Circulation and Gas Exchange

Circulatory systems link exchange surfaces with cells throughout the body
- Diffusion time is proportional to the square of the distance
- Diffusion is only efficient over small distances
- In small and/or thin animals, cells can exchange materials directly with the surrounding medium
- In most animals, cells exchange materials with the environment via a fluid-filled circulatory system

Gastrovascular Cavities
- Some animals lack a circulatory system
- Some cnidarians, such as jellies, have elaborate gastrovascular cavities
  - digestion and distribution of substances throughout the body
- The body wall that encloses the gastrovascular cavity is only two cells thick
- Flatworms have a gastrovascular cavity and a large surface area to volume ratio

General Properties of Circulatory Systems
- A circulatory system has
  - A circulatory fluid
  - A set of interconnecting vessels
  - A muscular pump, the heart
- The circulatory system connects the fluid that surrounds cells with the organs that exchange gases, absorb nutrients, and dispose of wastes
- Circulatory systems can be open or closed and vary in the number of circuits in the body
- A circulatory system minimizes the diffusion distance in animals with many cell layers

Open and Closed Circulatory Systems
- In insects, other arthropods, and most molluscs, blood bathes the organs directly in an open circulatory system
  - general body fluid is called hemolymph
- In a closed circulatory system, blood is confined to vessels and is distinct from the interstitial fluid
  - Annelids, cephalopods, and vertebrates have closed circulatory systems
Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system called the cardiovascular system.
- The three main types of blood vessels are arteries, veins, and capillaries.
- Blood flow is one way in these vessels.
- Arteries branch into arterioles and carry blood away from the heart to capillaries.
- Networks of capillaries called capillary beds are the sites of chemical exchange between the blood and interstitial fluid.
- Venules converge into veins and return blood from capillaries to the heart.

Single Circulation

- Bony fishes, rays, and sharks have single circulation with a two-chambered heart.
- In single circulation, blood leaving the heart passes through two capillary beds before returning.

Double Circulation

- Amphibian, reptiles, and mammals have double circulation.
- Oxygen-poor and oxygen-rich blood are pumped separately from the right and left sides of the heart.

Amphibians

- Three-chambered heart: two atria and one ventricle.
- The ventricle pumps blood into a forked artery that splits the ventricle’s output into the pulmocutaneous circuit and the systemic circuit.
- When underwater, blood flow to the lungs is nearly shut off.

Reptiles (Except Birds)

- Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle.
- In alligators, caimans, and other crocodilians a septum divides the ventricle.
- Reptiles have double circulation, with a pulmonary circuit (lungs) and a systemic circuit.

Mammals and Birds

- Mammals and birds have a four-chambered heart with two atria and two ventricles.
- The left side of the heart pumps and receives only oxygen-rich blood, while the right side receives and pumps only oxygen-poor blood.
- Mammals and birds are endotherms and require more O₂ than ectotherms.
The heart contracts and relaxes in a rhythmic cycle called the **cardiac cycle**
- The contraction, or pumping, phase is called **systole**
- The relaxation, or filling, phase is called **diastole**
- The **heart rate**, also called the pulse, is the number of beats per minute
- The **stroke volume** is the amount of blood pumped in a single contraction
- The **cardiac output** is the volume of blood pumped into the systemic circulation per minute and depends on both the heart rate and stroke volume

**Coordinated cycles of heart contraction drive double circulation in mammals**
- Blood begins its flow with the right ventricle pumping blood to the lungs
- In the lungs, the blood loads O₂ and unloads CO₂
- Oxygen-rich blood from the lungs enters the heart at the left atrium and is pumped through the aorta to the body tissues by the left ventricle
- The aorta provides blood to the heart through the coronary arteries
- Blood returns to the heart through the superior vena cava (blood from head, neck, and forelimbs) and inferior vena cava (blood from trunk and hind limbs)
- The superior vena cava and inferior vena cava flow into the right atrium
The “lub-dup” sound of a heart beat is caused by the recoil of blood against the AV valves (lub) then against the semilunar (dup) valves.

Backflow of blood through a defective valve causes a heart murmur.

- The sinoatrial (SA) node, or pacemaker, sets the rate and timing at which cardiac muscle cells contract.
- Impulses that travel during the cardiac cycle can be recorded as an electrocardiogram (ECG or EKG).

Pacemaker regulation

- Nervous System Control
  - The sympathetic division speeds up the pacemaker.
  - The parasympathetic division slows down the pacemaker.
  - The pacemaker is also regulated by hormones and temperature.
Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels.

Changes in Blood Pressure During the Cardiac Cycle
- **Systolic pressure** is the pressure in the arteries during ventricular systole; it is the highest pressure in the arteries.
- **Diastolic pressure** is the pressure in the arteries during diastole; it is lower than systolic pressure.
- A **pulse** is the rhythmic bulging of artery walls with each heartbeat.
- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles.
- **Vasoconstriction** is the contraction of smooth muscle in arteriole walls; it increases blood pressure.
- **Vasodilation** is the relaxation of smooth muscles in the arterioles; it causes blood pressure to fall.

Fainting is caused by inadequate blood flow to the head.
- Animals with longer necks require a higher systolic pressure to pump blood a greater distance against gravity.
- Blood is moved through veins by smooth muscle contraction, skeletal muscle contraction, and expansion of the vena cava with inhalation.
- One-way valves in veins prevent backflow of blood.

Blood pressure is generally measured for an artery in the arm at the same height as the heart.

Blood flows through only 5–10% of the body’s capillaries at a time.

Two mechanisms regulate distribution of blood in capillary beds:
- Contraction of the smooth muscle layer in the wall of an arteriole constricts the vessel.
- Precapillary sphincters control flow of blood between arterioles and venules.
**Figure 42.15**

**INTERSTITIAL FLUID**

Net fluid movement out

Blood pressure

Osmotic pressure

Arterial end of capillary

Direction of blood flow

Venous end of capillary

Body cell

The difference between blood pressure and osmotic pressure drives fluids out of capillaries at the arteriole end and into capillaries at the venule end.

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**Fluid Return by the Lymphatic System**

- The **lymphatic system** returns fluid that leaks out from the capillary beds.
- Fluid, called lymph, reenters the circulation directly at the venous end of the capillary bed and indirectly through the lymphatic system.
- The lymphatic system drains into veins in the neck.
- Valves in lymph vessels prevent the backflow of fluid.
- **Lymph nodes** are organs that filter lymph and play an important role in the body’s defense.
- Edema is swelling caused by disruptions in the flow of lymph.

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**Blood components contribute to exchange, transport, and defense**

<table>
<thead>
<tr>
<th>Plasma (55%)</th>
<th>Cellular elements (45%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constituent</strong></td>
<td><strong>Major Functions</strong></td>
</tr>
<tr>
<td>Water</td>
<td>Solvent for carrying other substances</td>
</tr>
<tr>
<td>Ions (blood electrolytes)</td>
<td>Osmotic balance, pH buffering, and regulation of membrane permeability</td>
</tr>
<tr>
<td>Sodium</td>
<td>Separated blood elements</td>
</tr>
<tr>
<td>Potassium</td>
<td></td>
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<tr>
<td>Calcium</td>
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<td>Magnesium</td>
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<tr>
<td>Chloride</td>
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<tr>
<td>Bicarbonate</td>
<td></td>
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<tr>
<td>Plasma proteins ( Albumin Fibrinogen Immunoglobulins (antibodies) )</td>
<td>Osmotic balance, pH buffering</td>
</tr>
<tr>
<td></td>
<td>Defense</td>
</tr>
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</tr>
</tbody>
</table>

**Leukocytes**

- There are five major types of white blood cells, or **leukocytes**: monocytes, neutrophils, basophils, eosinophils, and lymphocytes.
- They function in defense by phagocytizing bacteria and debris or by producing antibodies.
- They are found both in and outside of the circulatory system.

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**Blood Clotting**

- Coagulation is the formation of a solid clot from liquid blood.
- A cascade of complex reactions converts inactive fibrinogen to fibrin.

1. Collagen fibers
2. Platelet plug
3. Fibrin clot
4. Red blood cells
5. Thrombin

Clotting factors from: Platelets, Damaged cells, Plasma (factors include calcium, vitamin K).

Enzymatic cascade:

- **Prothrombin**
- **Thrombin**
- **Fibrinogen**
- **Fibrin**
Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** supplies \( O_2 \) for cellular respiration and disposes of \( CO_2 \)
- A gas diffuses from a region of higher partial pressure to a region of lower partial pressure
  - **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases
  - Gases diffuse down pressure gradients in the lungs and other organs as a result of differences in partial pressure

**Respiratory Media and Surfaces**

- Animals can use air or water as a source of \( O_2 \), or respiratory medium
- In a given volume, there is less \( O_2 \) available in water than in air
- Obtaining \( O_2 \) from water requires greater efficiency than air breathing
- Animals require large, moist respiratory surfaces for exchange of gases between their cells and the respiratory medium, either air or water
- Gas exchange across respiratory surfaces takes place by diffusion
- Respiratory surfaces vary by animal and can include the outer surface, skin, gills, tracheae, and lungs

**Gills in Aquatic Animals**

- Gills are outfoldings of the body that create a large surface area for gas exchange

- **Ventilation** moves the respiratory medium over the respiratory surface
- Aquatic animals move through water or move water over their gills for ventilation
- Fish gills use a **countercurrent exchange** system, where blood flows in the opposite direction to water passing over the gills; blood is always less saturated with \( O_2 \) than the water it meets
Tracheal Systems in Insects

- The tracheal system of insects consists of tiny branching tubes that penetrate the body.
- The tracheal tubes supply O₂ directly to body cells.
- The respiratory and circulatory systems are separate.
- Larger insects must ventilate their tracheal system to meet O₂ demands.

Mammalian Respiratory Systems: A Closer Look

- A system of branching ducts conveys air to the lungs.
- Air inhaled through the nostrils is warmed, humidified, and sampled for odors.
- The pharynx directs air to the lungs and food to the stomach.
- Swallowing tips the epiglottis over the glottis in the pharynx to prevent food from entering the trachea.

Lungs

- Lungs are an infolding of the body surface.
- The circulatory system (open or closed) transports gases between the lungs and the rest of the body.
- The size and complexity of lungs correlate with an animal’s metabolic rate.

Gas exchange takes place in alveoli, air sacs at the tips of bronchioles.
- Oxygen diffuses through the moist film of the epithelium and into capillaries.
- Carbon dioxide diffuses from the capillaries across the epithelium and into the air space.
- Alveoli lack cilia and are susceptible to contamination.
- Secretions called surfactants coat the surface of the alveoli.
- Preterm babies lack surfactant and are vulnerable to respiratory distress syndrome; treatment is provided by artificial surfactants.
Breathing ventilates the lungs

- The process that ventilates the lungs is **breathing**, the alternate inhalation and exhalation of air.
- An amphibian such as a frog ventilates its lungs by **positive pressure breathing**, which forces air down the trachea.

Mammals ventilate their lungs by **negative pressure breathing**, which pulls air into the lungs.
- Lung volume increases as the rib muscles and **diaphragm** contract.
- **The tidal volume** is the volume of air inhaled with each breath.

Control of Breathing in Humans

- The medulla oblongata and the pons.
  - The medulla regulates the rate and depth of breathing in response to pH changes in the cerebrospinal fluid.
  - The medulla adjusts breathing rate and depth to match metabolic demands.
  - The pons regulates the tempo.
- Sensors in the aorta and carotid arteries monitor **O\textsubscript{2}** and **CO\textsubscript{2}** concentrations in the blood:
  - These sensors exert secondary control over breathing.

Adaptations for gas exchange include pigments that bind and transport gases.

- The metabolic demands of many organisms require that the blood transport large quantities of **O\textsubscript{2}** and **CO\textsubscript{2}**.
Coordination of Circulation and Gas Exchange

- Blood arriving in the lungs has a low partial pressure of O$_2$ and a high partial pressure of CO$_2$ relative to air in the alveoli.
- In the alveoli, O$_2$ diffuses into the blood and CO$_2$ diffuses into the air.
- In tissue capillaries, partial pressure gradients favor diffusion of O$_2$ into the interstitial fluids and CO$_2$ into the blood.

Respiratory Pigments

- **Respiratory pigments**, proteins that transport oxygen, greatly increase the amount of oxygen that blood can carry.
- Arthropods and many molluscs have hemocyanin with copper as the oxygen-binding component.
- Most vertebrates and some invertebrates use hemoglobin.
- In vertebrates, hemoglobin is contained within erythrocytes.

Respiratory Adaptations of Diving Mammals

- Diving mammals have evolutionary adaptations that allow them to perform extraordinary feats.
  - For example, Weddell seals in Antarctica can remain underwater for 20 minutes to an hour.
  - For example, elephant seals can dive to 1,500 m and remain underwater for 2 hours.
- These animals have a high blood to body volume ratio.
- Deep-diving air breathers stockpile O$_2$ and deplete it slowly.
- Diving mammals can store oxygen in their muscles in myoglobin proteins.
- Diving mammals also conserve oxygen by:
  - Changing their buoyancy to glide passively
  - Decreasing blood supply to muscles
  - Deriving ATP in muscles from fermentation once oxygen is depleted.

- Carbon Dioxide from body tissues diffuses into interstitial fluid and plasma.
- 90% diffuses into RBC.
- Reacts with water to form carbonic acid which dissociates into bicarbonate and hydrogen ions.
- Hemoglobin binds to the hydrogen ions preventing acidification of blood.
- Bicarbonate diffuses into plasma and is carried to lungs.
- Bicarbonate diffuses into RBC and combines with hydrogen released from hemoglobin to form carbonic acid.
- Carbonic acid is converted back to carbon dioxide and water.
- Carbon dioxide is released from hemoglobin and diffuses into plasma and interstitial fluid, then into alveolar space for exhalation.
Cardiovascular Disease

- Cardiovascular diseases are disorders of the heart and the blood vessels
- Cardiovascular diseases account for more than half the deaths in the United States
- Cholesterol, a steroid, helps maintain membrane fluidity

- Low-density lipoprotein (LDL) delivers cholesterol to cells for membrane production
- High-density lipoprotein (HDL) scavenges cholesterol for return to the liver
- Risk for heart disease increases with a high LDL to HDL ratio
- Inflammation is also a factor in cardiovascular disease

Atherosclerosis, Heart Attacks, and Stroke

- One type of cardiovascular disease, atherosclerosis, is caused by the buildup of plaque deposits within arteries

- A heart attack, or myocardial infarction, is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries
- Coronary arteries supply oxygen-rich blood to the heart muscle
- A stroke is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head
- Angina pectoris is caused by partial blockage of the coronary arteries and results in chest pains
**Risk Factors and Treatment of Cardiovascular Disease**

- A high LDL to HDL ratio increases the risk of cardiovascular disease
- The proportion of LDL relative to HDL can be decreased by exercise, not smoking, and avoiding foods with trans fats
- Drugs called statins reduce LDL levels and risk of heart attacks

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