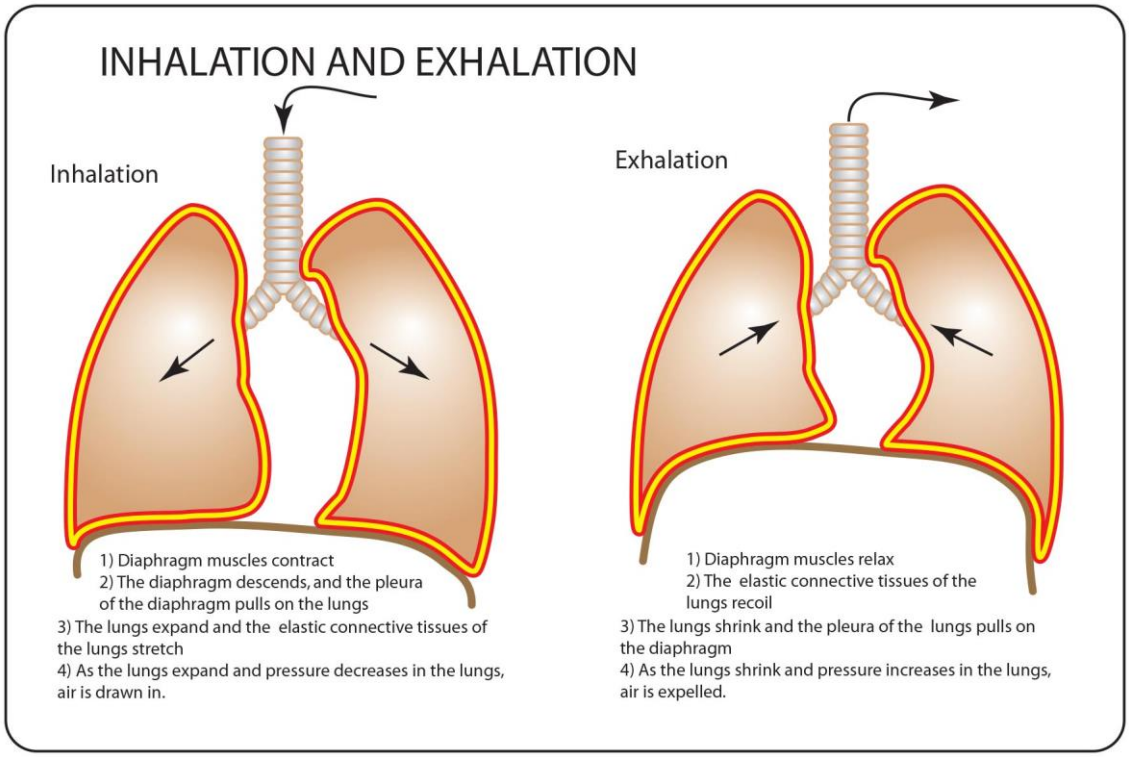

Figure 19.5 © 2015 David G. Ward, Ph.D.

Inhalation and Exhalation

The processes of inhalation and exhalation are illustrated in Figure 19.5.

During quiet inhalation:

1. The diaphragm muscles contract
2. The diaphragm descends and the pleura of the diaphragm pull on the lungs
3. The lungs expand and the elastic connective tissues of the lungs stretch
4. As the lungs expand and pressure decreases in the lungs, 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:

1. The diaphragm muscles relax
2. The elastic connective tissues of the lungs recoil and the lungs shrink
3. The pleura of the lungs pull on the diaphragm
4. As the lungs shrink and pressure increases in the lungs, 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 contracting the ribcage and compressing the abdomen.

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 19.6. 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 exhalation and normal exhalation 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.

$$VC = IRV + TV + ERV$$

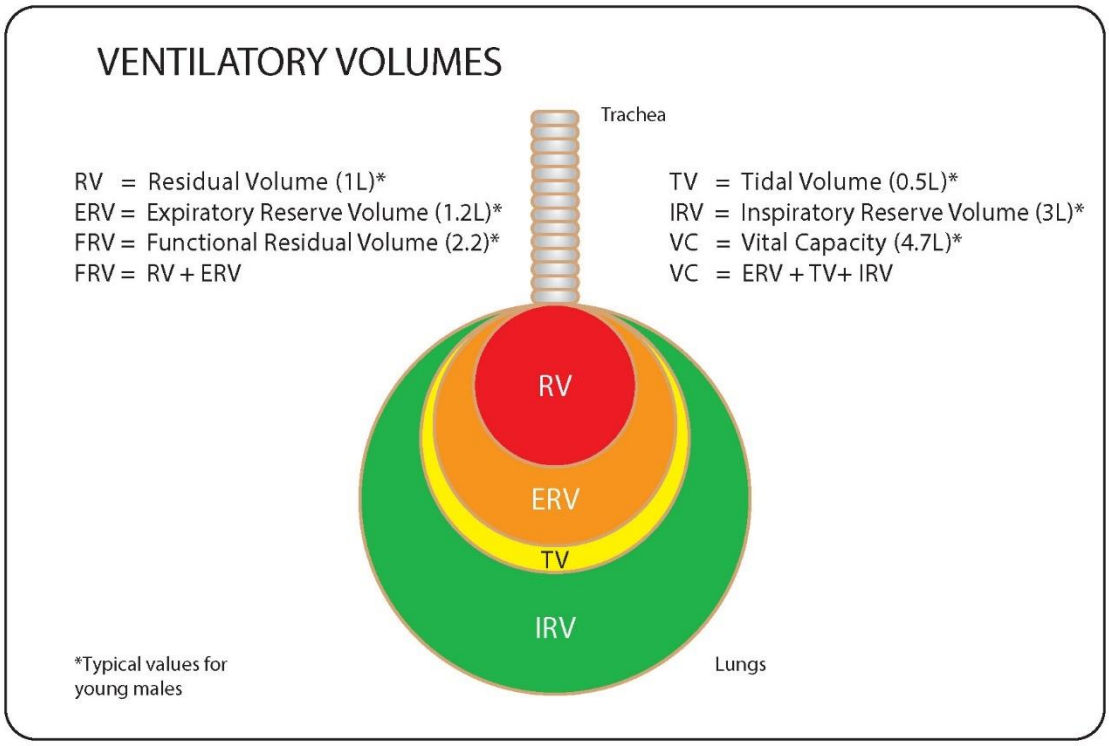

Figure 19.6 © 2018 David G. Ward, Ph.D.

- Residual volume (RV) = volume of air remaining in the lungs after maximum exhalation
- Expiratory Reserve Volume (ERV) = volume of air that can be expelled from the lungs between normal expiration and maximum exhalation

- Functional Residual Volume (FRV) = RV + ERV
- Tidal Volume (TV) = volume of air moved by the lungs between normal inhalation and normal exhalation
- Inspiratory Reserve Volume (IRV) = volume of air that can be moved into the lungs between normal inhalation and maximum inhalation;
  IRV can be calculated as IRV = VC – (ERV + TV).
- Vital Capacity (VC) = volume of air moved by the lungs between maximum inhalation and maximum exhalation; VC = ERV + TV + IRV

Minute volume

Minute respiratory volume (MV, F_{air}, V_{min}) is comparable to cardiac output, and is the volume of air moved by the lungs each minute. MV is usually expressed as mL/min or L/min and equals the respiratory rate (RR) times the volume per breath (tidal volume (TV)).

$$MV = RR \times TV$$

However, the airways form a dead space and only part of the tidal volume reaches the alveoli. Alveolar ventilation (AV, V_{alv}) is the volume of air moved into the alveoli each minute and equals the respiratory rate (RR) times the difference between the volume per breath (TV) and the dead space (DS).

$$AV = RR \times (TV - DS)$$

The dead space (DS) in the airways is typically about 150 mL and tidal volume (TV) is about 500 mL. Therefore, for each breath only about 350 mL of fresh air reaches the alveoli.

Airway flow

Air flow through the airways (F_{air}) is comparable to blood flow, and is the volume of air moved through the airways each minute. Airway flow (F_{air}) is usually expressed as mL/min or L/min. Airway flow (F_{air}) out of the lungs is the same as respiratory minute volume (MV).

Air flow through the airways is dependent on the pressure driving the air and the resistance of the airways (R_{aw}). The pressure driving the air (ΔP) is the difference between the higher pressure at one end of the airways and the lower pressure at the other end of the airways. In the respiratory system, the pressure driving the air is called respiratory system pressure (P_{rs}) and is the difference between the alveolar pressure (P_{alv}) and the atmospheric pressure (P_{atm}). Formally, air flow (F_{air}) equals the pressure driving the air (P_{rs}) divided by the resistance of the airways (R_{aw}).

$$F = \frac{\Delta P}{R} \quad ; \quad MV = F_{air} = \frac{P_{alv} - P_{atm}}{R_{aw}} = \frac{P_{rs}}{R_{aw}}$$

Airway resistance

Like we have seen before, the equation for the calculation of air flow is easily rearranged to show the concept of airway resistance.

$$F_{air} = \frac{P_{rs}}{R_{aw}} \quad ; \quad R_{aw} = \frac{P_{rs}}{F_{air}}$$

Airway resistance (R_{aw}) is simply measured as the change in respiratory system pressure (P_{rs}) for a given change in air flow (F_{air}). Pressure is usually measured in mmHg, and flow is usually measured in mL/min or L/min. Therefore, airway resistance is expressed as mmHg/ mL/min or mmHg/ L/min.

As airway resistance (R_{aw}) increases, a greater change in respiratory system pressure (P_{rs}) is needed to produce the same change in air flow (F_{air}). Airway resistance (R_{aw}) 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

An example of normal mechanical manipulation is seen during inhalation when there is a pulling on the airways that tends to decrease the resistance. Conversely, during exhalation there is a pushing on the airways that tends to increase the resistance.

Changes in smooth muscle contraction are a major factor affecting airway resistance.

- Asthma increases resistance by causing spastic contraction of the smooth muscle of the airways, increasing mucus secretion, and increasing inflammation.
- Histamine release increases airway resistance by stimulating bronchoconstriction and increasing mucus secretion.
- CO_2 decreases resistance by stimulating bronchodilation.
- Acetylcholine increases airway resistance by stimulating bronchoconstriction via activation of M3 receptors.
- Epinephrine decreases resistance by stimulating bronchodilation via activation of β2 receptors.

Lung compliance

Lung compliance (C_{lung}) is a description of the flexibility of the lungs measured as the change in lung volume (V_{lung}) for a given change in transpulmonary pressure (P_{tp}). Lung compliance is usually expressed as mL/mmHg or L/mmHg.

$$P_{tp} = \frac{V_{lung}}{C_{lung}} \quad ; \quad C_{lung} = \frac{V_{lung}}{P_{tp}}$$

As lung compliance (C_{lung}) increases a smaller change in transpulmonary pressure (P_{tp}) is necessary for a given change in lung volume. Conversely, as lung compliance (C_{lung}) decreases a larger change in transpulmonary pressure (P_{tp}) 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.

Local, Neural, and Hormonal Control of Airways

Control of the size of the respiratory airways is critical for the delivery of air to the alveoli of the lungs.

Local control of respiratory airways

As shown in Figure 19.7, changes in regional arteriolar blood flow are matched by changes in regional air flow. Arteriolar vasoconstriction leads to decreased blood flow and decreased delivery of CO_2 and causes bronchoconstriction in affected parts of the lung. Conversely, arteriolar vasodilation leads to increased blood flow and increased delivery of CO_2 and causes bronchodilation in affected parts of the lung.

- Decreased carbon dioxide in the blood locally leads to bronchoconstriction
- Increased carbon dioxide in the blood locally leads to bronchodilation

In addition, local inflammatory responses cause bronchoconstriction.

- Inflammation, increased leukotrienes, and irritants lead to bronchoconstriction

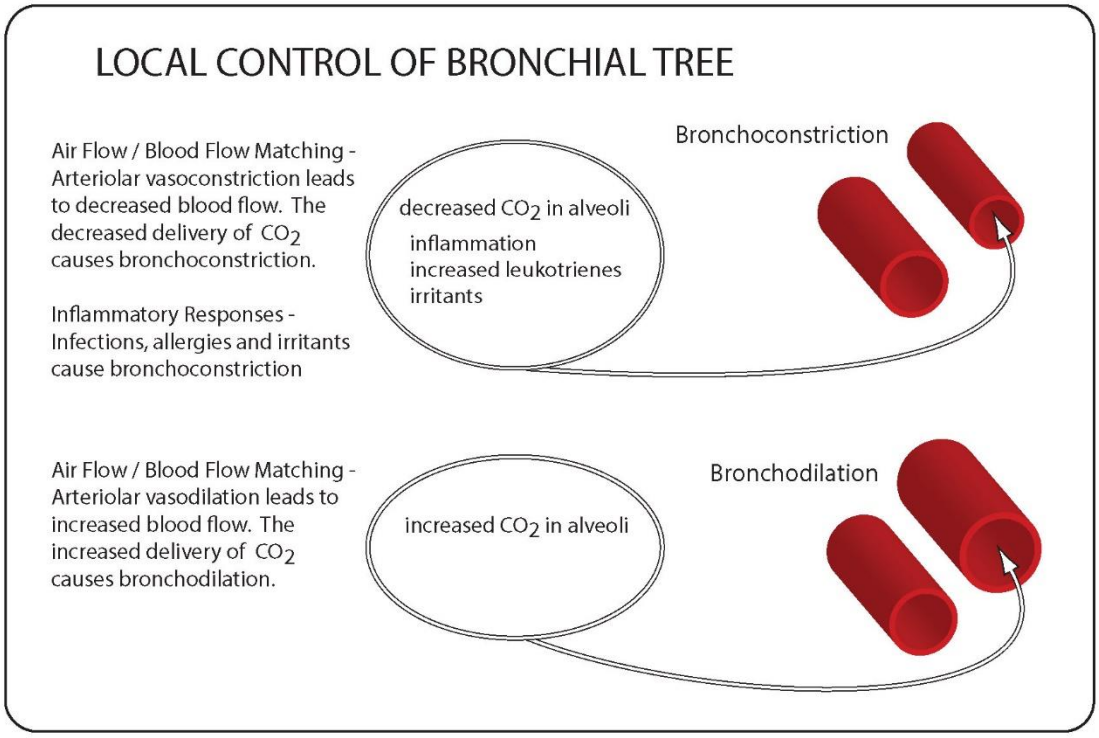

Figure 19.7 © 2018 David G. Ward, Ph.D.

Neural and hormonal factors

Parasympathetic

Postganglionic neurons of the parasympathetic nervous system secrete acetylcholine which acts on smooth muscle of the respiratory airways to cause bronchoconstriction, as shown in Figure 19.8.

- Stimulation of cholinergic muscarinc-3 receptors leads to bronchoconstriction.

Sympathetic

Postganglionic neurons of the sympathetic nervous system secrete norepinephrine and the adrenal medulla secretes epinephrine which acts on smooth muscle of the respiratory airways to cause bronchodilation, as shown in Figure 19.9.

- Stimulation of adrenergic beta-2 receptors leads to bronchodilation

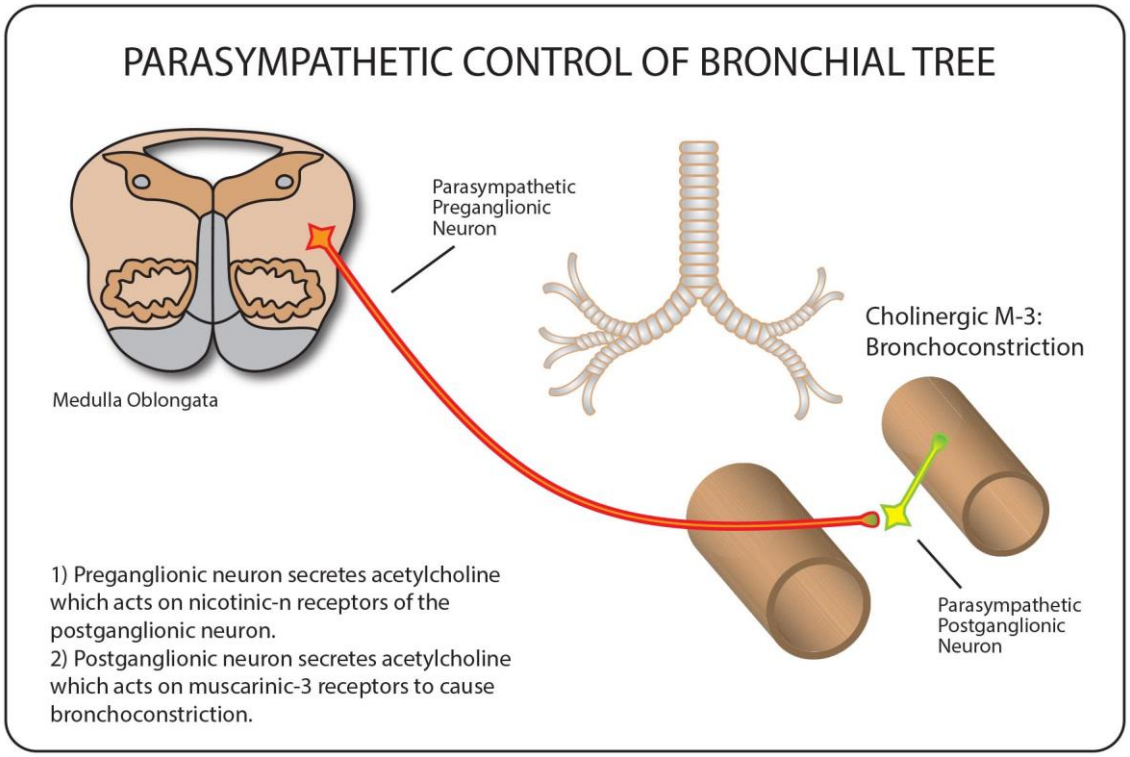

Figure 19.8 © 2019 David G. Ward, Ph.D.

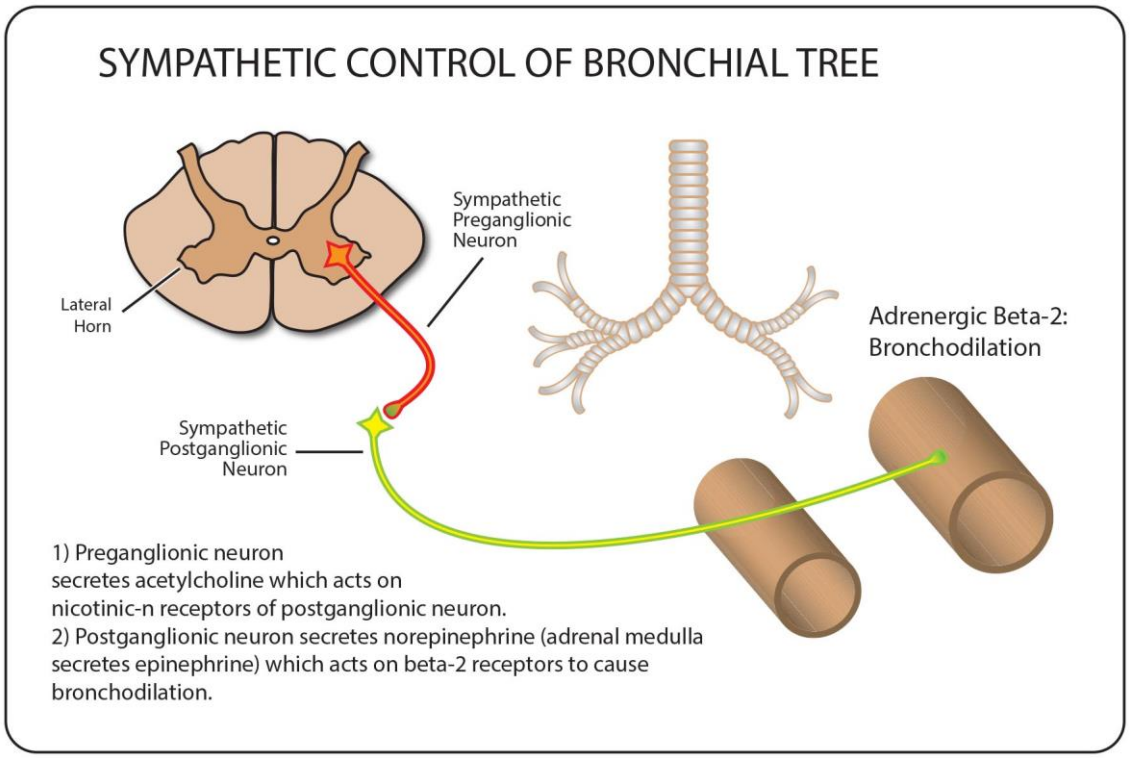

Figure 19.9 © 2019 David G. Ward, Ph.D.

Gas Exchange and Transport

Partial Pressures

Atmospheric air is composed of many gases and the most common are as shown in Table 19.1. The total pressure of air at sea level is 760mmHg (sometimes called Torr, T). The contribution to the total pressure by a given gas is called the partial pressure of that gas. The partial pressure of oxygen in the atmosphere is about 160 mmHg (usually expressed as $pO_2 = 160T$). The partial pressure of carbon dioxide is considerably less, about 0.3 (usually expressed as $pCO_2 = 0.3T$)

Table 19.1. Composition of atmospheric air.

	percent of atmosphere	partial pressure (mmHg) (T)
All gases in Air	100	760
Nitrogen	78.08	593.4
Oxygen	20.95	159.2
Argon	0.93	7.1
Carbon Dioxide	~0.04	~0.3

In the alveoli of the lungs, and in the systemic and pulmonary blood vessels, the partial pressures of oxygen and carbon dioxide are quite different from what is seen in atmospheric air. As shown in Figure 19.10, the partial pressure of oxygen is about 105T in the alveoli compared to 160T in the atmosphere. Most dramatically, the partial pressure of carbon dioxide is about 40T in the alveoli compared to about 0.3T in the atmosphere. This disparity occurs in large part because of the functional residual volume of the lungs and the dead space of the airways. The tidal volume, typically about 500 mL, brings in and removes a relatively small volume of air compared to the functional residual volume, typically about 2200 mL. As a result carbon dioxide accumulates in the alveoli.

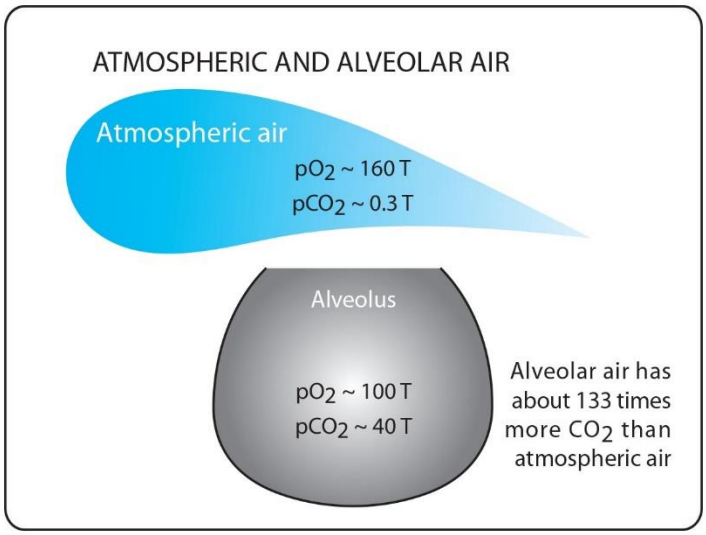

Figure 19.10 © 2015 David G. Ward, Ph.D.

Gas exchange

The partial pressures of oxygen and carbon dioxide in the alveoli, blood vessels and systemic tissues are summarized in Table 19.2. Please refer to chapter 16 and Figure 16.1 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 19.2. 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 19.11 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.

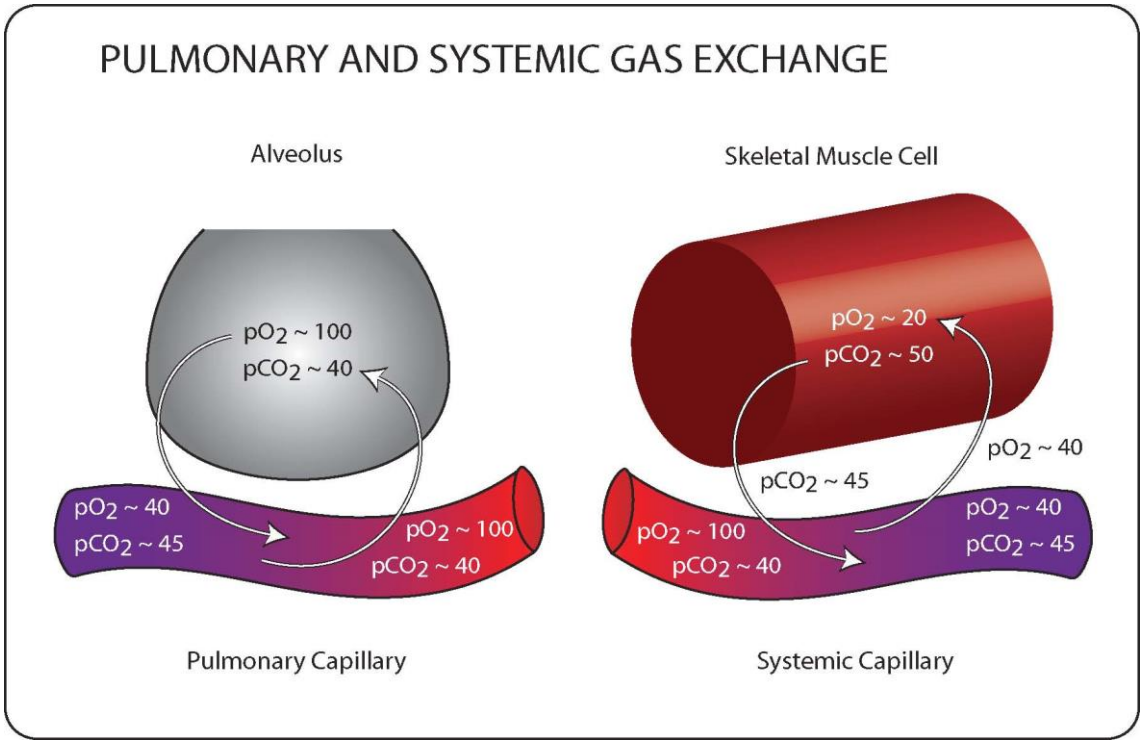

Figure 19.11 © 2007 David G. Ward, Ph.D.

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.

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.

The competition for oxygen binding sites by H^+ is referred to as the Bohr effect, and the competition for oxygen binding sites by CO_2 is referred to as the carbamino effect. Increased H^+ and CO_2 as seen in metabolically active tissue will dislodge more O_2 from the hemoglobin, making more oxygen available for the tissues.

Oxygen gas transport is illustrated in Figure 19.12. 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.

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

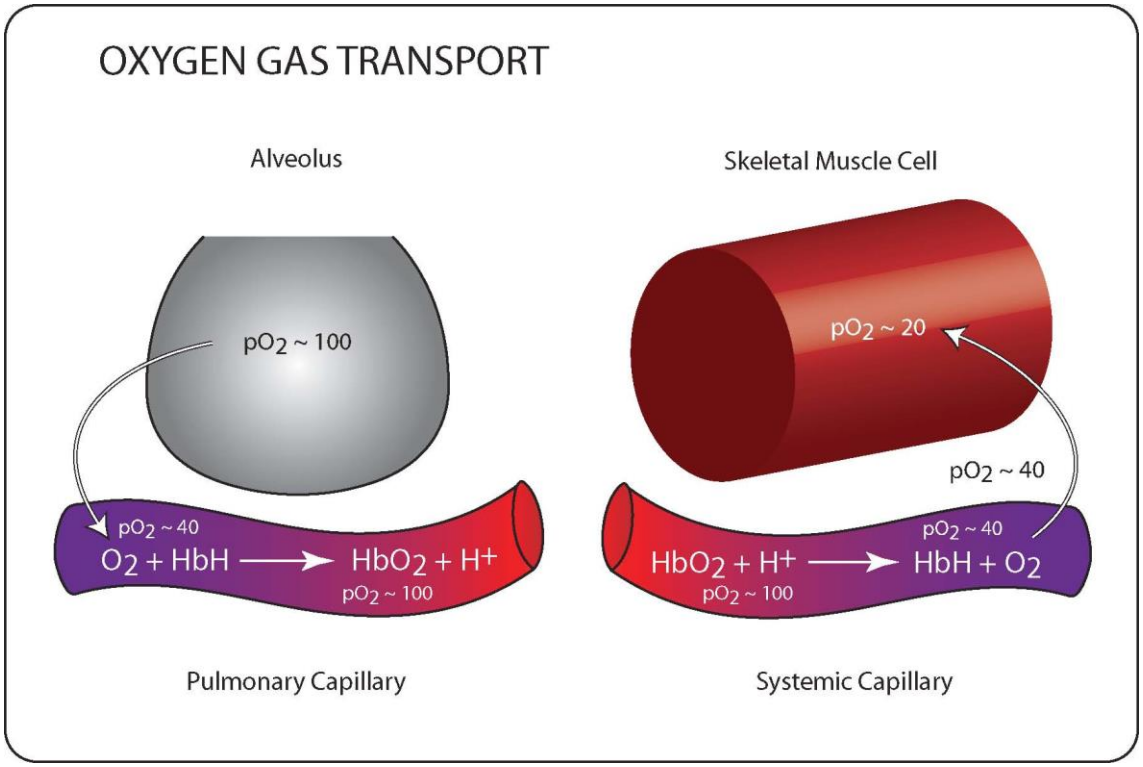

Figure 19.12 © 2007 David G. Ward, Ph.D.

Carbon Dioxide Transport

Most carbon dioxide (CO_2) combines with water (H_2O) in the erythrocytes in a reversible reaction to form carbonic acid (H_2CO_3) that in turn dissociates in a reversible reaction to form bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). Carbonic anhydrase (CA) is necessary to catalyze the reaction between carbon dioxide and water and carbonic acid. The direction of the reaction depends largely on the concentrations of CO_2 and H_2CO_3.

$$H_2O + CO_2 \xleftrightarrow{CA} H_2CO_3 \longleftrightarrow HCO_3^- + H^+$$

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 19.13. 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.

$$HCO_3^- + H^+ \rightarrow H_2CO_3 \xrightarrow{CA} H_2O + CO_2$$

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.

$$H_2O + CO_2 \xrightarrow{CA} H_2CO_3 \rightarrow HCO_3^- + H^+$$

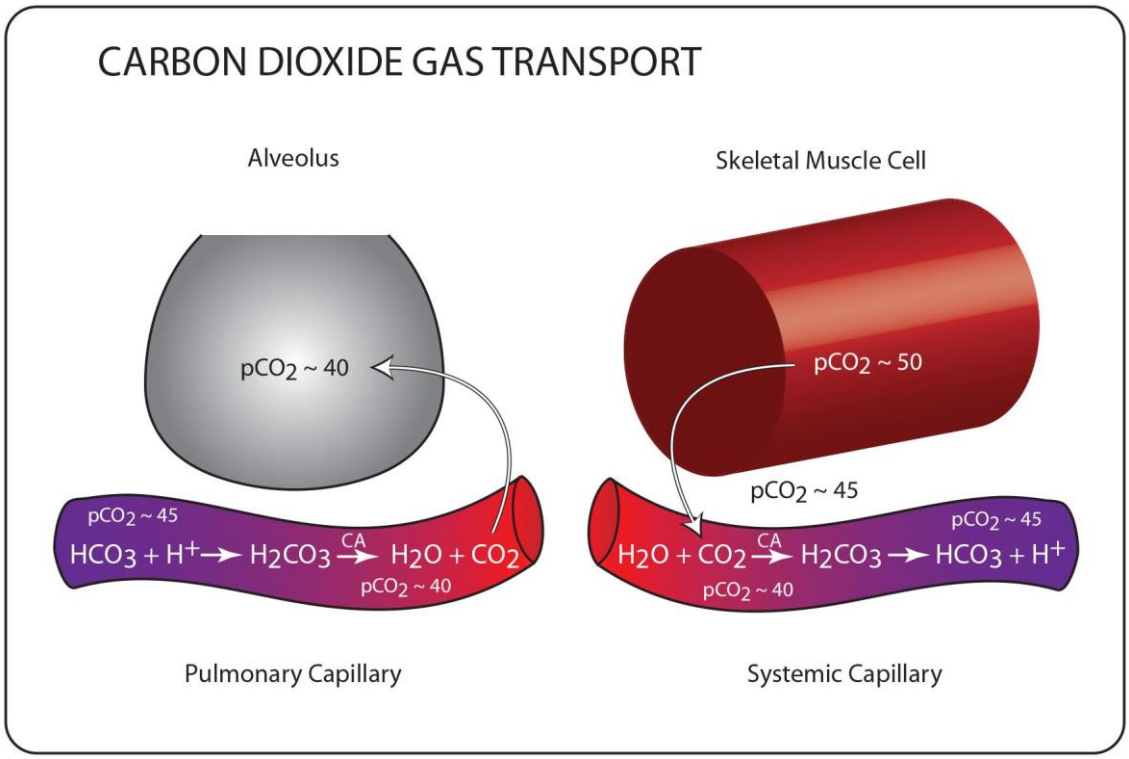

Figure 19.13 © 2015 David G. Ward, Ph.D.

Respiratory Control and Acid-Base Balance

Brainstem control of respiration

The rhythm and depth of respiration is controlled by structures in the brainstem, as shown in Figure 19.14. A group of neurons in the ventrolateral part of the middle portion of the medulla oblongata act as the pacemaker for the basic rhythm of inhalation. This group is often referred to as the pre-Botzinger complex. Just posterior to these pacemaker neurons is another group of neurons that stimulate inhalation, and probably determine the basic depth of respiration. These inspiratory neurons form the rostral ventral respiratory group. More posterior in the posterior medulla oblongata are a group of neurons that stimulate exhalation, probably causing forced respiration. These expiratory neurons form the caudal ventral respiratory group. Much more anterior in the pons is a group of neurons that inhibit inhalation, probably causing an increase in the rate of respiration. These neurons form the pontine respiratory group.

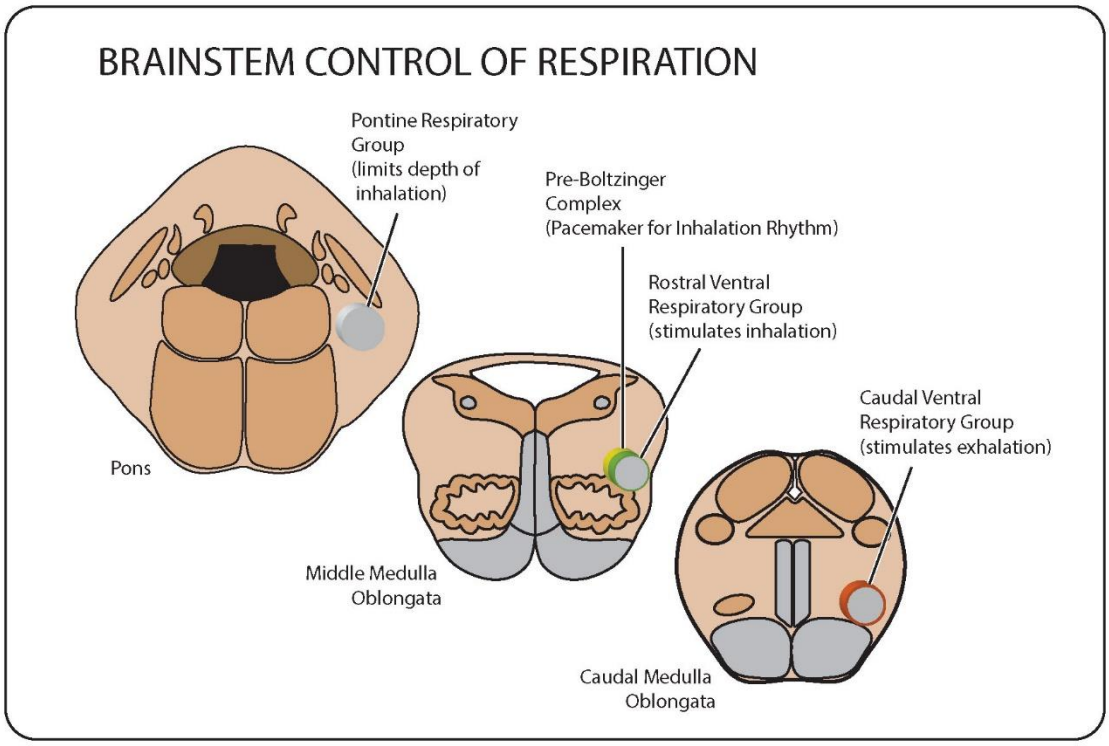

Figure 19.14 © 2018 David G. Ward, Ph.D.

- Pre-Botzinger complex acts as a pacemaker and establish the basic rate of respiration
- Rostral ventral respiratory group stimulates inhalatory muscles and establish the basic depth of respiration
- Caudal ventral respiratory group stimulates exhalatory muscles during forced breathing
- Pontine respiratory group influence the medullary respiratory neurons via a multisynaptic pathway for fine control of the respiratory rhythm by setting the lung volume at which inhalation is terminated.

Mechanoreceptor reflexes

The lungs contain stretch receptors that monitor inflation and deflation of the lungs. Signals from these receptors travel to the brainstem where respiratory responses are generated. During inhalation, signals from stretch receptors prevent overinflation of the lungs by inhibiting inspiratory neurons. During exhalation, signals from stretch receptors prevent collapse of the lungs by inhibiting expiratory and stimulating inspiratory neurons.

Chemoreceptor reflexes

The cardiovascular system and brainstem contain sensory receptors that monitor the partial pressure of oxygen (pO_2), carbon dioxide (pCO_2) and the concentration of hydrogen ions ($[H^+]$) in the blood. Signals from these sensory receptor travel into the brainstem where they are compared to reference values. Respiratory responses are generated to normalize the blood gases and pH.

- Carotid body chemoreceptors respond to increased blood pCO_2 (increased $[H^+]$) or decreased pO_2.
- Aortic body chemoreceptors respond similarly to carotid body chemoreceptors.
- Medullary chemoreceptors near the ventral respiratory group respond preferentially to increased $[H^+]$.

Chemoreceptor control of respiration is shown in Figure 19.15. Decreases in pO_2 or increases in blood pCO_2 (increased $[H^+]$) stimulate the carotid body chemoreceptors. The glossopharyngeal nerve carries the chemoreceptor signal into the medulla of the brainstem. Therefore, by way of interneurons, inspiratory neurons in or near the rostral ventral respiratory group are stimulated and respiratory rate and depth are increased.

Conversely, increases in pO_2 or decreases in blood pCO_2 (decreased $[H^+]$) "de-stimulate" the carotid body chemoreceptors. Therefore, inspiratory neurons in or near the rostral ventral respiratory group are less stimulated and respiratory rate and depth are decreased.

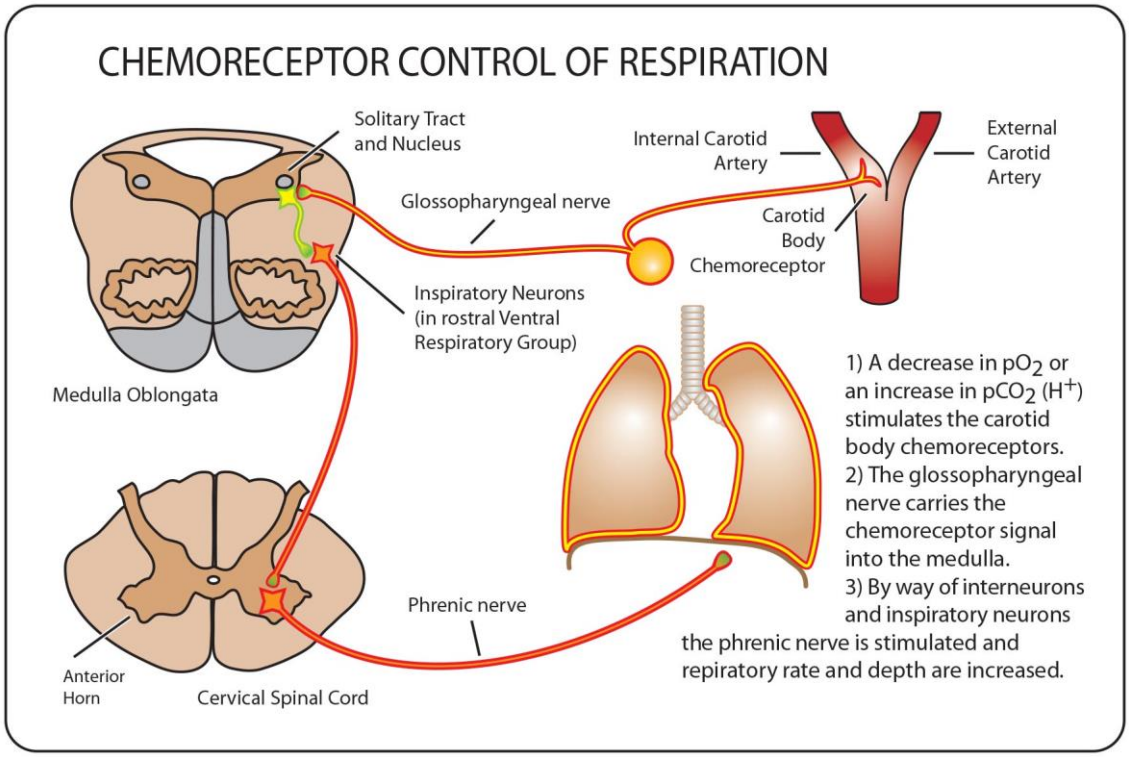

Figure 19.15 © 2015 David G. Ward, Ph.D.

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.

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

- 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 thus 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 and H_2O by the lungs will thus decrease the H^+ concentration and raise the pH.

$$HCO_3\text{-} + H^+ \rightarrow H_2CO_3 \rightarrow H_2O + CO_2$$

CO_2 and H_2O → 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 19.3.

- 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 19.3 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

Quiz Yourself

1-5. Matching

A)	during exhalation	the lungs are shrinking	1) _____
B)	during inhalation	respiratory system pressure is about -3 mmHg	2) _____
		respiratory system pressure is about +3 mmHg	3) _____
		alveolar pressure is lower than atmospheric pressure	4) _____
		alveolar pressure is higher than atmospheric pressure	5) _____

6-10. Matching

A)	tidal volume (TV)	Vital Capacity (VC) – (TV + ERV)	6) _____
B)	residual volume (RV)	about 3 L in young males	7) _____
C)	inspiratory reserve volume (IRV)	VC – (IRV + ERV)	8) _____
D)	expiratory reserve volume (ERV)	about 500 mL	9) _____
E)	functional residual volume (FRV)	RV + ERV	10) _____

11-15. Matching

A)	respiratory system pressure (P_{rs})	= P_{rs} / R_{air}	11) _____
B)	airway resistance (R_{air})	is about 6 to 8 L/min	12) _____
C)	air flow (F_{air})	is comparable to Blood Flow (BF)	13) _____
		is comparable to Vascular Resistance (VR)	14) _____
		is comparable to arterial pressure - venous pressure (~MAP)	15) _____

16-20. Matching

A)	shortage of CO_2	makes the blood acidic	16) _____
B)	excess CO_2	makes the blood alkaline	17) _____
		stimulates reflex increases in rate and depth of breathing	18) _____
		stimulates reflex decreases in rate and depth of breathing	19) _____
		makes the blood have a higher hydrogen ion concentration	20) _____

Fill in

21. During inhalation the <u>transpulmonary</u> pressure is less _____ than during exhalation.

22. During exhalation the <u>respiratory</u> system pressure _____.

23. Carbon dioxide is about _____ times more concentrated in the alveoli than in the atmosphere.

24. Gases move <u>from</u> an area of _____ pressure to an area of _____ pressure.

25. Breathing into a bag will _____ the pCO_2 in the blood.

Study Questions

1. Explain how the airways, lungs, pleura and relevant muscles <u>function together</u> to cause inhalation and exhalation.
2. Explain the inter-relationships between lung compliance and transpulmonary pressure, and between airway resistance, respiratory system pressure, and airflow.
3. Explain how gas is exchanged in the lungs and in the systemic tissues.
4. Explain how O_2 and CO_2 are transported in the blood, <u>and</u> how ventilation affects pCO_2 and pH.