Mechanism of Respiration

Objectives

After going through the lesson, the learners will be able to understand the following:

- Respiratory Volumes
- Control of Ventilation
- Gas Exchange and Transport
- Effects of Aging

Content Outline

- Introduction
- Respiratory Volumes
- Control of Ventilation
- Gas Exchange and Transport
- External Respiration
- Internal Respiration
- Gas Transport
- Carbon Dioxide Transport
- Effects of Aging
- Homeostasis
- Gas Exchange
- Regulation of Blood pH
- Working with Other Systems

Introduction

The lungs are situated in the thoracic chamber, which is anatomically an air-tight chamber. The thoracic chamber is formed dorsally by the vertebral column, ventrally by the sternum, laterally by the ribs and on the lower side by the dome-shaped diaphragm. The anatomical setup of lungs in the thorax is such that any change in the volume of the thoracic cavity will be reflected in the lung (pulmonary) cavity. Such an arrangement is essential for breathing, as we cannot directly alter the pulmonary volume.

Respiration involves the following steps:

a. Breathing or pulmonary ventilation by which atmospheric air is drawn in and CO_2 rich alveolar air is released out.
b. Diffusion of gases (O_2 and CO_2) across the alveolar membrane.
c. Transport of gases by the blood.
d. Diffusion of O_2 and CO_2 between blood and tissues.
e. Utilisation of O_2 by the cells for catabolic reactions and result in the release of CO_2.

During breathing, air moves into the lungs from the nose or mouth (called inspiration, or inhalation) and then moves out of the lungs during expiration or exhalation. A free flow of air from the nose or mouth to the lungs and vice-versa is vitally important. Therefore, a technique has been developed that allows physicians to determine if there is a medical problem that prevents the lungs from filling with air upon inspiration and releasing air from the body upon expiration. An instrument called a spirometer records the volume of air exchanged during normal breathing and during deep breathing. A spirogram shows the measurements recorded by a spirometer when a person breathes as directed by a technician.

Respiratory Volumes

Normally when we are relaxed, only a small amount of air moves in and out with each breath. This amount of air, called the **tidal volume**, is only about 500 ml. It is possible to increase the amount of air inhaled, and therefore the amount exhaled by deep breathing. The maximum volume of air that can be moved in plus the maximum volume that can be moved out during a single breath is the **vital capacity**. It is called vital capacity because your life depends on breathing, and the more air you can move, the better off you are.

Vital capacity varies by how much we can increase inspiration and expiration over the tidal volume amount. We can increase inspiration by not only expanding the chest but also by lowering the diaphragm. Forced inspiration usually increases the volume of air beyond the tidal volume by 2,900 ml, and that amount is called the **inspiratory reserve volume**. We can increase the amount of air expired by contracting the abdominal and internal intercostal muscles. This so-called **expiratory reserve volume** is usually about 1,400 ml of air. You can see from Figure 14.6 that vital capacity is the sum of the tidal, inspiratory reserve, and expiratory reserve volumes.

It's a curious fact that some of the inhaled air never reaches the alveoli; instead, it fills the nasal cavities, trachea, bronchi, and bronchioles (see Fig. 14.1). In an average adult, some 70% of the tidal volume does reach the alveoli; but 30% remains in the airways. These passages are not used for gas exchange, and therefore they are said to contain dead-space air. To ensure that a large portion of inhaled air reaches the lungs, it is better to breathe slowly and deeply. Also, note in Figure 14.6 that even after a very deep exhalation, some air (about 1,000 ml) remains in the alveoli; this is called the **residual volume**. This air is not as useful for gas exchange because it has been depleted of oxygen. In some lung diseases, such as emphysema (see What's New on page 280), the residual volume builds up because the individual has difficulty emptying the lungs. This means that the vital capacity is reduced because the lungs have more residual volume.

Ventilation

To understand **ventilation,** the manner in which air enters and exits the lungs, it is helpful to be aware of the following conditions:

The lungs lie within the sealed-off thoracic cavity.

The rib cage, consisting of the ribs joined to the vertebral column posteriorly and to the sternum anteriorly, forms the top and sides of the thoracic cavity. The intercostal muscles lie between the ribs. The diaphragm and connective tissue form the floor of the thoracic cavity.

The lungs adhere to the thoracic wall by way of the pleura.

Any space between the two layers of the pleura is minimal due to the surface tension of the fluid between them.

A continuous column of air extends from the pharynx to the alveoli of the lungs.

Inspiration is the active phase of ventilation because this is the phase in which the diaphragm and the external intercostal muscles contract (Fig. 14.7*a*). In its relaxed state, the diaphragm is dome-shaped; during deep inspiration, it contracts and lowers. Also, the external intercostal muscles contract,and the rib cage moves upward and outward.

Following contraction of the diaphragm and the external intercostal muscles, the volume of the thoracic cavity will be larger than it was before. As the thoracic volume increases, the lungs expand due to conditions 1 and 2. Now the air pressure within the alveoli (called intrapulmonary pressure) decreases, creating a partial vacuum. In other words, alveolar pressure is now less than atmospheric pressure (air pressure outside the lungs), and air will naturally flow from outside the body into the respiratory passages and into the alveoli due to condition 3.

It is important to realize that air comes into the lungs because they have already opened up; air does not force the lungs open. This is why it is sometimes said that *humans breathe by negative pressure.* The creation of a partial vacuum in the alveoli causes air to enter the lungs. While inspiration is the active phase of breathing, the actual flow of air into the alveoli is passive

Expiration

Usually, expiration is the passive phase of ventilation, and no effort is required to bring it about. During expiration, the diaphragm and the intercostal muscles relax. Therefore, the diaphragm resumes its dome shape and the rib cage moves down and in (Fig. 14.7*b*). Now the air pressure within the alveoli (called intrapulmonary pressure) increases above atmospheric pressure and air will naturally flow to outside the body due to condition 3.

What keeps the alveoli from collapsing as a part of expiration? The presence of surfactant lowers the surface tension within the alveoli. Also, as the lungs recoil, the pressure between the two layers of pleura decreases, and this tends to make the alveoli stay open. The importance of a reduced intrapleural pressure is demonstrated when, by design or accident, air enters the intrapleural space. Now the lung collapses.

While inspiration is the active phase of breathing, expiration is usually passive—that is, the diaphragm and external intercostal muscles are relaxed when expiration occurs. However, when breathing is deeper and/or more rapid, expiration can also be active. Contraction of the internal intercostal muscles can force the rib cage to move downward and inward. Also, when the abdominal wall muscles contract, they push on the viscera, which pushes against the diaphragm, and the increased pressure in the thoracic cavity helps expel air.

Control of Ventilation

Normally, adults have a breathing rate of 12 to 20 ventilations per minute. The rhythm of ventilation is controlled by a **respiratory center** located in the medulla oblongata of the brain.

The respiratory center automatically sends out impulses by way of nerves to the diaphragm and the external intercostal muscles of the rib cage (Fig. 14.8). When the respiratory center stops sending neuronal signals to the diaphragm and the ribcage, the diaphragm relaxes, resuming its dome shape and the rib cage moves down and in. The respiratory center acts rhythmically to bring about breathing at a normal rate and volume.
Although the respiratory center controls the rate and depth of breathing, its activity can be influenced by nervous input and chemical input.

Nervous Input An example of nervous control of the respiratory center is the so-called *Hering-Breuer reflex.* During exercise, the depth of inspiration can increase due to recruitment of muscle fibers in the diaphragm and intercostal muscles.
Then, stretch receptors in the alveolar walls are stimulated, and they initiate inhibitory nerve impulses that travel from the inflated lungs to the respiratory center. This causes the respiratory center to stop sending out nerve impulses. This reflex helps support rhythmic respiratory movements by limiting the extent of inspiration.

Chemical Input The respiratory center is directly sensitive to the levels of carbon dioxide CO_2 and hydrogen ions H^+. When they rise, due to cellular respiration, the respiratory center increases the rate and depth of breathing. The center is not affected directly by low oxygen (O_2) levels. However, chemoreceptors in the **carotid bodies**, located in the carotid arteries, and in the **aortic bodies**, located in the aorta, are sensitive to the level of oxygen in the blood. (Do not confuse the carotid and aortic bodies with the carotid and aortic sinuses, which monitor blood pressure.) When the concentration of oxygen decreases, these bodies communicate with the respiratory center, and the rate and depth of breathing increase.

Gas Exchange and Transport

Gas exchange and transport are critical to homeostasis. As mentioned previously, respiration includes not only the exchange of gases in the lungs but also the exchange of gases in the tissues. Recall that diffusion is the movement of molecules from the area of higher concentration to the area of lower concentration. The principles of diffusion alone govern whether oxygen (O_2) or carbon dioxide (CO_2) enters or leaves the blood in the lungs and in the tissues.

External Respiration

External respiration is the exchange of gases in the lungs. Specifically, during external respiration, gases are exchanged between the air in the alveoli and the blood in the pulmonary capillaries. Blood that enters the pulmonary capillaries is dark maroon because it is relatively O_2-poor. Once inspiration has occurred, the alveoli have a higher concentration of O_2 than does blood entering the lungs. Therefore, O_2 diffuses from the alveoli into the blood. Thereverse is true of CO_2. The alveoli have a lower concentration of CO_2 than does blood entering the lungs. Therefore, CO_2 diffuses out of the blood into the alveoli. This CO_2 exits the body during expiration.

Another way to explain gas exchange in the lungs is to consider the partial pressure of the gases involved. Gases exert pressure and the amount of pressure each gas exerts is its partial pressure, symbolized as PO_2 and PCO_2. Alveolar air has a much higher PO_2 than does blood. Therefore, O_2 diffuses into the blood from the alveoli. The pressure pattern is the reverse for CO_2. Blood entering the pulmonary capillaries has a higher PCO_2 than the air in the alveoli. Therefore, CO_2 diffuses out of the blood into the alveoli.

Internal Respiration

Internal respiration refers to the exchange of gases in the tissues. Specifically, during internal respiration, gases are exchanged between the blood in systemic capillaries and the tissue fluid. Blood that enters the systemic capillaries is a bright red color because the blood is O_2 -rich. Tissue fluid, on the other hand, has a low concentration of O_2. Why? Because the cells are continually consuming O_2during cellular respiration.

Therefore, O_2 it diffuses from the blood into the tissue fluid. Tissue fluid has a higher concentration of CO_2 than does the blood entering the tissues. Why? Because CO_2 is an end product of cellular respiration. Therefore, CO_2 it diffuses from the tissue fluid into the blood.

Figure 14.9 summarizes our discussion of gas exchange in the lungs and tissues and shows the differences in O_2 and CO_2 that leads to diffusion of these gases. Again, we can explain exchange in the tissues by considering the partial pressure of the gases involved. In this case, oxygen diffuses out of the blood into the tissues because the PO_2 in tissue fluid is lower than that of the blood. And the carbon dioxide diffuses into the blood from the tissues because the PCO_2 in tissue fluid is higher than that of the blood.

Gas Transport

The mode of transport of oxygen and carbon dioxide in the blood differs, although red blood cells are involved in transporting both of these gases.

Oxygen Transport

After O_2 entering the blood in the lungs, it enters red blood cells and combines with the iron portion of **hemoglobin**, the pigment in red blood cells. Hemoglobin is remarkably suited to the task of transporting oxygen because it both combines with and releases oxygen. The higher concentration of oxygen in the alveoli, plus the slightly higher pH and slightly cooler temperature, causes hemoglobin to take up oxygen and become **oxyhemoglobin** (HbO_2). The lower concentration of oxygen in the tissues, plus the slightly lower pH and slightly warmer temperature in the tissues, causes hemoglobin to release oxygen and become deoxyhemoglobin (Hb). This equation summarizes our discussion of oxygen transport:

$$Hb + O_2 \underset{}{\overset{\text{lungs}}{\rightleftharpoons}} HbO_2$$

Carbon Dioxide Transport

Transport of CO_2 to the lungs involves a number of steps. After CO_2 diffuses into the blood at the tissues, it enters the red blood cells, where:

- A small amount is taken up by hemoglobin, forming **carbaminohemoglobin**.
- Most of the CO_2 combine with water, forming carbonic acid (H_2CO_3). The carbonic acid dissociates to hydrogen ions (H^-) and bicarbonate ions (HCO_3^-). The release of these hydrogen ions explains why the blood in systemic capillaries has a lower pH than the blood in pulmonary capillaries.
- The difference in pH is slight because the globin portion of hemoglobin combines with excess hydrogen ions and becomes **reduced hemoglobin (HHb).**

Bicarbonate ions are carried in the plasma because they diffuse out of red blood cells and go into the plasma. Most of the carbon dioxide in blood is carried as HCO_3^-, the **bicarbonate ion**. As bicarbonate ions diffuse out of red blood cells, chloride ions (Cl^-) diffuse into them. This so-called **chloride shift** maintains the electrical balance between the plasma and the red blood cells.

In pulmonary capillaries, a reverse reaction occurs. Bicarbonate Combines with hydrogen ions to form carbonic acid, which this time splits into CO_2 and H_2O and the CO_2 diffuses out of the blood into the alveoli. The following equation summarizes our discussion of carbon dioxide transport:

$$CO_2 + H_2O \underset{\text{lungs}}{\overset{\text{tissues}}{\rightleftharpoons}} H_2CO_3 \underset{\text{lungs}}{\overset{\text{tissues}}{\rightleftharpoons}} H^+ + HCO_3^-$$

Effects of Aging

Respiratory fitness decreases with age. Maximum breathing capacities decline, while the likelihood of fatigue increases. Inspiration and expiration are not as effective in older persons. With age, weakened intercostal muscles and increased elasticity of the rib cage combine to reduce the inspiratory reserve volume, while the lungs' inability to recoil reduces the expiratory reserve volume. More residual air is found in the lungs of older people.

With age, gas exchange in the lungs becomes less efficient, not only due to changes in the lungs but also due to changes in the blood capillaries. The respiratory membrane thickens,and the gases cannot diffuse as rapidly as they once did. In the elderly, the ciliated cells of the trachea are reduced in number, and those remaining are not as effective as they once were. Respiratory diseases, such as those discussed in section 14.4, are more prevalent in older people than in the general public. Pneumonia and other respiratory infections are among the leading causes of death in older persons.

Homeostasis

The respiratory system contributes to homeostasis in many ways—in particular, by carrying on gas exchange and regulating blood pH.

Gas Exchange

First and foremost, the respiratory system performs gas exchange. Carbon dioxide, a waste molecule given off by cellular respiration, exits the body, and oxygen, a molecule needed for cellular respiration, enters the body at the lungs. Cellular respiration produces ATP, a molecule that allows the body to perform all sorts of work, including muscle contraction and nerve conduction. It is estimated that the brain uses 15-20%of the oxygen taken into the blood. Not surprisingly, a lack of oxygen affects the functioning of the brain and our judgment before it affects other organs.

Regulation of Blood pH

The respiratory system can alter blood pH by changing blood carbon dioxide levels. In the tissues, carbon dioxide enters the blood and red blood cells where this reaction occurs. The bicarbonate ion (HCO_3^-) diffuses out of the red blood cells to be carried in the plasma:

$$CO_2 + H_2O \underset{\text{lungs}}{\overset{\text{tissues}}{\rightleftharpoons}} H_2CO_3 \underset{\text{lungs}}{\overset{\text{tissues}}{\rightleftharpoons}} H^+ + HCO_3^-$$

This reaction lowers the blood pH because it gives off H^-. When carbon dioxide starts to diffuse out of the blood in the lungs, the reaction occurs in the reverse direction. Now, the blood pH rises. What happens to your blood pH if you hyperventilate, that is, breathe at a low rate? A low blood pH, called acidosis, results because hydrogen ions are being held in the body. Any condition, such as emphysema, that hinders the passage of carbon dioxide out of the blood also results in acidosis. What happens to your blood pH if you hyperventilate — that is, breathe at a high rate? A high blood pH, called alkalosis, results because carbon dioxide is leaving the body at a high rate. Severe anxiety can cause a person to hyperventilate.

Working with Other Systems

The illustration in Human Systems Work Together on page 291 tells how the respiratory system depends on and assists other systems of the body. The contributions of the respiratory system to homeostasis cannot be overemphasized. The respiratory tract assists defence against pathogens by preventing their entry into the body and by removing them from respiratory surfaces. For example, the cilia that line the trachea sweep impurities toward the throat. The respiratory tract also assists immunity. We now know that the tonsils serve as a location where T cells are presented with antigens before they enter the body as a whole. This action helps the body prepare to respond to an antigen before it enters the bloodstream!

The cardiovascular system transports oxygen from the lungs to the tissues and carbon dioxide from the tissues to the lungs. As mentioned in Chapter 12, the expansion of the chest during inspiration causes a reduced pressure that promotes the flow of blood toward the thoracic cavity and the heart. Therefore, the act of breathing assists the return of blood to the heart and the transport of carbon dioxide to the lungs. The rib cage protects the lungs, and inspiration could not occur without the contraction of external intercostal muscles, which lift the rib cage. The respiratory system is able to respond to the increased gas exchange needed by the body during exercise. Exercise causes the tissues to warm up and the pH to lower; under these conditions, hemoglobin unloads more oxygen than usual. These conditions are also detected by the carotid and aortic bodies, leading to an increase in the ventilation rate.

In the nervous system, the brain stem controls rhythmic ventilation, but it is possible through the cerebral cortex to consciously increase or decrease the rate and depth of the respiratory movements. This is often done while talking or singing, for example. The nasal cavities house the sense organs for olfaction. The sensation of smell only occurs after airborne molecules are drawn into the nasal cavity.