

B3.2 Transport

Form and function—Organism

Standard level and higher level: 3 hours

Additional higher level: 2 hours

Guiding questions

- What adaptations facilitate transport of fluids in animals and plants?
- What are the differences and similarities between transport in animals and plants?

SL and HL

B3.2.1—Adaptations of capillaries for exchange of materials between blood and the internal or external environment

Adaptations should include a large surface area due to branching and narrow diameters, thin walls, and fenestrations in some capillaries where exchange needs to be particularly rapid.

- **Capillaries** are the smallest blood vessels in the body that are adapted for nutrient and gas exchange
- Blood flows into capillaries from **arterioles** and exits into **venules**
 - Their **thin walls** are composed of a **single layer of endothelial cells** to reduce diffusion distance
 - Endothelial cells have **small pores** between each other to allow nutrients and gases to diffuse from the blood into tissues
 - Some capillaries have **fenestrations** (more frequent and larger pores in their endothelium) where gas/nutrient exchange needs to be particularly rapid in cells with high metabolism (e.g. muscles)
 - Capillaries branch to form **capillary beds** to increase surface area for materials exchange
 - Capillaries have **narrow diameters** to reach most body cells

B3.2.2—Structure of arteries and veins

Application of skills: Students should be able to distinguish arteries and veins in micrographs from the structure of a vessel wall and its thickness relative to the diameter of the lumen.



B3.2.3—Adaptations of arteries for the transport of blood away from the heart

Students should understand how the layers of muscle and elastic tissue in the walls of arteries help them to withstand and maintain high blood pressures.

- Arteries and veins are **vascular structures** with 3 layers of tissue:
 - **Tunica interna (endothelium)**: protective barrier
 - **Tunica media (smooth muscles)**: contains a mixture of smooth muscles and elastic fibers
 - **Tunica externa/adventitia (connective tissue)**: contains lymphatic and nerve structures
- The relative ratios of smooth muscle, elastic fibers, and connective tissue vary significantly between arteries and veins to account for their different functions
- **Arteries** are vessels that carry blood **away** from the heart
 - Arterial blood is oxygenated in systemic circulation & deoxygenated in pulmonary circulation
- Arterial structure makes them adapted to **withstand & maintain high blood pressures**:
 - **High elastic & collagen fiber** content in tunica media leads to **elastic recoil** when blood is pumped from the heart, which stores potential energy and maintains high blood pressures
 - **Narrow arterial lumen** leads to & maintains high blood pressure
 - **Thick tunica externa** allows arteries to withstand high blood pressures

B3.2.4—Measurement of pulse rates

Application of skills: Students should be able to determine heart rate by feeling the carotid or radial pulse with fingertips. Traditional methods could be compared with digital ones.

- Every heartbeat leads to a wave of blood that passes at high blood pressure across blood vessels, which can be felt if the vessel is close to the body surface
- Measuring **carotid and radial pulses** with fingertips is used to count heart beats per minute
- **Pulse oximetry** is a digital method that uses infrared and red light to measure heart rate & oxygen saturation

B3.2.5—Adaptations of veins for the return of blood to the heart

Include valves to prevent backflow and the flexibility of the wall to allow it to be compressed by muscle action.

- **Veins** are vessels that carry blood **towards** the heart
 - Venous blood is deoxygenated in systemic circulation & oxygenated in pulmonary circulation
- Veinous structure makes them adapted to **return blood to the heart & prevent backflow**:
 - **Large venous lumen** maintains low blood pressure to allow for higher blood flow to the heart
 - **Valves** prevent the backflow of blood & ensure unidirectional flow to the heart
 - Veins have **flexible walls** because they are **situated near skeletal muscles**, which upon contraction compress veins to assist with blood flow
 - **Low elastic and collagen fiber** content since blood flows at low pressures

B3.2.6—Causes and consequences of occlusion of the coronary arteries

Application of skills: Students should be able to evaluate epidemiological data relating to the incidence of coronary heart disease.

- **Coronary arteries** supply oxygenated blood & nutrients to cardiac muscles
- **Occlusion** (narrowing of lumen) of coronary arteries is caused by **fatty deposits** building up in the **tunica intima** (but can spread to deeper vascular layers) of these arteries
- The **plaques** (accumulated fatty deposits) weaken the endothelial lining by reducing its elasticity & strength, which increases its risk of rupture
- Rupture of the endothelial wall leads to the formation of a clot in the occluded coronary artery, which can become dislodged and block blood flow to the heart (leading to a heart attack)
- **Risk factors** of coronary arteries occlusion: hypertension (high blood pressure), nutrition, sedentary lifestyle, smoking, obesity

NOS: Students should understand that correlation coefficients quantify correlations between variables and allow the strength of the relationship to be assessed. Low correlation coefficients or lack of any correlation could provide evidence against a hypothesis, but even strong correlations such as that between saturated fat intake and coronary heart disease do not prove a causal link.

- Epidemiological data show positive correlations between saturated fat intake and coronary heart disease (CHD), but they do not provide causal links since other factors can affect CHD incidence
- **Correlation coefficients (R^2)** quantify correlations between variables and allow the strength of the relationship to be assessed
- **Low correlation coefficients** (i.e. close to zero) or lack of any correlation (i.e. zero) can provide evidence against a hypothesis
- **Strong correlations (i.e. close to 1)** establish correlational but not causal links between 2 variables as other **confounding variables** can affect the relationship between the 2 variables

B3.2.7—Transport of water from roots to leaves during transpiration

Students should understand that loss of water by transpiration from cell walls in leaf cells causes water to be drawn out of xylem vessels and through cell walls by capillary action, generating tension (negative pressure potentials). It is this tension that draws water up in the xylem. Cohesion ensures a continuous column of water.

- Transpiration leads to water loss by evaporation from the cell walls of mesophyll cells
- Water is replenished by being drawn out of xylem vessels and through cell walls by **capillary action**
- This creates **tension (negative pressure potentials)** that draws water up in the xylem
- **Cohesion** of water molecules ensures the entire xylem column moves up in a **continuous stream**

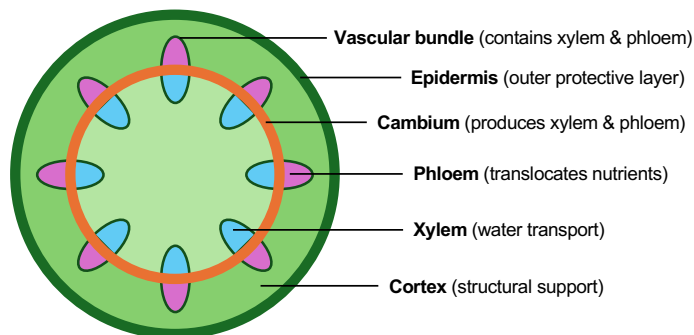
B3.2.8—Adaptations of xylem vessels for transport of water

Include the lack of cell contents and incomplete or absent end walls for unimpeded flow, lignified walls to withstand tensions, and pits for entry and exit of water.

- **Xylem vessels** transport **xylem sap** (water with minerals ions) from roots to leaves
- Xylem walls are composed of a column of cells that undergo programmed cell death upon maturity, **losing their cell contents & end walls** to form **hollow tubes for unimpeded water flow**
- **Lignin** is a polymer in xylem cell walls that provides reinforcement & structural support to xylem vessels, which enables them to withstand high tension
- **Pits** are unligified, small porous openings in the cell walls of xylem that allow for the passage of water (but not air) between xylem and surrounding tissue

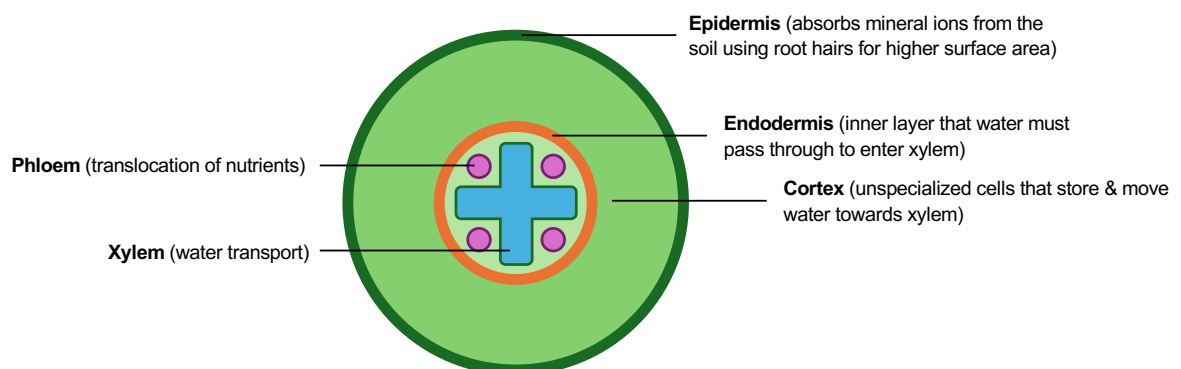
B3.2.9—Distribution of tissues in a transverse section of the stem of a dicotyledonous plant

Application of skills: Students should be able to draw plan diagrams from micrographs to identify the relative positions of vascular bundles, xylem, phloem, cortex and epidermis. Students should annotate the diagram with the main functions of these structures.



B3.2.10—Distribution of tissues in a transverse section of the root of a dicotyledonous plant

Application of skills: Students should be able to draw diagrams from micrographs to identify vascular bundles, xylem and phloem, cortex and epidermis.

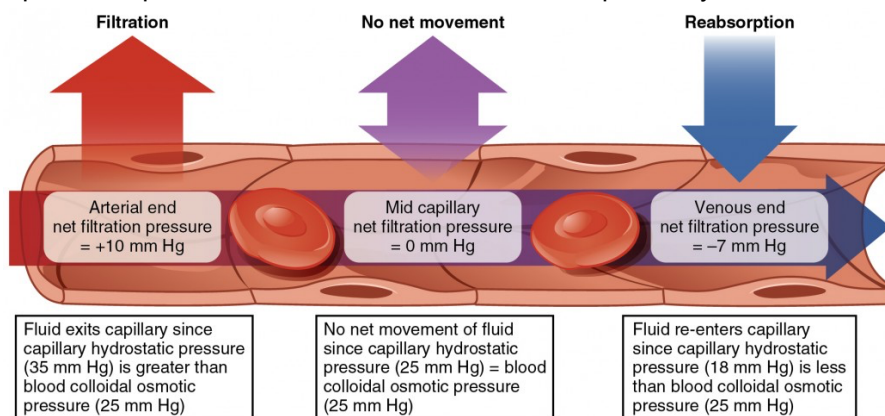


Additional higher level

B3.2.11—Release and reuptake of tissue fluid in capillaries

Tissue fluid is formed by pressure filtration of plasma in capillaries. This is promoted by the higher pressure of blood from arterioles. Lower pressure in venules allows tissue fluid to drain back into capillaries.

- **Hydrostatic pressure** is the pressure exerted by fluid (blood or interstitium) against vessel walls
- The heart pumps blood to generate pressure and drive blood flow throughout the vascular system
- **Blood pressure** is highest at the arteriolar end and lowest at the venular end of the capillary
- **Interstitial hydrostatic pressure** has a value between arterial and venular blood pressure
- **Net filtration pressure (NFP)** is the difference between blood and interstitial hydrostatic pressure, which determines the movement of fluids between capillaries & surrounding interstitium/fluid
 - **NFP > 0 (positive; arteriolar end)** causes net filtration out of capillaries (from blood to interstitium) in order to deliver nutrients and oxygen to tissues
 - **NFP < 0 (negative; venular end)** causes net filtration into capillaries (from interstitium to blood) in order to expel waste products from tissues that can be transported by blood for renal excretion



B3.2.12—Exchange of substances between tissue fluid and cells in tissues

Discuss the composition of plasma and tissue fluid.

- **Plasma** is the liquid & major component of blood that contains nutrients, plasma proteins, & hormones
- **Tissue fluid** surrounds body cells and is formed when fluid is filtered out of capillaries
 - Lacks plasma proteins since capillary pores prevent their filtration out of blood

B3.2.13—Drainage of excess tissue fluid into lymph ducts

Limit to the presence of valves and thin walls with gaps in lymph ducts and return of lymph to the blood circulation.

- The **lymphatic system** is an **open transport system** that drains excess tissue fluid from capillary filtration & returns it to the cardiovascular system
- Tissue fluid becomes **lymph** when it enters **lymph vessels**, which are adapted for drainage:
 - **Valves** ensure unidirectional flow towards blood circulation
 - **Thin walls with gaps** facilitate the movement of tissue fluid into the lymphatic system
- Lymph vessels eventually converge to form the **left & right lymphatic ducts**, which drain into blood circulation via the **subclavian veins**

B3.2.14—Differences between the single circulation of bony fish and the double circulation of mammals

Simple circuit diagrams are sufficient to show the sequence of organs through which blood passes.

- Fish have a **single circulation system**:
 - **2-chambered heart** pumps deoxygenated blood to gills via **afferent arteries** (the gills can withstand high pressure, unlike mammalian lungs, because ventilation by water reduces risk of capillary rupture)
 - Gills carry out gas exchange & oxygenated blood is transported via **efferent arteries** to other organs at low pressure
 - Deoxygenated blood returns from the organs to the heart via veins
- Mammals have a **double circulation system**:
 - **4-chambered heart** pumps deoxygenated blood from the right ventricle to the **pulmonary circulation** via the **pulmonary artery**
 - The pulmonary artery delivers deoxygenated blood to the lungs, which carry out gas exchange and return oxygenated blood to the left side of the heart via the **pulmonary vein**
 - The **left ventricle pumps** oxygenated blood to the **systemic circulation** via the **aorta** to deliver nutrients to body cells that carry out nutrient exchange and return deoxygenated blood to the right side of the heart via the **vena cava**
- There are advantages to a double circulation system in mammals:
 - Blood can be pumped to the lungs at **lower pressure to prevent capillary rupture**
 - Blood can be pumped to organ systems at **higher pressure which increases transport efficiency**
 - Complete separation of oxygenated & deoxygenated blood enables tissues to receive blood that has maximum oxygen saturation to **meet high metabolic needs**

B3.2.15—Adaptations of the mammalian heart for delivering pressurized blood to the arteries

Include form–function adaptations of these structures: cardiac muscle, pacemaker, atria, ventricles, atrioventricular and semilunar valves, septum and coronary vessels. Students should be able to identify these features on a diagram of the heart in the frontal plane and trace the unidirectional flow of blood from named veins to arteries.

- **Cardiac muscle** spreads electrical signals to other **cardiomyocytes** & generates contractile force by:
 - **Intercalated discs** that enable **electric coupling** (simultaneous depolarization) of cardiomyocytes
 - **Branching** of cardiomyocytes that enable **coordinated contraction**
- **Pacemaker cells** in the **sinoatrial (SA) node** initiate each heartbeat by **rhythmic depolarization** because they are **myogenic** (do not require nervous system input to depolarize)
- **Atria** are composed of thin walls as they receive blood from the veins & pump it to the ventricles
- **Ventricles** are composed of thick walls in order to generate a strong contractile force
 - **Left ventricle is thicker** than the right ventricle as it pumps to systemic circulation at higher pressure
- **Septum** separates the left & right heart sides to prevent mixing of oxygenated & deoxygenated blood
- **Atrioventricular valves** are located between the atria & ventricles to prevent blood backflow during ventricular contraction
- **Semilunar valves** are located between the ventricles & arteries to prevent blood backflow from the aorta & pulmonary artery
- **Coronary vessels** provide oxygenated blood with nutrients to the heart & remove waste from it

B3.2.16—Stages in the cardiac cycle

Application of skills: Students should understand the sequence of events in the left side of the heart that follow the initiation of the heartbeat by the sinoatrial node (the “pacemaker”). Students should be able to interpret systolic and diastolic blood pressure measurements from data and graphs.

- The **cardiac cycle** describes the sequence of the events in one heartbeat

1. Atrial systole:

- Atrial contraction occurs when electrical signals from the SA node depolarize atrial cardiomyocytes
- Pressure builds up in the atria due to contraction, which forces more blood into the ventricles through the (already open) AV valves

2. Isovolumetric ventricular systole:

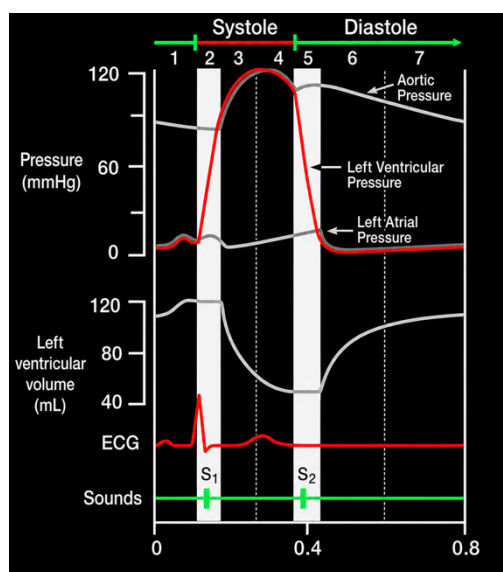
- Ventricles depolarize & contract when delayed signals from the SA node reach their cardiomyocytes
- Ventricular contraction leads to the closer of the AV valve when intraventricular pressure exceeds atrial pressure, producing the **first heart sound (S1; ‘lub’)**
- Semilunar valve remains closed; blood volume does not change but pressure increases

3. Ventricular ejection:

- Semilunar valve opens when intraventricular pressure exceeds aortic pressure
- Blood is ejected into the aorta/pulmonary artery at high pressure
- **Systolic pressure** is the blood pressure measured during left ventricular ejection (when the semilunar valve is open)

4. Ventricular diastole:

- Ventricles relax as they enter the refractory period after depolarization
- Semilunar valve closes when intraventricular pressure decreases due to diastole, producing the **second heart sound (S2; ‘dub’)**
- AV valve opens when intraventricular pressure becomes lower than atrial pressure, causing **passive ventricular filling**
- **Diastolic pressure** is blood pressure measured during ventricular diastole (when semilunar valves are closed)



B3.2.17—Generation of root pressure in xylem vessels by active transport of mineral ions

Root pressure is positive pressure potential, generated to cause water movement in roots and stems when transport in xylem due to transpiration is insufficient, for example when high humidity prevents transpiration or in spring, before leaves on deciduous plants have opened.

- Transpiration pull is not always sufficient/present to cause water movement in xylem vessels:
 - **High humidity** may decrease transpiration rates sufficiently enough to disturb xylem transport
 - At **night**, most plants **close their stomata**, preventing transpiration
 - **Deciduous plants** are **leafless** (i.e. no stomata so no transpiration) in the winter
- Plants overcome this by generating root pressure in xylem vessels
 - Root cells adjacent to xylem vessels **pump mineral ions** into xylem by active transport
 - Mineral ions cause movement of water by osmosis into xylem, which creates a **positive pressure potential in roots** that makes xylem sap move upwards against gravity

B3.2.18—Adaptations of phloem sieve tubes and companion cells for translocation of sap

Include sieve plates, reduced cytoplasm and organelles, no nucleus for sieve tube elements and presence of many mitochondria for companion cells and plasmodesmata between them. Students should appreciate how these adaptations ease the flow of sap and enhance loading of carbon compounds into phloem sieve tubes at sources and unloading of them at sinks.

- **Phloem sap** contains sugars, proteins, & plant hormones that are transported from sources to sinks
 - **Sources** are plant structures that photosynthesize & produce organic compounds, like leaves
 - **Sinks** are plant structures receive organic compounds, like roots
- **Translocation** is the mechanism by which phloem sap moves in the plant
 - **Palisade mesophyll cells** produce sugars & transport them to companion cells via **plasmodesmata** (small cytoplasmic channels that allow substances to move between connected plant cells)
 - **Companion cells** actively **load sucrose** into phloem sieve tube elements/cells
 - Contain **many mitochondria** to meet the energy demands for active transport
 - **High metabolic activity** to support the functioning of phloem sieve tube elements/cells
 - Contain **larger than normal plasmodesmata** to facilitate sucrose loading & unloading
 - **Phloem sieve tube elements/cells** are adapted for phloem sap transport
 - Contain **minimal organelles** to allow room for transport
 - Adjacent elements/cells are connected to each other by **sieve plates** (cell wall perforations) to facilitate movement of phloem sap
 - **Strong cell walls** that can withstand high pressures
 - **Sucrose loading** into phloem sieve tube elements draws in water from adjacent cells (like xylem vessels) by osmosis
 - Water cannot be compressed so **hydrostatic pressure increases**, causing water to move to areas of lower pressure (i.e. towards sinks, like roots)
 - **Sucrose unloading** occurs at sinks by active transport, which reduces hydrostatic pressure & draws water out of phloem sieve tube elements into adjacent cells (like xylem)

Linking questions

- How do pressure differences contribute to the movement of materials in an organism?
- What processes happen in cycles at each level of biological organization?

Review questions

SL and HL

- Compare the adaptations of xylem vessels and arteries. [2]
- Outline the causes of coronary artery occlusion. [3]
- Describe the adaptations of capillaries for exchange of materials between blood and body tissues. [4]
- Describe the adaptations of arteries for the transport of blood away from the heart. [4]
- Describe the adaptations of veins for the transport of blood towards the heart. [4]

Additional Higher Level

- Explain the effect of a genetic defect that leads to a hole in the septum of the heart. [2]
- Explain why generation of root pressure in xylem vessels by active transport of mineral ions is required. [3]
- Compare and contrast the circulation systems in fish and mammals. [4]
- Describe the adaptations of phloem sieve tubes and companion cells for translocation of sap. [6]
- Explain how fluid moves along a capillary. [6]
- Describe the differences between the single circulation of bony fish and the double circulation of mammals. [8]
- Describe the events in the cardiac cycle. [8]
- Describe the adaptations of the mammalian heart for delivering pressurized blood to arteries. [8]
- Describe phloem translocation. [8]
- Discuss the role of pressure differences in the transport of materials in plants and mammals. [8]

References

Ann Clark, Mary, et al. *Biology 2e*. E-book, OpenStax, 2018, <https://openstax.org/books/biology-2e/pages/1-introduction>. OpenStax.

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