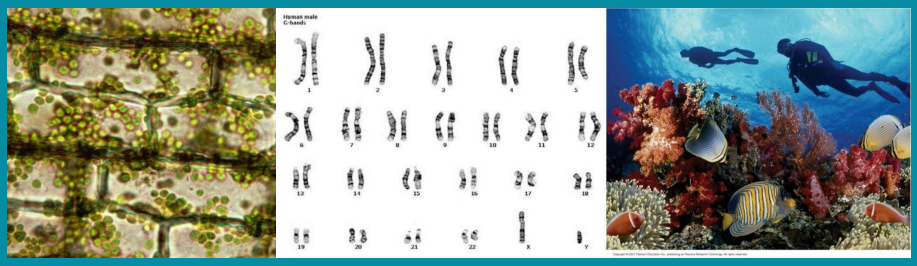
SLE 132 – Form and Function
The Circulatory System



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Learning Objectives

- Understand the need for circulatory system and the limits of diffusion.
- Describe the functions of circulatory systems and the different types of circulatory systems.
- Describe the different vertebrate circulatory systems
- Understand the features of the double circulatory system of mammals and the advantages of double circulatory systems.
- Identify the structures of:
  blood vessels and the heart and how this relates to their function.
- Understand the cardiac cycle and the sequence of events that regulated the beating of the heart

Learning Objectives

- Describe arterial blood pressure and its measurement.
- Understand regulation of blood flow through different tissues.
- Describe the exchange of material between capillaries and interstitial fluid the tissues.
- Describe the components of the blood and the functions of red blood cells, white blood cells and platelets.

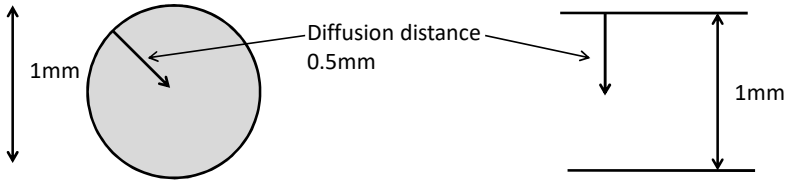
The need for a circulatory system

- The problem:
  - The need to exchange nutrients, oxygen, wastes and carbon dioxide between cells and the environment
  - Diffusion (the movement of molecules from areas of high concentration to areas of lower concentration) is the way these molecules enter and leave cells
  - Diffusion of materials across cell membranes is the simplest means of exchange

Diffusion alone is not an adequate mechanism in large complex animals

•For example the exchange of oxygen

- Oxygen diffuses very slowly
- Diffusion distance for oxygen is about 0.5mm in most animal tissues
- Basically limits the size of any organism to quite a small size or thickness



Larger organisms need a transport system

A transport system = circulatory system

- Needs to be able to distribute gases and other chemicals including nutrients around the body

- **Must come in close contact with every cell of the body**

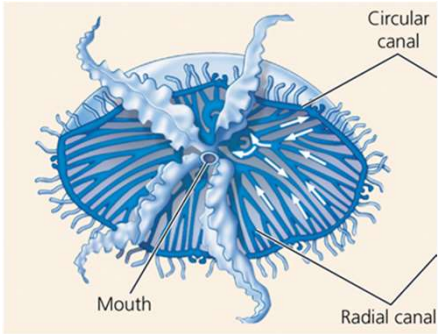
Functions of circulatory systems

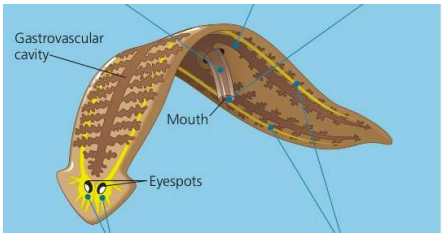
- **Transport** of oxygen and carbon dioxide to/from cells
- **Supply of nutrients** to cells (Glucose, AAs)
- **Waste removal** – e.g. Ammonia (NH_3), lactic acid
- **Homeostasis** (keeping the internal environment constant – temperature and pH)
- **Transport of hormones** – which control functioning of some organs
- **Defence against disease** – e.g. White blood cells

Types of transport systems

1. No Circulatory system

- Simply a very branched gastrovascular cavity
- Materials and gases **exchanged directly** across outer surface or via gastrovascular cavity
- Examples
  - Cnidarians: Hydra, sea jellies
  - Platyhelminthes (flatworms)



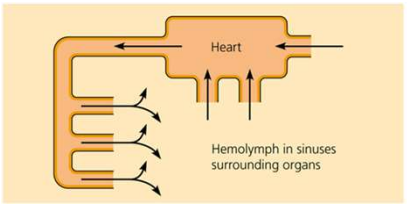


Types of transport systems

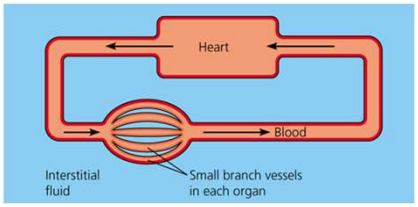
2. Circulation in blood vessels

- Requires some form of pump – a heart
- Requires a specialised circulatory fluid – blood
- Requires a set of tubes – blood vessels

Open Circulatory system

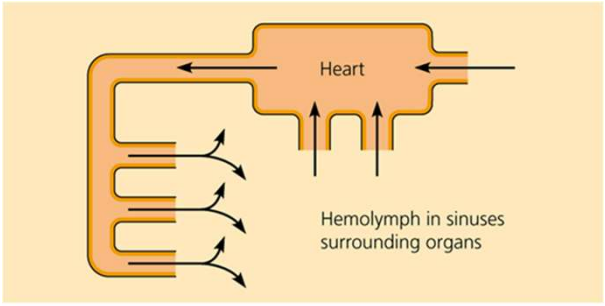


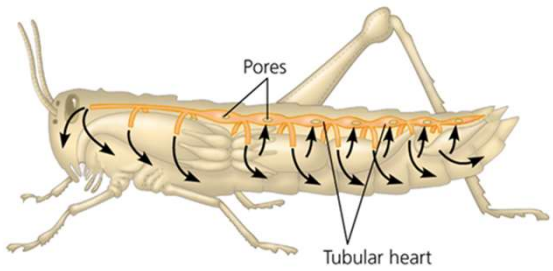
Closed circulatory system



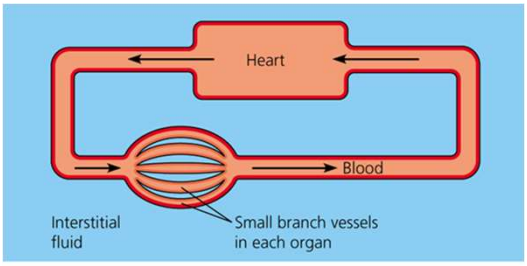
Open Circulatory System

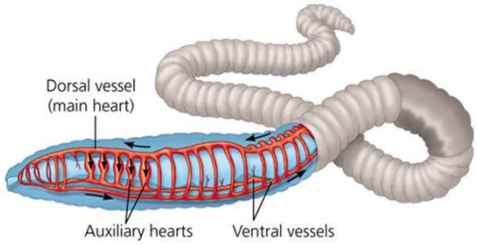
- Fluid is pumped through vessels then out among cells
- 'Blood' and interstitial fluid are the same and called **haemolymph**
- Nutrients diffuse from haemolymph directly into cells
- When heart relaxes, haemolymph returns (valves stop backflow)
- Examples
  - Arthropods e.g insects, crustaceans
  - Most molluscs





Closed Circulatory Systems





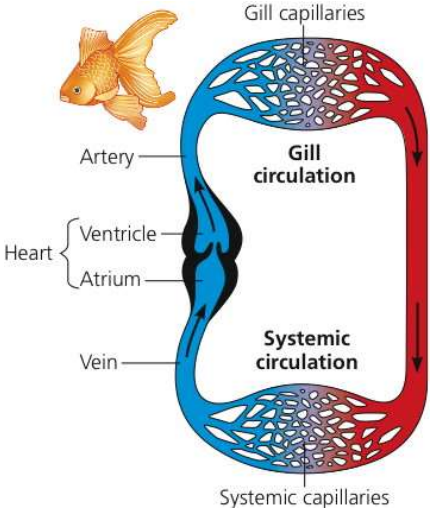
Example 1 – Annelids
e.g. Earthworms

- Specialised fluid '**blood**' inside blood vessels
- Materials move between blood and interstitial fluid and then between fluid and cells

Closed Circulatory Systems

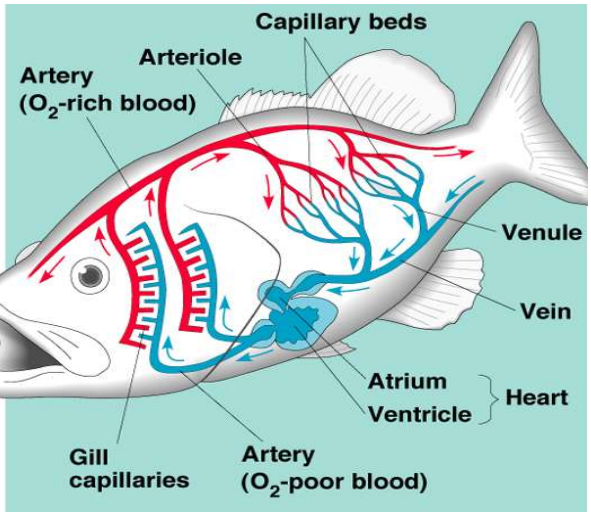
Example 2: Vertebrate e.g. Fish

- One heart with <u>2 main chambers</u>: atrium and ventricle
- Blood circulates in a single loop
- Oxygen poor blood is pumped through heart into gills
- Counter-current exchange at gills



Problems with a single closed circulatory system

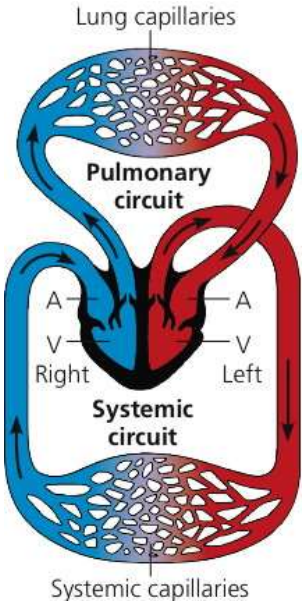
- Large blood pressure drop in the capillaries of the gills
- Low blood pressure in the tissues
  - Means a slow supply of oxygen to the tissues with limits the activity of animals



Evolution of the double circulatory system

Double circulatory systems

- High blood pressure in both parts of the system
- Maintains vigorous supply to brain, muscles and other organs
- Blood returns (oxygenated) to the heart from the lungs before being pumped out to the organs

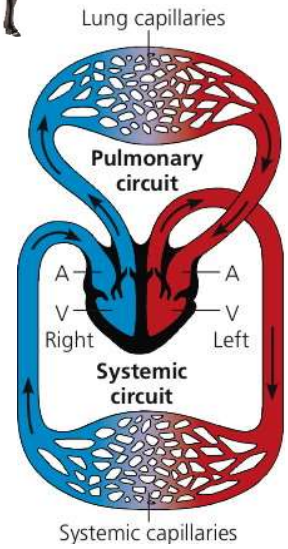


Closed Circulatory Systems

Example 3: Vertebrate Amphibians and Reptiles

- Have double circulation
- Partial separation of oxygenated and deoxygenated blood
- Amphibians have partial division of ventricle **(3 chambered heart)**
- Reptiles have partial division of ventricle as well **(still only 1)**
  - Except for crocodiles which show complete division of the heart **(4 chambers)**

Closed Circulatory Systems



Example 4: Birds and Mammals... & crocs!

- Two atria and Two ventricles **(4 chambers)**
- Complete double circulation
  - No mixing of oxygenated and deoxygenated blood
- This allows for:
  - Higher blood pressure
  - Higher flow rates
  - Quicker delivery of blood to all organs
  - The support of more active animals (high metabolic rates)

Comparing Closed and Open Systems

Closed Systems	Open System
• Blood	• Haemolymph
• Small volume circulated (mammals 7 – 10% of body fluid)	• Large volume circulated (crayfish 25% of body weight, gastropods 90%)
• High blood pressure (Humans, 125/75 mmHg)	• Low pressure system (crayfish 13/1 mmHg)
• High circulation velocity (Humans 21 seconds)	• Low Circulation velocity (crayfish 8 minutes)
• Can control supply of blood to different parts of the body (e.g. In exercise blood to muscles, away from gut)	•Limited ability to regulate flow to different parts of the body

Quick Question

Which of the following is an incorrect statement about circulatory systems?

a) All hearts consist of 4 chambers.
b) Both blood and haemolymph are types of circulatory fluid.
c) Some organisms don't need a circulatory system.
d) They must come in contact with every cell within the body.

Quick Question

Organisms in which a circulating body fluid is distinct from the fluid that directly surrounds the body's cells are likely to have:

a) An open circulatory system
b) A closed circulatory system
c) A gastrovascular cavity
d) Haemolymph

Quick Question

Which of the following are the only vertebrates in which blood flows directly from respiratory organs to body tissues without first returning to the heart?

a) amphibian
b) birds
c) fish
d) mammals

3 Kinds of Blood Vessels

Arteries

- Carry blood – heart to organ (Away from heart)
- In organs: arteries branch into arterioles

Capillaries

- Form capillary beds
- Site of gas exchange

Veins

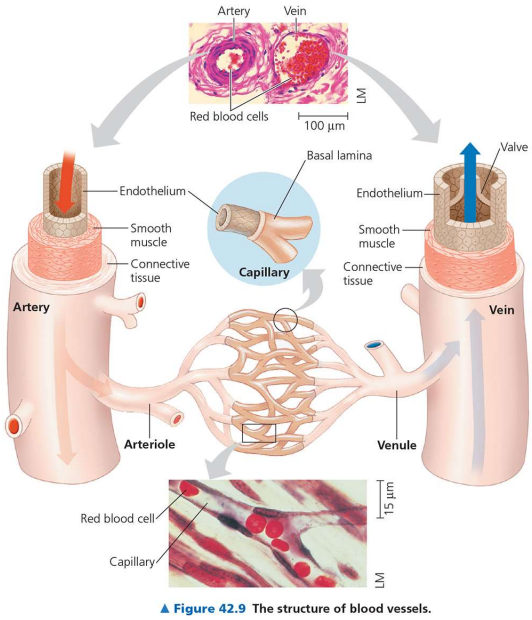
- Carry blood from organs back to the heart
- In organs venules converge into veins

Structure of blood vessels

Arteries and veins have 3 layers of tissue:

- **Epithelium** (endothelium) - which is simple squamous epithelium
- **Smooth muscle**
- **Connective tissue** outside

- The central hole of each vessel is called the **lumen**

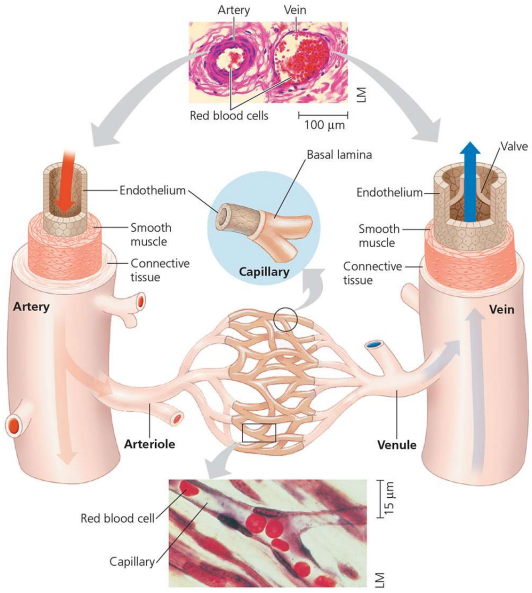


▲ **Figure 42.9** The structure of blood vessels.

Structure of blood vessels

Capillaries are very small

- lack muscle and connective tissue layers
- Very thin layer of epithelial cells on basement membrane only
- Allows for exchange



▲ **Figure 42.9** The structure of blood vessels.

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Activity 1 - Comparing Arteries and Veins

Use the information on the following two slides (or Figure 42.9 page 955 in the textbook) to complete the following table.

	Veins	Arteries
Direction blood is carried		
Wall thickness		
Lumen size		
Valves		
Pressure		

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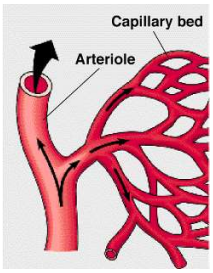
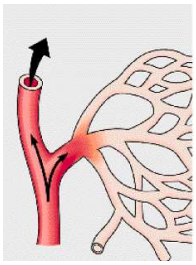
Control of blood flow in capillaries

- At any one time only 5 – 10% of capillaries have blood flowing through them
- Blood flow into capillary beds is controlled in 2 ways

1. There is **dilation and constriction** of smooth muscle of arterioles

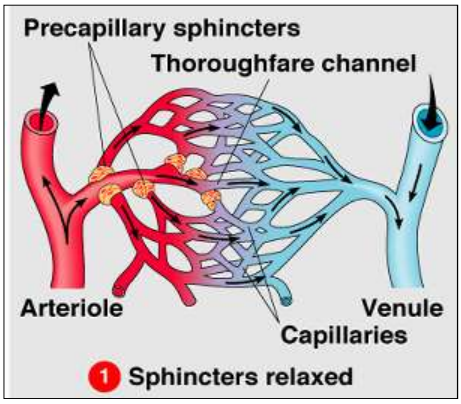


Relaxation of muscle of arteriole

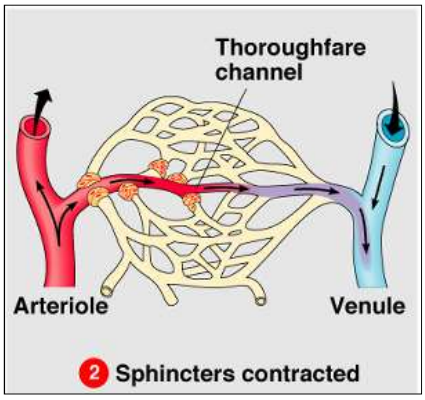


Contraction of the muscle of arteriole - restricting blood into capillary bed

2. Pre-capillary **sphincters** (ring-like valves in a muscular tube) and thoroughfare channels



Blood flows through a capillary bed when its pre-capillary sphincters are relaxed

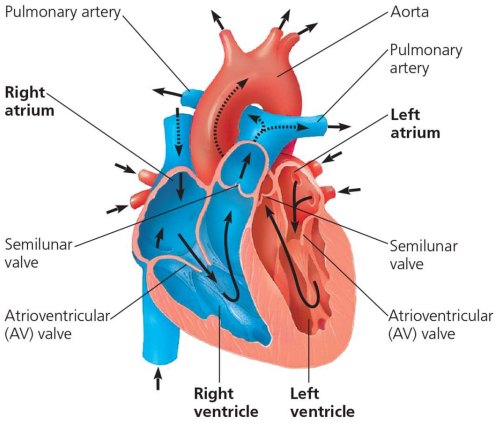


Blood bypasses the capillary bed when the sphincters are contracted *e.g. during strenuous exercise many of the capillaries in the digestive tract are closed off, blood diverted to skeletal muscle*

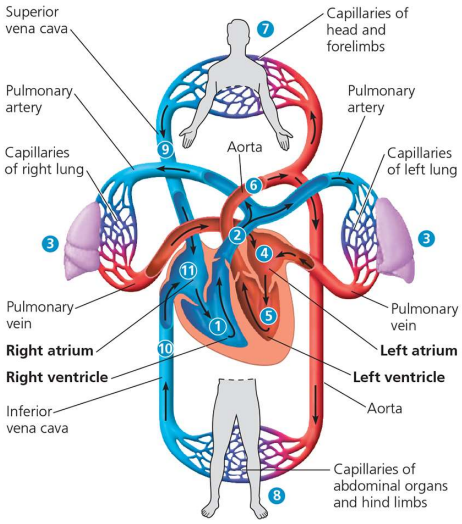
Fig. 42.13

From before class activity: The Mammalian heart

- **Atria** - Collect blood, have thin walls (only pump to nearby ventricles)
- **Ventricles** have thick muscular walls, contract more strongly (sending blood outwards)
- Left ventricle much thicker than right ventricle (pumps out to tissues)
- **Valves** to prevent backflow



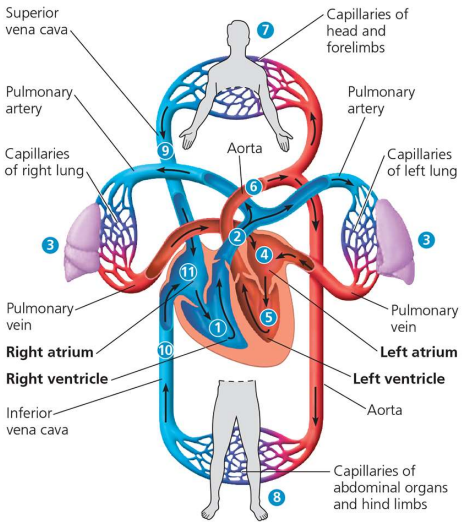
▲ **Figure 42.6 The mammalian heart: a closer look.** Notice the locations of the valves, which prevent backflow of blood within the heart. Also notice how the atria and left and right ventricles differ in the thickness of their muscular walls.



▲ **Figure 42.5 The mammalian cardiovascular system: an overview.** Note that the dual circuits operate simultaneously, not in the serial fashion that the numbering in the diagram suggests. The two ventricles pump in unison; while some blood is travelling in the pulmonary circuit, the rest of the blood is flowing in the systemic circuit.

Blood Flow through the mammalian cardiovascular system

1. **Right ventricle** pumps de ox blood to the lungs via
2. The **Pulmonary arteries**.
3. **Capillary beds** load O_2 and unload CO_2.
4. O_2 rich blood flows into **left atrium**
5. **Left ventricle** pumps oxygenated blood out to the **tissues** (7 & 8). Blood gives up O_2 and picks up CO_2.



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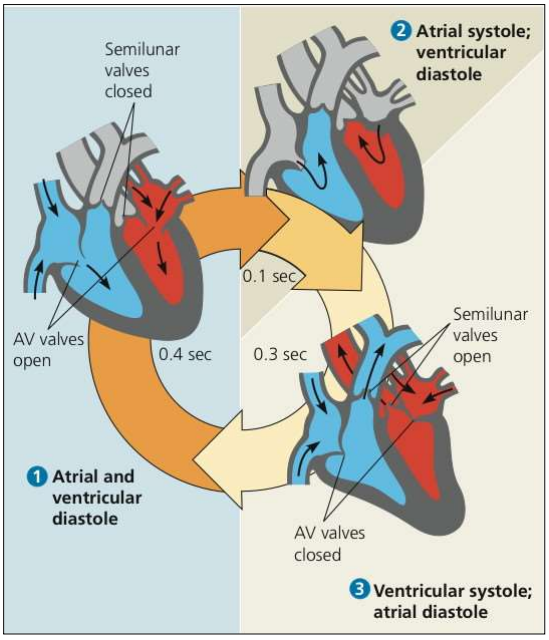
Blood Flow through the mammalian cardiovascular system

9. Oxygen poor blood from head neck and forelimbs is channelled to **Superior Vena Cava**.
10. **Inferior Vena Cava** drains blood from the trunk and hind limbs.
11. The two Vena Cava empty into the **Right atrium.**
12. Cycle repeats.

The Cardiac cycle

A complete heartbeat from its generation to the beginning of the next.

- contraction called **systole**
- relaxation called **diastole**.

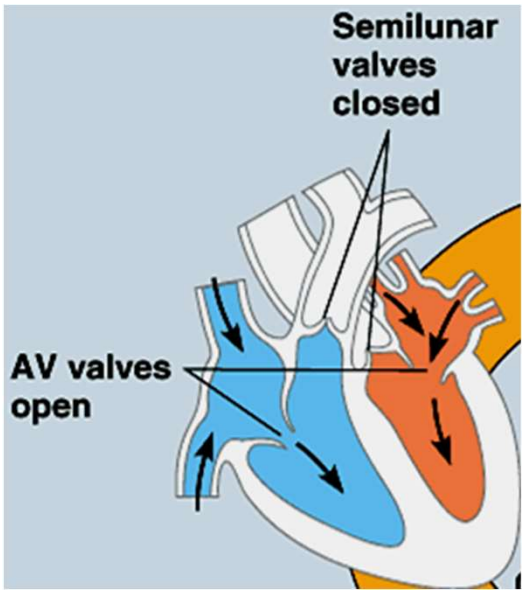


The mammalian heart – cardiac cycle

- The heart contracts and relaxes in a rhythmic cycle
- cardiac cycle duration of 0.8 seconds, which works out at ~75 beats per minute

Diastole – (**filling** - 0.4 seconds)

- heart is relaxed & **atrio-ventricular valves** (into ventricles) **are open**
- **Semilunar valves** (leading out of ventricles) **are closed**
- Blood flows into the atria
  - Right atrium from the vena cava
  - Left atrium from the pulmonary veins
- And then into the ventricles



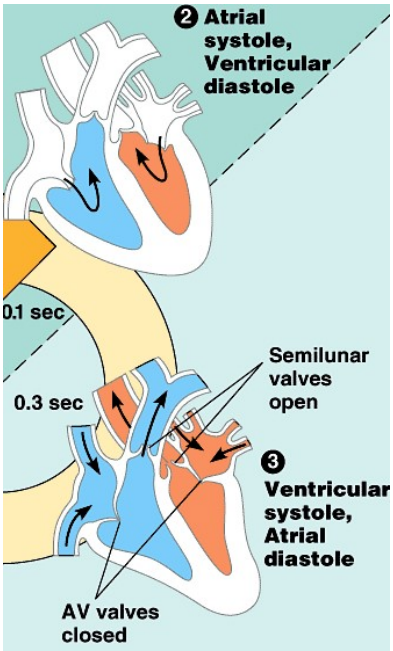
Systole (= *contraction*)

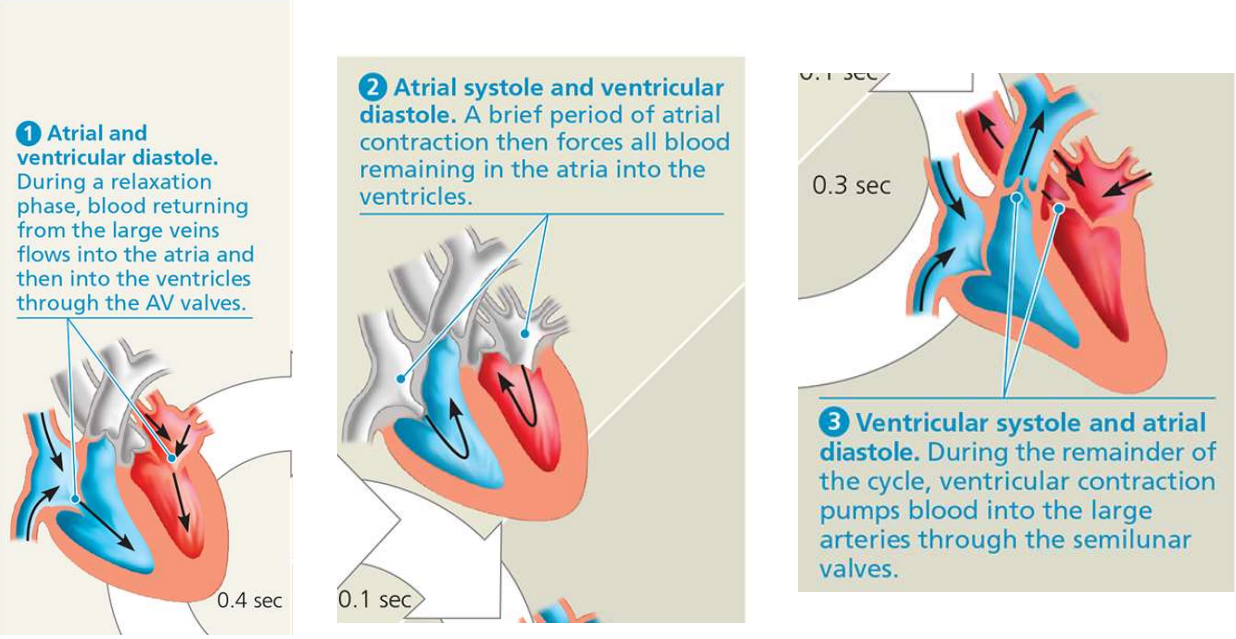
Atrial systole (**Fills Ventricles**)

- lasts 0.1 seconds
- contraction of the atria forces more blood into the ventricles

Ventricular systole (**pushes blood out**)

- lasts about 0.3 seconds
- Contraction of ventricles closes atrioventricular valves
- And opens semilunar valves
- Rapid ejection of blood into the arteries
  - This provides the PULSE (pressure wave)





Cardiac Output

- Cardiac output = the volume of blood the left ventricle pumps per minute, e.g. average person:

volume	**x**	**heart rate**
~75 ml	**x**	**~70 beats/min = 5.25 L/min**

- Cardiac output is altered by:
  - activity levels (strenuous exercise can lead to a 5 fold increase)
  - hormones e.g. adrenalin
  - other chemicals e.g. caffeine
  - drugs e.g. beta-blockers

Regulation of the heart beat

- cardiac muscle can contract spontaneously but it needs some form of coordination

- There are two types of heart regulation:
  - By **pacemaker cells** in heart
    -> coordinated & regular beat
  - By **nervous messages** from brain
    e.g.: to increase heart rate/cardiac output in exercise
    (provides a way for heart to respond to external stimuli)
    - **2 sets of nerves:** 1 set speeds up heart // 1 set slows it down
  - *Hormones e.g. Adrenalin influence pacemaker*

- Two parts of heart responsible for regulation:
  - **Sinoatrial (SA)** node: a specialized region of cardiac muscle with pacemaker cells
  - Responsible for establishing rate of heart beat
  - **Atrioventricular (AV)** node:
    a larger node controlling ventricular contraction

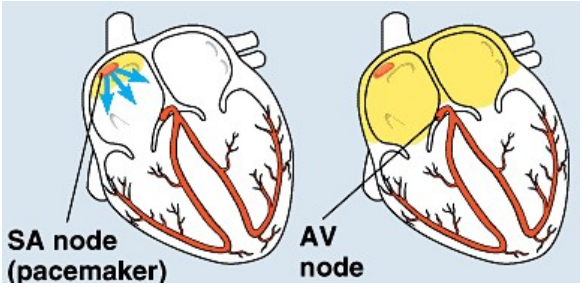


Fig.42.8

Regulation of the heart beat

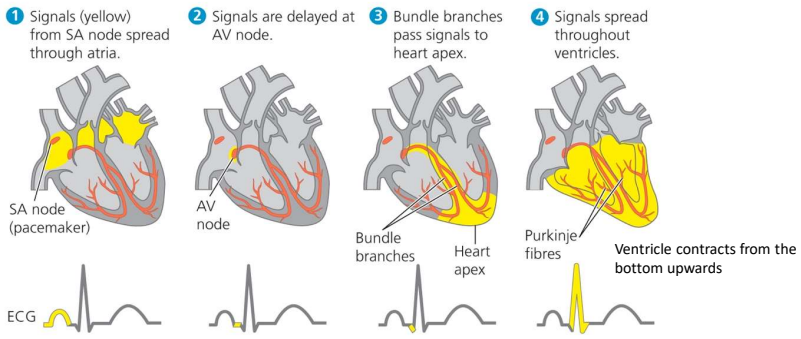


Fig. 42.8

Sequence of events

1. Pacemaker cells **generate electrical signals**
2. **Signals spread quickly** over both atria which contract together
3. The signals pass through the **atrioventricular node** (where signal is delayed 0.1 sec)
4. Specialised muscle fibres **carry the signal** to the cardiac muscle of the ventricles
5. **Ventricles contract**.

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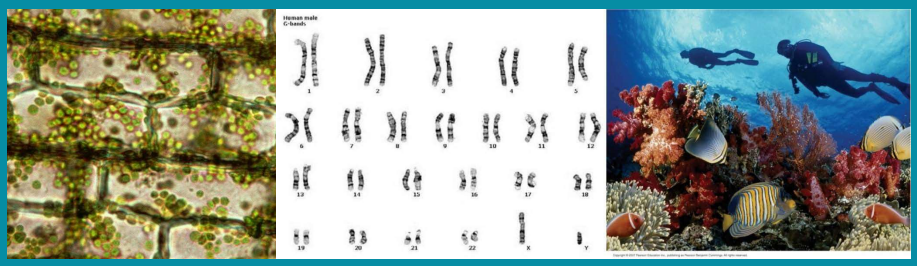

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So how does blood return to the heart?

- Low pressure in heart during diastole
  - blood flows into heart
- Contraction of skeletal muscles including those involved with breathing

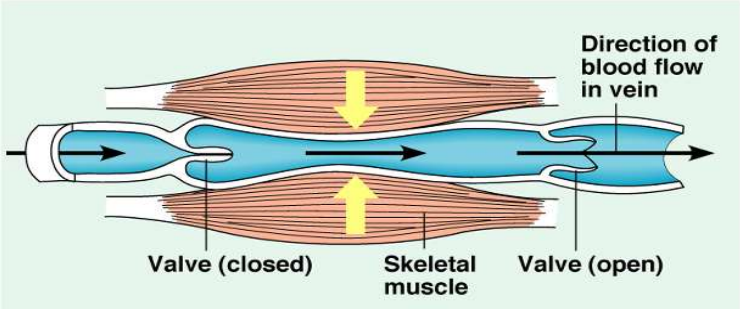
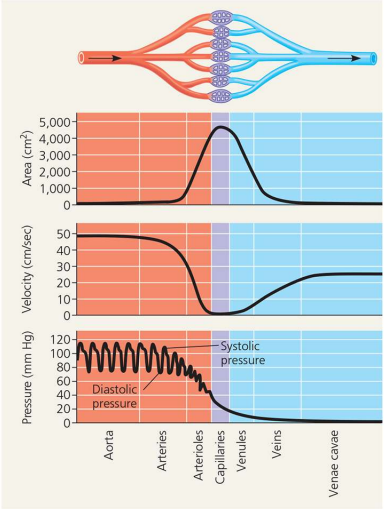


Fig.42.10

Blood pressure

- is the force that blood exerts on the blood vessels
- is determined by the **cardiac output** & **the resistance to blood flow** in the blood vessels
  - is highest in the aorta
  - declines slightly in arteries but falls considerably in arterioles
  - slow, steady flow in the capillaries as blood encounters resistance
  - very low pressure in veins



▲ **Figure 42.10 The interrelationship of cross-sectional area of blood vessels, blood flow velocity, and blood pressure.** As a result of an increase in total cross-sectional area, blood flow velocity decreases markedly in the arterioles and is lowest in the capillaries. Blood pressure, the main force driving blood from the heart to the capillaries, is highest in the aorta and other arteries.

Measuring blood pressure (pulse pressure)

- Reference range for humans is (125/75):
  - between 110 and 140mmHg **systolic pressure**
  - between 70 and 90mmHg **diastolic pressure**

When pressure in cuff matches systolic pressure, blood will flow through, creating a audible sound via turbulence

- Sphygmomanometer and stethoscope are used
  - measures blood pressure as millimeters of mercury (mmHg)

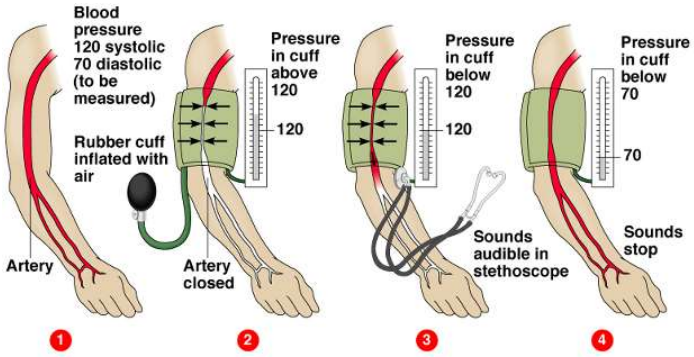


Fig. 42.12

Taps = systolic pressure

No sound = diastolic pressure

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Ted Ed – How Blood pressure works

https://ed.ted.com/lessons/how-blood-pressure-works-wilfred-manzano (4:30 min)

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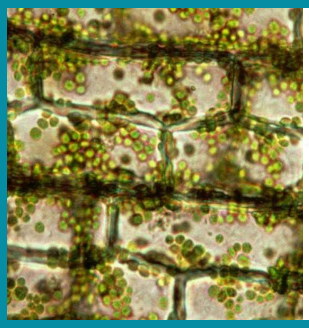
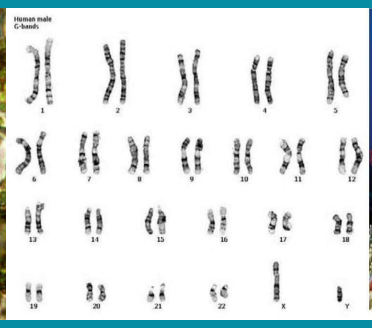
The Circulatory System





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Exchange in Capillaries

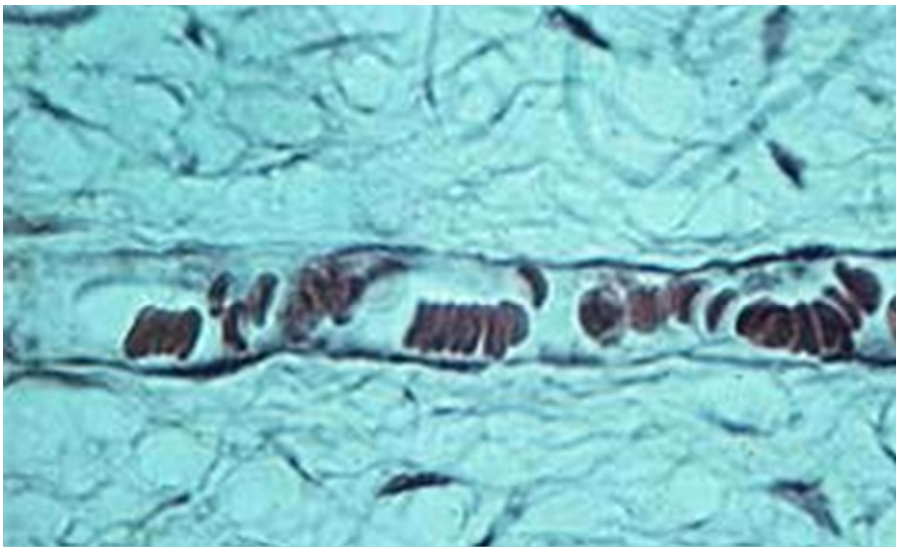
- Capillaries have very thin walls – only one cell thick
  - one layer of epithelium with a basement membrane
  - **are the only blood vessels with walls thin enough for substances to move across**

- exchange of materials between blood and cells occurs via diffusion

	blood		*tissue*
Oxygen	high	→	low
Carbon dioxide	low	←	high
Glucose	high	→	low

- Molecules can diffuse **through** epithelial cells and **between** epithelial cells
- Large molecules such as proteins stay in the blood

Capillaries with red blood cells in lumen



Overall there is a small net flow of fluid **OUT** of capillaries (~ 1%)

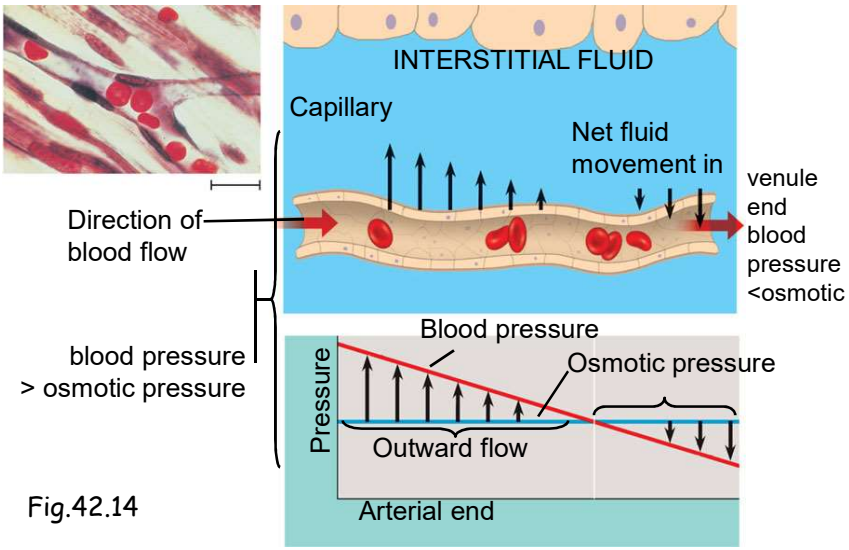
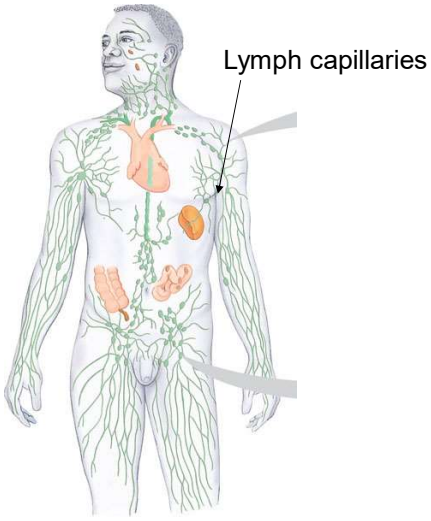


Fig.42.14

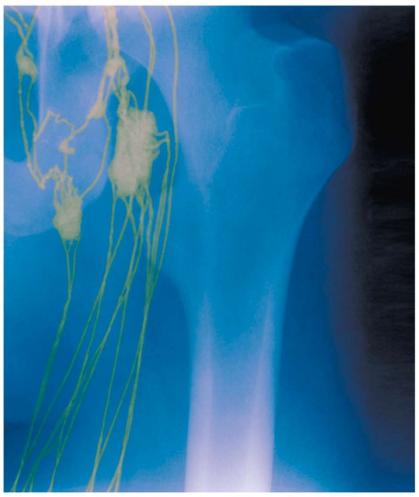
What prevents tissues swelling up?

- Lymphatic system
  - drains tissues



FYI: The Lymphatic System

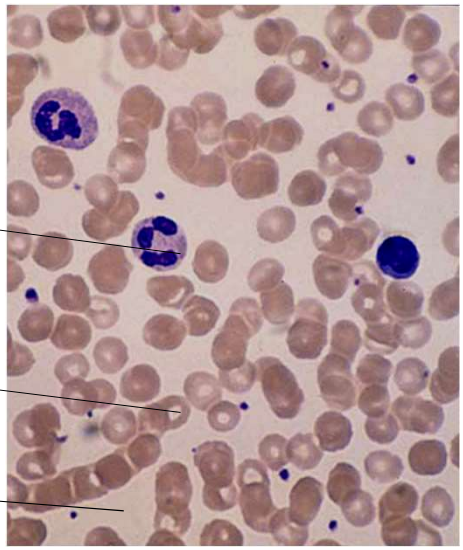
- **What is its function?**
  - Returns fluid to blood
- Lymph capillaries are intermingled among capillaries
- **Composition fluid (lymph)?**
  - Similar to interstitial fluid
- **Where does it drain into the circulatory system?**
  - Junction venae cava & right atrium



Components of blood

Blood is a connective tissue with cells suspended in plasma.

- Avg. human body contains about 4 to 6 liters of blood.
- **Plasma** makes up 55% & comprises
  - water
  - salts
  - proteins
  - substances being transported
    e.g. nutrients, gases, wastes, hormones
- **Cellular elements make up 45%**



Blood Cells

- **Erythrocytes** – red blood cells, biconcave discs
- **Leucocytes** – white blood cells - 5 types**:**

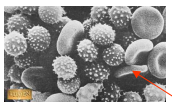
Neutrophil - Attack/digest bacteria
Lymphocyte - immune response
Monocyte - macrophages - engulf
Eosinophil – Parasites/allergies
Basophil - migrate to injury sites.
Some contain anti clotting agents and histamine which dilates blood vessels

Platelets – fragments of cells, involved in clotting

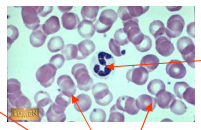
Cellular elements 45% Fig. 42.15

Cell type	Number per μL (mm³) of blood	Functions
Erythrocytes (red blood cells)	5–6 million	Transport oxygen and help transport carbon dioxide
Leukocytes (white blood cells)	5,000–10,000	Defense and immunity
Platelets	250,000–400,000	Blood clotting

FYI: Human blood cells

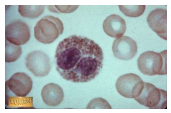


SEM

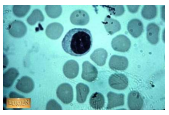


Erythrocytes

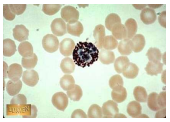
Neutrophils – 50-70% of circulating WBCs
First to arrive at an injury site



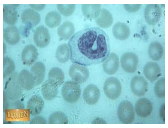
Eosinophils – 2-4% of circulating WBCs
Engulf bacteria, protozoa, cell debris, allergens



Lymphocytes – immune response



Basophils – <1% of circulating WBCs
Migrate to an injury site



Monocytes – engulf foreign matter

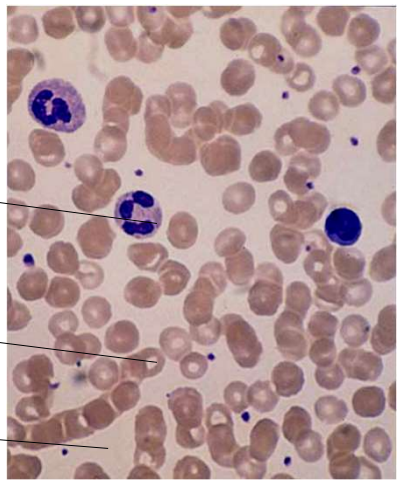
Functions of Blood cells

Erythrocytes -red blood cells

- The most numerous blood cells
- Mammalian RBCs eventually have no nuclei or mitochondria
- **specialised to carry Oxygen**
- each cell contains 250 million molecules of haemoglobin (protein containing iron which binds O_2)

Leucocytes - white blood cells

- Collective function is to **fight infection**
- They spend much of their time outside blood system
- Numbers increase temporarily when fighting infection

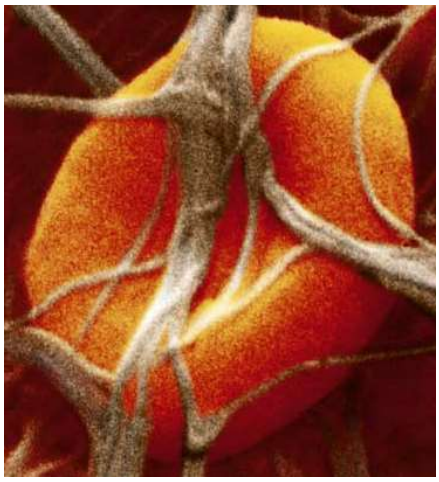


Clotting of blood

- Helps to plug leaks in damaged blood vessels

  1. platelet clots: *platelets form a plug*

  able to stop bleeding from small wound (e.g. pin prick)



  2. fibrin clots

- a complex series of reactions
  - fibrinogen being converted to fibrin, a thread-like protein
- fibrin traps blood cells and forms a clot
  - eventually seals the damaged vessel

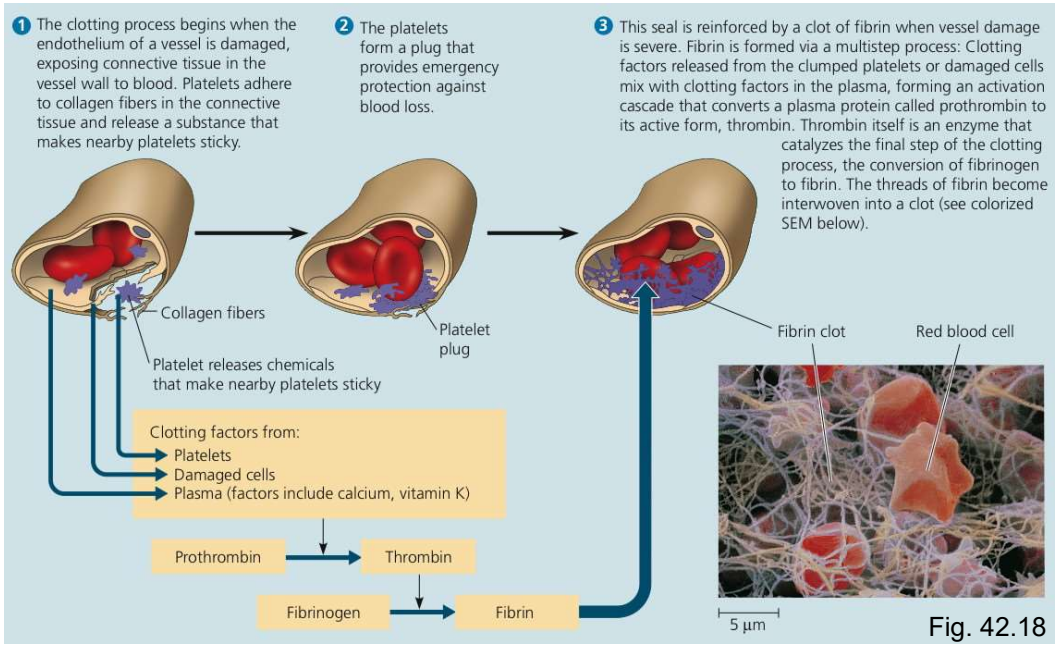


Fig. 42.18

Quick Question

Three chambered hearts generally consist of which of the following numbers of atria and ventricles?

a) One atrium, one ventricle
b) Two atria, one ventricle
c) Three atria, no ventricles
d) no atria, three ventricles
e) One atrium, two ventricles

Quick Question

Blood is carried directly to the lungs from which of the following?

a) Superior vena cava
b) Aorta
c) Pulmonary artery
d) Inferior vena cava
e) Carotid artery

Quick Question

Through how many capillary beds must a human red blood cell travel if it takes the shortest possible route from the right ventricle to the right atrium?

a) one

b) two

c) three

d) four