Chapter 42

Circulation and Gas Exchange

PowerPoint® Lecture Presentations for

Biology

Eighth Edition
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Circulation: Gastrovascular Cavities, open and closed circulatory systems

• Simpler Invertebrates use gastrovascular cavity for distribution of substances throughout the body and sometimes also for digestion.

• More complex Invertebrates have either open or closed circulatory systems.

• Both systems have three basic components:
  – A circulatory fluid (blood or hemolymph)
  – A set of tubes (blood vessels)
  – A muscular pump (the heart)
• In insects, other arthropods, and most molluscs, blood bathes the organs directly in an **open circulatory system**

• In an open circulatory system, there is no distinction between blood and interstitial fluid, and this general body fluid is more correctly called **hemolymph**

• In a **closed circulatory system**, blood is confined to vessels and is distinct from the interstitial fluid

• Closed systems are **more efficient** at transporting circulatory fluids to tissues and cells
Heart

Hemolymph in sinuses surrounding organs

Heart

Interstitial fluid

Small branch vessels In each organ

Blood

Dorsal vessel

(main heart)

Pores

Tubular heart

(a) An open circulatory system

Interstitial fluid

Small branch vessels In each organ

Dorsal vessel

(main heart)

Auxiliary hearts

Ventral vessels

(b) A closed circulatory system
Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system, often called the cardiovascular system

- The three main types of blood vessels are arteries, veins, and capillaries

- **Arteries** carry blood to **capillaries**

- Networks of capillaries called **capillary beds** are the sites of **chemical exchange** between the blood and interstitial fluid

- **Veins** return blood from capillaries to the heart
• Vertebrate hearts contain two or more chambers

• Blood enters through an atrium and is pumped out through a ventricle
Fish have two-chambered heart

Hart has always oxygen-poor blood

2 chambers

Artery
Heart
Vein

Systemic circulation
Gill circulation
Gill capillaries
Ventricle
Atrium
Systemic capillaries
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

- Pulmocutaneous circuit
- Lung and skin capillaries

Reptiles (Except Birds)

- Pulmonary circuit
- Lung capillaries
- Right systemic aorta

Mammals and Birds

- Pulmonary circuit
- Lung capillaries
- Left systemic aorta

Partial septum divides ventricle
- In reptiles and mammals, oxygen-poor blood flows through the **pulmonary circuit** to pick up oxygen through the lungs.

- In amphibians, oxygen-poor blood flows through a **pulmocutaneous circuit** to pick up oxygen through the lungs and skin.

- Oxygen-rich blood delivers oxygen through the **systemic circuit**.

- Double circulation maintains **higher blood pressure** in the organs than does single circulation.
Mammalian Circulation

• 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 also 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
Pulmonary veins contain oxygen-rich blood

Pulmonary arteries contain oxygen-poor blood
The Mammalian Heart: A Closer Look

• A closer look at the mammalian heart provides a better understanding of double circulation

• **Four valves** prevent backflow of blood in the heart

• The **atrioventricular (AV) valves** separate each atrium and ventricle and prevent backflow into atria when ventricles contract

• The **semilunar valves** control blood flow to the aorta and the pulmonary artery and prevent backflow into ventricles when ventricles relax
Maintaining the Heart’s Rhythmic Beat

Some cardiac muscle cells are self-excitable (autorhythmic), meaning they contract without any signal from the nervous system. The **sinoatrial (SA) node**, or **pacemaker**, sets the rate and timing at which cardiac muscle cells contract. Impulses from the SA node travel to the **atrioventricular (AV) node**. At the AV node, the impulses are delayed and then travel to the **Purkinje fibers** that make the ventricles contract.
• The pacemaker is influenced by nerves, hormones, body temperature, and exercise.

• 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.
Semilunar valves closed

Atrial systole; ventricular diastole

AV valves open

Semilunar valves open

Atrial and ventricular diastole

0.4 sec

0.1 sec

0.3 sec

AV valves closed

Ventricular systole; atrial diastole

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

2nd heart sound (SL valves close)

1st heart sound (AV valves close)
• The **heart rate (HR)**, also called the **pulse**, is the number of beats per minute.

• The **stroke volume (SV)** is the amount of blood pumped in a single contraction.

• The **cardiac output (CO)** is the volume of blood pumped into the systemic circulation per minute (mL/min) and depends on both the heart rate and stroke volume.

• \[ \text{CO} = \text{SV} \times \text{HR} \]
Concept 42.3: Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels

- The **physical principles that govern movement of water in plumbing systems** also influence the functioning of **animal circulatory systems**
• Capillaries have thin walls to facilitate the exchange of materials

• Arteries and veins have smooth muscle, and connective tissue

• Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart

• In the thinner-walled veins, blood flows back to the heart mainly as a result of muscle action
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.
Regulation of Blood Pressure

- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles.
- Blood pressure is generally measured for an artery in the arm at the same height as the heart.
- Blood pressure for a healthy 20 year old at rest is 120 mm Hg at systole and 70 mm Hg at diastole.
Pressure in cuff greater than 120 mm Hg

Rubber cuff inflated with air

Artery closed

Pressure in cuff drops below 120 mm Hg

Sounds audible in stethoscope

Pressure in cuff below 70 mm Hg

Sounds stop

Blood pressure reading: 120/70
• Fainting is caused by inadequate blood flow to the head

• 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
Direction of blood flow in vein (toward heart)

Valve (open)

Skeletal muscle

Valve (closed)
Capillary Function

- Capillaries in major organs are usually filled to capacity.
- $O_2, CO_2, \text{nutrients mostly diffuse across capillary walls.}$
- Fluid forced out at arterial ends and returned at venous ends.
- Not all fluid returned, rest returned to circulation by lymph vessels.
Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid that leaks out in the capillary beds
- This system **aids in body defense**
- 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**
- **Lymph nodes** are organs that filter lymph and play an important role in the body’s defense
Concept 42.4: Blood components function in exchange, transport, and defense

- **In invertebrates** with open circulation, blood (hemolymph) is not different from interstitial fluid.

- Blood in the circulatory systems of **vertebrates** is a specialized connective tissue.
Blood Composition and Function

- Blood consists of several kinds of cells suspended in a liquid matrix called plasma.
- Plasma is composed mainly of water, and contains dissolved solutes.
- The cellular elements (formed elements) occupy about 45% of the volume of blood.
### Plasma 55%

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Major functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Solvent for carrying other substances</td>
</tr>
<tr>
<td>Ions (blood electrolytes)</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td></td>
</tr>
<tr>
<td>Bicarbonate</td>
<td></td>
</tr>
<tr>
<td>Osmotic balance, pH buffering, and regulation of membrane permeability</td>
<td></td>
</tr>
<tr>
<td>Plasma proteins</td>
<td></td>
</tr>
<tr>
<td>Albumin</td>
<td></td>
</tr>
<tr>
<td>Fibrinogen</td>
<td></td>
</tr>
<tr>
<td>Immunoglobulins (antibodies)</td>
<td></td>
</tr>
<tr>
<td>Substances transported by blood</td>
<td></td>
</tr>
<tr>
<td>Nutrients (such as glucose, fatty acids, vitamins)</td>
<td></td>
</tr>
<tr>
<td>Waste products of metabolism</td>
<td></td>
</tr>
<tr>
<td>Respiratory gases (O₂ and CO₂)</td>
<td></td>
</tr>
<tr>
<td>Hormones</td>
<td></td>
</tr>
</tbody>
</table>

### Cellular elements 45%

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Number per µL (mm³) of blood</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erythrocytes (red blood cells)</td>
<td>5–6 million</td>
<td>Transport oxygen and help transport carbon dioxide</td>
</tr>
</tbody>
</table>

####Separated blood elements

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Number per µL (mm³) of blood</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leukocytes (white blood cells)</td>
<td>5,000–10,000</td>
<td>Defense and immunity</td>
</tr>
<tr>
<td>Basophil</td>
<td></td>
<td>Lymphocyte</td>
</tr>
<tr>
<td>Eosinophil</td>
<td></td>
<td>Neutrophil</td>
</tr>
<tr>
<td>Neutrophil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocyte</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platelets</td>
<td>250,000–400,000</td>
<td>Blood clotting</td>
</tr>
</tbody>
</table>
Cellular Elements

• Suspended in blood plasma are two types of cells:
  – Red blood cells (erythrocytes) transport oxygen
  – White blood cells (leukocytes) function in defense

• Platelets (thrombocytes), a third cellular element, are fragments of cells that are involved in clotting
Erythrocytes

• Red blood cells, or *erythrocytes*, are by far the most numerous blood cells

• They contain *hemoglobin*, the iron-containing protein that transports oxygen

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
$\beta$ Chains

Iron

Heme

$\alpha$ Chains

Hemoglobin
Concept 42.5: Gas exchange occurs across specialized respiratory surfaces

• **Gas exchange** supplies oxygen for cellular respiration and disposes of carbon dioxide

• Animals can use air or water as a source of $O_2$, or respiratory medium

• **Respiratory surface** is a site of gas exchange between body and environment

• **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.

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.
Anatomy of gills

Water flow

Gill arch

Operculum

Gill filaments

Blood vessels

Gill filament organization

Oxygen-poor blood

Oxygen-rich blood

Fluid flow through gill filament

Lamella

Blood flow through capillaries in lamella

Water flow between lamellae

Countercurrent exchange

\( P_{O_2} \) (mm Hg) in water

150 120 90 60 30

Net diffusion of \( O_2 \) from water to blood

\( P_{O_2} \) (mm Hg) in blood

140 110 80 50 20
Tracheal Systems in Insects

The tracheal system of insects consists of tiny branching tubes that penetrate the body. The tracheal tubes supply \( O_2 \) directly to body cells.
Mammalian Respiratory Systems: A Closer Look

- A system of branching ducts conveys air to the lungs
- Air inhaled through the nostrils passes through the pharynx via the larynx, trachea, bronchi, bronchioles, lungs, and alveoli, where gas exchange occurs
How a Bird Breathes

- Birds have eight or nine air sacs that function as bellows that keep air flowing through the lungs.
- Air passes through the lungs in one direction only.
- Every exhalation completely renews the air in the lungs.
Anterior air sacs

Posterior air sacs

Lungs

Air tubes (parabronchi) in lung

EXHALATION
Air sacs empty; lungs fill

INHALATION
Air sacs fill

1 mm
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
(a) Oxygen

- Alveolus: $P_{O_2} = 100$ mm Hg
- Circulatory system: $P_{O_2} = 100$
- $P_{O_2} = 40$
- Body tissue: $P_{O_2} \leq 40$ mm Hg

(b) Carbon dioxide

- Alveolus: $P_{CO_2} = 40$ mm Hg
- Circulatory system: $P_{CO_2} = 40$
- $P_{CO_2} = 46$
- Body tissue: $P_{CO_2} \geq 46$ mm Hg
Thank you for your attention and participation!
You should now be able to:

1. Compare and contrast open and closed circulatory systems

2. Compare and contrast the circulatory systems of fish, amphibians, non-bird reptiles, and mammals or birds

3. Distinguish between pulmonary and systemic circuits and explain the function of each

4. Trace the path of a red blood cell through the human heart, pulmonary circuit, and systemic circuit
5. Define cardiac cycle and explain the role of the sinoatrial node

6. Relate the structures of capillaries, arteries, and veins to their function

7. Define blood pressure and cardiac output and describe two factors that influence each

8. Describe the role played by the lymphatic system in relation to the circulatory system

9. Describe the function of erythrocytes, leukocytes, platelets
10. For humans, describe the exchange of gases in the lungs and in tissues