

Respiratory Structures and Processes

Take a deep breath! You have just captured between 3 L and 4 L of air in your lungs. We are completely surrounded by air. Remember from your previous science studies that air is a fluid consisting of a number of gases, including oxygen and carbon dioxide. Aquatic organisms such as fish are surrounded by water. Water is also a fluid that usually has some oxygen and carbon dioxide dissolved in it.

The structures and mechanisms for obtaining oxygen vary significantly depending on the size of the organism and where it lives.

Respiratory Structures in Mammals

The human respiratory system is typical of mammalian respiratory systems. It has four important structural features that enable it to function properly:

- a thin permeable respiratory membrane through which diffusion can occur
- a large surface area for gas exchange
- a good supply of blood
- a breathing system for bringing oxygen-rich air to the respiratory membrane

The Structure of the Lungs

The major organs of the respiratory system are a pair of lungs. Lungs fulfill the first three structural requirements of a respiratory system: they provide a respiratory membrane, a large surface area, and a good supply of blood. The lungs are enclosed within the thoracic, or chest, cavity and are protected by the rib cage.

Air from the outside enters the respiratory system through the nose and mouth. The air is warmed and moistened in the nasal passages and mouth before it travels to the lungs (**Figure 1**). This prevents damage to the thin, delicate tissue of the respiratory membrane. The nasal passages are lined with tiny hairs and mucus that filter out and trap dust and other airborne particles, preventing them from entering the lungs.

Investigation 11.1.1

Fetal Pig Dissection (page 510)

Consider what you have read about respiratory structures in mammals. At the end of this unit you will dissect a fetal pig to observe the structures of a typical mammalian respiratory system.

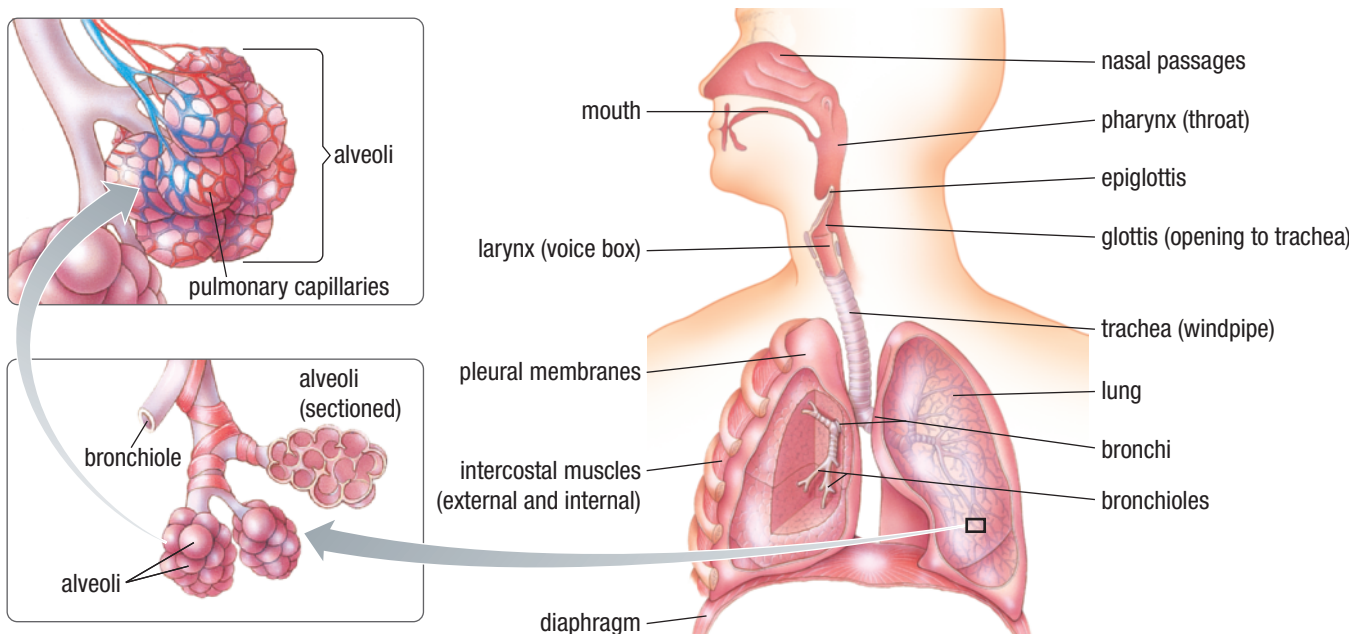


Figure 1 The human respiratory system

The air then travels from the mouth or nasal passages into the pharynx. Recall from the previous chapter that during swallowing, the epiglottis closes the glottis, the entrance to the trachea, so that food goes into the esophagus. During breathing, however, the glottis remains open so that air flows into the trachea, or windpipe. The **trachea** is a semi-rigid tube of soft tissue wrapped around c-shaped bands of cartilage. These bands of cartilage are necessary to keep the trachea open. The walls of the trachea are lined with mucus-producing cells and cilia, which further protect the lungs from foreign matter (**Figure 2**). The mucus is sticky and traps dust and other particles. Cilia are tiny hair-like structures that are found on some cells. The wave-like motions of the cilia sweep the trapped material upward through the trachea, where it is swallowed or, occasionally, expelled from the body when coughing or sneezing.

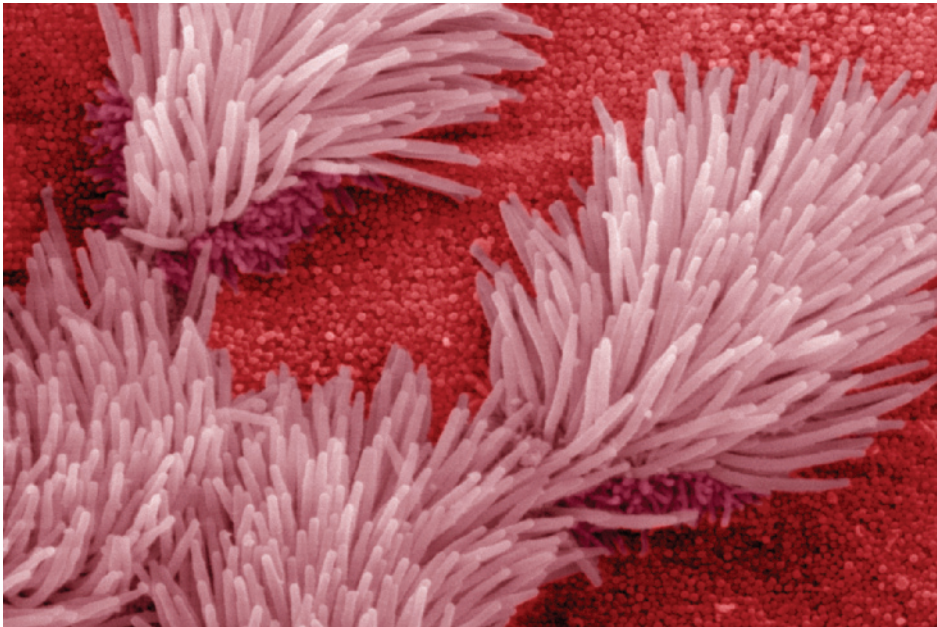


Figure 2 The trachea is lined with mucus-producing cells and cilia. Mucous cells, coloured red in this scanning electron micrograph (SEM), secrete mucus that traps dust and other airborne particles. The cilia, coloured pink, sweep the trapped material out of the trachea. *Magnification 5000 ×*.

The trachea branches into two **bronchi** (singular: bronchus). Each bronchus connects to a lung. Inside the lungs, the bronchi branch repeatedly into smaller and smaller tubes called **bronchioles** to form a respiratory tree. The airways end in clusters of tiny sacs called **alveoli** (singular: alveolus) (**Figure 1**, page 440). Each cluster of alveoli is surrounded by a network of capillaries, which are extremely small blood vessels. Each alveolus is tiny, measuring only 0.1 μm to 0.2 μm (micrometres) in diameter. It is the sheer number of alveoli, approximately 150 million in each lung, that provides the necessary surface area for gas exchange. If the entire surface area inside the lungs were flattened out, it would cover an area about the size of a tennis court!

GAS EXCHANGE IN THE ALVEOLI

By the time air reaches the alveoli, it is at normal body temperature, around 37 °C, and is saturated with moisture. The respiratory membrane that forms the alveoli is also moist. This moisture is critical because oxygen cannot diffuse across the respiratory membrane unless it is dissolved in a liquid.

The alveoli are perfectly adapted for gas exchange. The respiratory membrane is extremely thin (one cell layer thick), so that there is little distance between the air in an alveolus and the blood in the capillaries that surround the alveolus (**Figure 3**). Oxygen and carbon dioxide can easily diffuse across the respiratory membrane. The network of capillaries encapsulates the alveoli so that there is an adequate supply of blood for the oxygen to diffuse into and the carbon dioxide to diffuse from.

trachea the tube leading from the mouth toward the lungs

bronchus one of the two main branches of the trachea that lead toward the lungs

bronchiole a tiny branch of a bronchus that connects to a cluster of alveoli

alveolus a tiny sac at the end of a bronchiole that forms the respiratory membrane

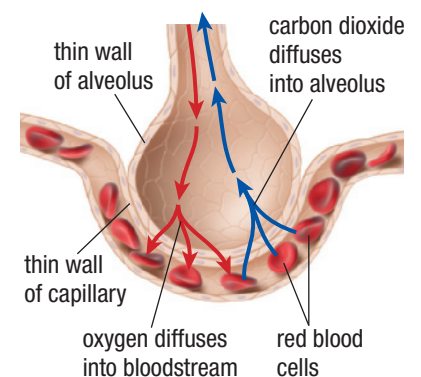


Figure 3 Only two cell layers separate the air in the alveolus from the bloodstream.

The Mechanism of Ventilation

As you have learned, the lungs fulfill three of the important structural features of the human respiratory system: a thin permeable respiratory membrane, a large surface area for gas exchange, and a good supply of blood. The mechanism of ventilation fulfills the fourth important structural feature: a breathing system for bringing oxygen-rich air to the respiratory membrane.

Ventilation, or breathing, is based on the principle of negative pressure. When the air pressure inside the lungs is lower than the atmospheric pressure, air is forced into the lungs. Conversely, when the air pressure inside the lungs is higher than the atmospheric pressure, air is forced out of the lungs. Air always flows from an area of higher pressure to an area of lower pressure. What creates these pressure differences?

The thoracic cavity is separated from the abdominal cavity by a large dome-shaped sheet of muscle called the **diaphragm**. During inhalation, the breathing control mechanisms in the brain cause the diaphragm to contract. This contraction shortens and flattens the diaphragm. At the same time, the **external intercostal muscles**, located between each rib, contract and pull the ribs upward and outward. These two actions together increase the volume of the thoracic cavity and reduce the pressure inside the lungs. Because the atmospheric pressure is greater than the pressure in the thoracic cavity, air rushes into the lungs to equalize the pressure (**Figure 4(a)**). The lungs fill with air, stretching and expanding like balloons.

diaphragm a large sheet of muscle located beneath the lungs that is the primary muscle in breathing

external intercostal muscle a muscle that raises the rib cage, decreasing pressure inside the chest cavity

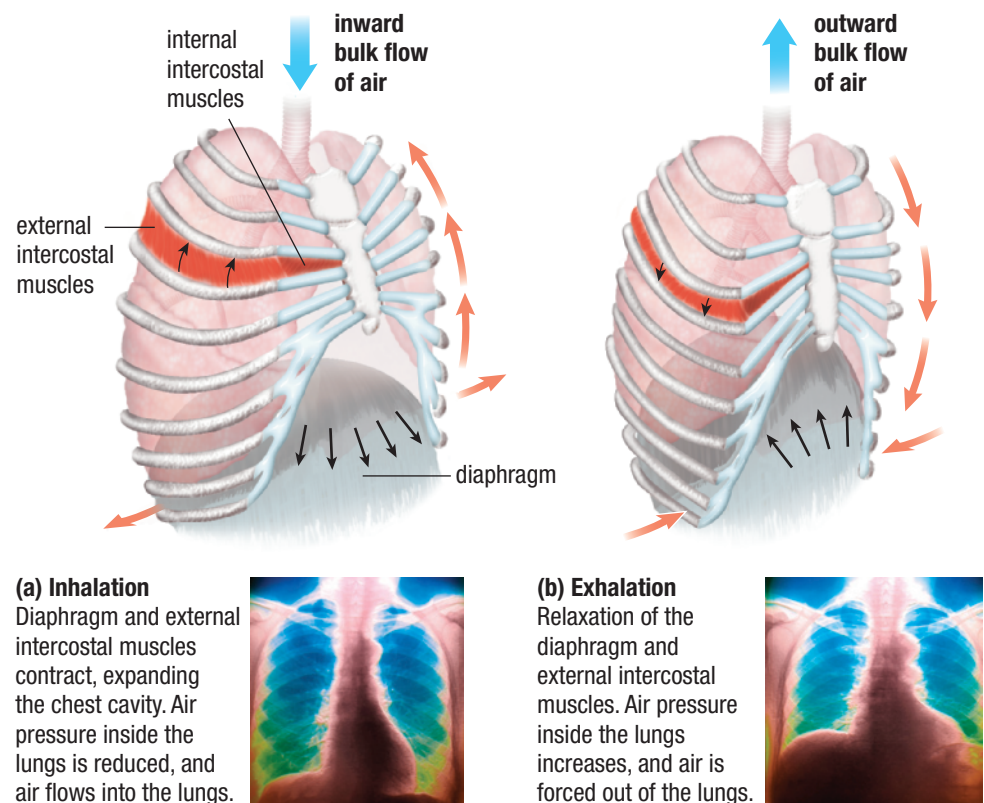


Figure 4 Ventilation in the human respiratory system

During normal exhalation, the diaphragm relaxes and returns to its regular domed shape (**Figure 4(b)**). This relaxation of the diaphragm pushes up on the lungs. The external intercostal muscles also relax and the ribs fall and return to their resting position. The air pressure inside the lungs is now greater than the atmospheric pressure, and air is forced out of the lungs. Like inflated balloons, the elasticity of the lung tissue causes the lungs to return to their resting size, which also helps to force air out.

During strenuous exercise or forced exhalation, a second set of intercostal muscles, called the **internal intercostal muscles**, start contracting and relaxing. When they contract, they pull the rib cage downward, increasing the pressure inside the lungs and forcing more air out of the lungs.

internal intercostal muscle a muscle that pulls the rib cage downward, increasing pressure inside the chest cavity

The movement of the lungs within the thoracic cavity might cause a friction problem if it were not for the pleural membranes. **Pleural membranes** cover the lungs and line the thoracic cavity. The space between the pleural membranes is called the pleural cavity. The pleural cavity is filled with fluid to prevent the membranes from separating and also to allow them to slide past each other easily. (Think about how two microscope slides stick together when they are wet. You cannot pull them apart directly; the only way to separate them is to slide them apart.) If air is introduced into the pleural cavity, such as in a stabbing or when a broken rib punctures the lung, then the membranes separate. This causes the lung to collapse, a condition known as a **pneumothorax** (Figure 5). In this situation, the rib cage can move but the lung cannot inflate because nothing is pulling on it to increase its volume and reduce its air pressure. This painful condition is characterized by sharp chest pain and breathing difficulty.

Lung Capacity

The volume of air in the lungs can vary depending on the circumstances. Strenuous physical activity will automatically increase not only the rate of your breathing, but also the depth of your breathing—you inhale and exhale a greater volume of air than during your normal breathing.

Total lung volume depends on sex, body type, and lifestyle. On average, males, non-smokers, and athletes have larger lung volumes than females, smokers, and non-athletes, respectively. The **total lung capacity** is the maximum volume of air that can be taken into the lungs during a single breath. During normal, involuntary breathing, we use only a small fraction of the total capacity of our lungs. This quantity is called the **tidal volume** and is about 0.5 L in the average adult. Normal breathing does not involve a complete exchange of the air in the lungs.

After a normal inhalation, there is room for considerably more air in the lungs. The **inspiratory reserve volume** is the amount of additional air that can be inhaled after a normal inhalation. Similarly, after a normal exhalation, there is still a considerable volume of air left in the lungs. This additional volume of air, called the **expiratory reserve volume**, can be exhaled after a normal exhalation. Even after the expiratory reserve volume has been expelled, the lungs are not completely empty. There is still a volume of air, called the **residual volume**, which prevents the lungs from collapsing.

During periods of high demand for oxygen, the reserve volumes decrease and tidal volume increases. The maximum tidal volume is called the **vital capacity** (Figure 6). Because of differences in average lung size, the vital capacity is about 4.4 L to 4.8 L in males and 3.4 L to 3.8 L in females.

pleural membrane a thin layer of connective tissue that covers the outer surface of the lungs and lines the thoracic cavity

pneumothorax a collapsed lung caused by the introduction of air between the pleural membranes

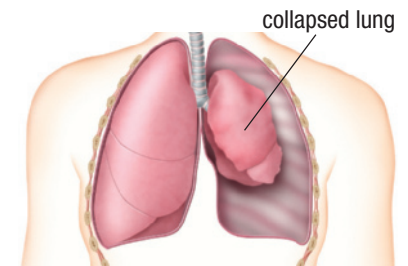


Figure 5 Air introduced into the pleural cavity causes the lung to collapse.

total lung capacity the maximum volume of air that can be inhaled during a single breath

tidal volume the volume of air inhaled or exhaled during a normal, involuntary breath

inspiratory reserve volume the volume of air that can be forcibly inhaled after a normal inhalation

expiratory reserve volume the volume of air that can be forcibly exhaled after a normal exhalation

residual volume the volume of air remaining in the lungs after a forced exhalation

vital capacity the maximum amount of air that can be inhaled or exhaled

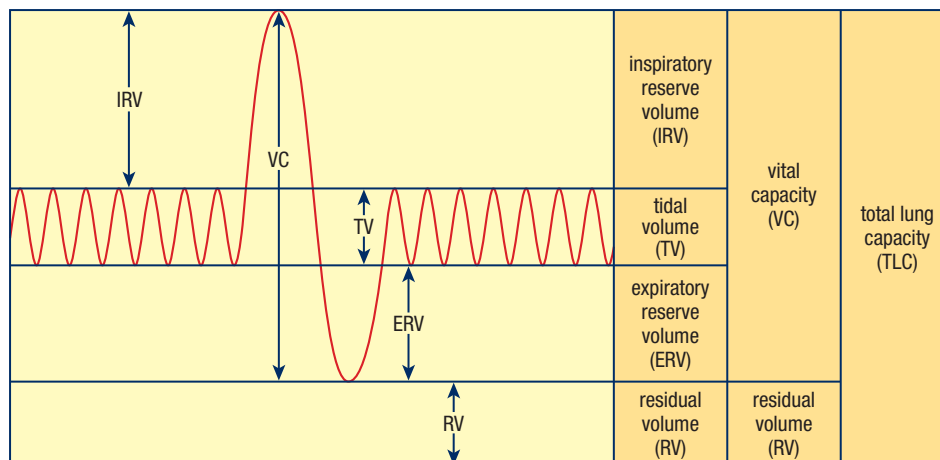


Figure 6 In this graph, each small wave represents the volume changes during a normal breath. For most of our lives, we use only a small proportion of our lung capacity. The tidal volume in normal breathing is approximately 10 % of the total lung capacity. The big wave represents the vital capacity, or a maximum inhalation and exhalation.

Investigation 10.2.1

Determining Lung Volume and Oxygen Consumption (page 465)

Now that you have read about lung capacity, you can perform Investigation 10.2.1.

In this observational study you will use a spirometer to measure your tidal volume and vital capacity. Using this information, you will determine your reserve volumes. You will also determine your oxygen consumption.

VO₂ an estimated or measured value representing the rate at which oxygen is used in the body, measured in millilitres per kilogram per minute

VO₂max the maximum rate at which oxygen can be used in an individual, measured in millilitres per kilogram per minute

Investigation 10.2.2

The Relationship between Long-Term Exercise and Vital Capacity (page 467)

Now that you have read about lung capacity, you can perform Investigation 10.2.1.

In this correlational study you will analyze data to identify the potential relationships between exercise and vital capacity.

WEB LINK

For information on methods of determining VO₂max,



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Oxygen Usage

Physical activity depends on the energy released during aerobic cellular respiration, and this, in turn, depends on the amount of oxygen and how quickly it is supplied. The maximum rate at which oxygen can be used in aerobic cellular respiration is an indicator of the efficiency of a respiratory system—a high maximum rate of oxygen usage indicates an efficient respiratory system.

The rate at which oxygen is used in the body, known as **VO₂**, is a function of the amount of oxygen delivered to the body in a given time. The maximum amount of oxygen that an individual can use during sustained, intense physical activity is called the **VO₂max**. VO₂ and VO₂max are both measured in millilitres of oxygen per kilogram of body mass per minute (mL/kg/min). **Table 1** provides a range of VO₂max values for males and females of different ages at different efficiency levels.

Table 1 VO₂max Norms for Men (M) and Women (F) (mL/kg/min)

Age	M/F	Very poor	Poor	Fair	Good	Excellent	Superior
13–19	M	<35.0	35.0–38.3	38.4–45.1	45.2–50.9	51.0–55.9	>55.9
	F	<25.0	25.0–30.9	31.0–34.9	35.0–38.9	39.0–41.9	>41.9
20–29	M	<33.0	33.0–36.4	36.5–42.4	42.5–46.4	46.5–52.4	>52.4
	F	<23.6	23.6–28.9	29.0–32.9	33.0–36.9	37.0–41.0	>41.0
30–39	M	<31.5	31.5–35.4	35.5–40.9	41.0–44.9	45.0–49.4	>49.4
	F	<22.8	22.8–26.9	27.0–31.4	31.5–35.6	35.7–40.0	>40.0
40–49	M	<30.2	30.2–33.5	33.6–38.9	39.0–43.7	43.8–48.0	>48.0
	F	<21.0	21.0–24.4	24.5–28.9	29.0–32.8	32.9–36.9	>36.9
50–59	M	<26.1	26.1–30.9	31.0–35.7	35.8–40.9	41.0–45.3	>45.3
	F	<20.2	20.2–22.7	22.8–26.9	27.0–31.4	31.5–35.7	>35.7
60+	M	<20.5	20.5–26.0	26.1–32.2	32.3–36.4	36.5–44.2	>44.2
	F	<17.5	17.5–20.1	20.2–24.4	24.5–30.2	30.3–31.4	>31.4


VO₂ and VO₂max can be calculated using a spirometer. A spirometer directly measures the volume of air that is taken into the lungs. A spirometer also calculates the rate at which oxygen is used by taking into account the breathing rate and body mass (**Figure 7**). There are also indirect methods that provide fairly accurate estimates of VO₂ and VO₂max. 



Figure 7 A spirometer measures the volume of oxygen used while exercising at maximum capacity. The VO₂max for the individual can be determined using this measurement.

Respiratory Structures in Fish

Most aquatic organisms obtain oxygen from the water that surrounds them, so their respiratory structures are considerably different from those of humans and other mammals. The respiratory system in many aquatic animals (including fish, clams, marine worms, and crayfish) involves gills. Gills are extensions of the body surface. They are folded and branched structures that provide a maximum surface area through which oxygen can be absorbed and carbon dioxide removed.

In bony fish, the gills are located underneath a protective, bony flap at the side of the head. The movement of the mouth and bony flap in some fish helps move water through the mouth and over the gills (**Figure 8**). This ensures a constant supply of oxygen-rich water to the gills. Some cartilaginous fish, such as the great white shark, have to swim continuously to ensure that water is flowing over their gills.

Fish gills are made up of several gill arches, which are made up of rows of feathery gill filaments. Within the filaments is a rich network of capillaries (**Figure 9(a)**). In the gill filaments, blood flows through the capillaries in the opposite direction to the flow of oxygen-rich water over the filaments (**Figure 9(b)**).

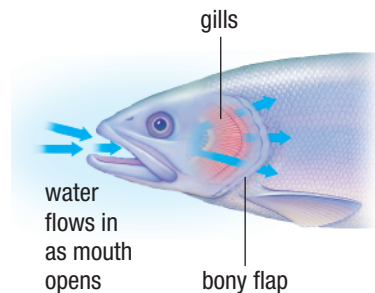


Figure 8 Water enters the fish's mouth and exits through the gill slits.

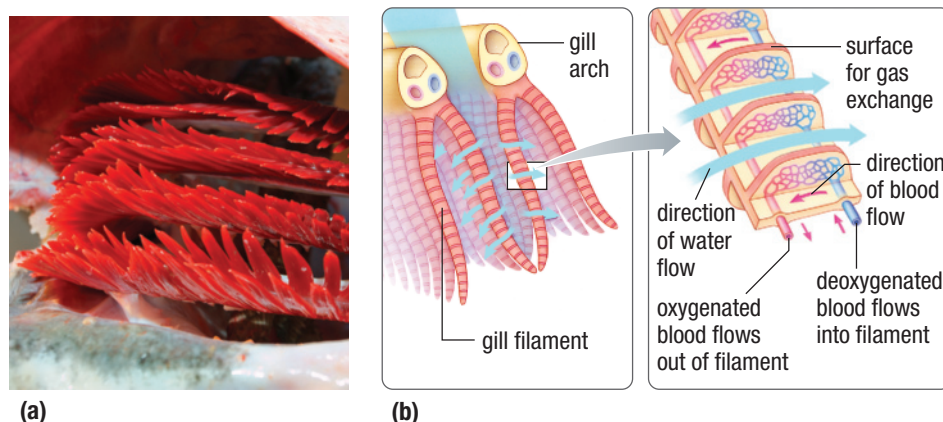


Figure 9 (a) Fish gills appear red because of the rich blood supply flowing through the thin filaments. (b) As water flows over the gills, oxygen diffuses from the water into the blood vessels and carbon dioxide diffuses from the blood into the water.

This process, known as countercurrent exchange, maximizes the amount of oxygen that diffuses into the blood (**Figure 10**). Since the blood and water move in opposite directions, blood with a lower oxygen concentration is always adjacent to water with a higher oxygen concentration. When the difference in oxygen concentration is greater, more oxygen diffuses from the water to the blood. At the same time that oxygen diffuses into the blood, carbon dioxide diffuses out.

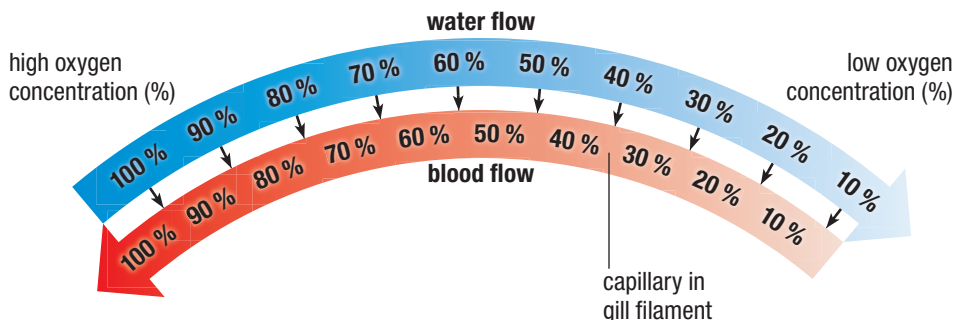


Figure 10 The oxygen concentration of water decreases as the water flows over the gills and oxygen diffuses into the blood. The oxygen concentration of blood increases as the blood flows against the flow of the water.

Consider what you have learned about the structures and functions of the respiratory system, in particular lung capacity and oxygen usage. How can this information help you as you complete the Unit Task?

10.2 Summary

- The respiratory system, along with the circulatory system, is responsible for delivering oxygen to, and removing carbon dioxide from, each cell of the body.
- In the human respiratory system the lungs provide the large surface area through which oxygen and carbon dioxide diffuse.
- Lung ventilation depends on negative pressure. Negative pressure is created in the lungs when the diaphragm and external intercostal muscles contract to increase the volume of the lungs, sucking air into the lungs. When the diaphragm and external intercostal muscles relax, volume decreases and air pressure increases, forcing air out of the lungs.
- The volume of air used in normal breathing, called the tidal volume, is only a small fraction of the total capacity of the lungs.
- VO_2 is the rate at which oxygen is used by the body. It can be determined from direct measurements or estimated by indirect methods. The maximum amount of oxygen that can be used by the body is called VO_{2max} .
- Fish and many other aquatic animals have gills that are adapted to obtaining oxygen from water.

10.2 Questions

1. What is the primary function of the respiratory system? K/U
2. (a) Use a simple labelled diagram to describe the structure of the human respiratory system.
(b) Explain the model you made in the Mini Investigation on page 437 by matching the parts and functions of your model with the structures and functions of the human respiratory system. K/U C A
3. The human respiratory system has a number of built-in safety features to protect the lungs from foreign matter. Describe these features and explain how they protect the lungs. K/U T/I
4. What physical characteristics of the alveoli make them ideal structures for gas exchange? Explain why. K/U T/I A
5. Describe and explain how negative pressure works in the human respiratory system. K/U A
6. A pneumothorax can be caused by a trauma to the rib cage or a number of other factors. Use the Internet and other sources to research other conditions that might cause a pneumothorax. Write a brief report on the causes, symptoms, diagnosis, and treatments of a pneumothorax. T/I C
7. Describe and explain the responses in the respiratory system when you start to exercise. K/U A
8. Explain the difference between total lung capacity and vital capacity. K/U A
9. During normal breathing, only a small proportion of the total lung capacity is used. How is this a survival feature? K/U T/I A

10. Why do you think mass (kg) is included in the unit for VO_2 and VO_{2max} (mL/kg/min)? K/U T/I
11. Examine **Figure 11**, which shows how oxygen would diffuse from water to blood if both water and blood were flowing in the same direction. Compare this with gas exchange in fish, where blood flows in the opposite direction of water flow over the gills.

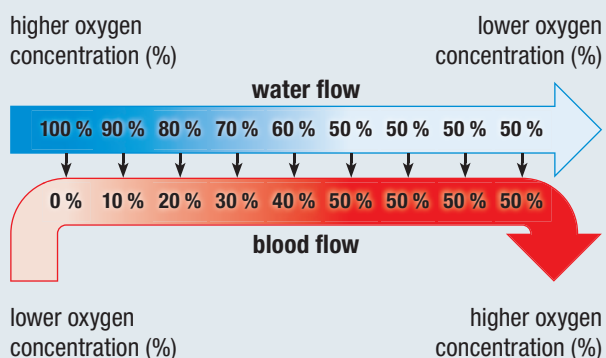


Figure 11

- (a) Is the countercurrent system in fish or the system shown in Figure 11 more efficient at transferring oxygen into the blood?
- (b) What would happen to oxygen uptake across a fish gill if blood flow continued but all water flow stopped? Explain your reasoning. K/U T/I A



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