THE UNIVERSITY OF MELBOURNE

Faculty of Veterinary and Agricultural Sciences

Veterinary Bioscience: Cardiovascular System
Lecture 1: Why have a cardiovascular system?

Dr Laura Dooley
Senior Lecturer
Melbourne Veterinary School

laura.dooley@unimelb.edu.au

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Lecture 1: Intended learning outcomes

- Describe the principal functions of a circulatory system and appreciate how the various components of such a system are structured to fulfil these functions
- Explain the factors that determine the movement of solutes and fluid across capillary walls
- Understand the basic flow equations that describe the movement of blood through the vascular system
- Describe the organisation of the dual circulatory system in the adult mammal
- Understand the basic structural and functional characteristics of the heart.

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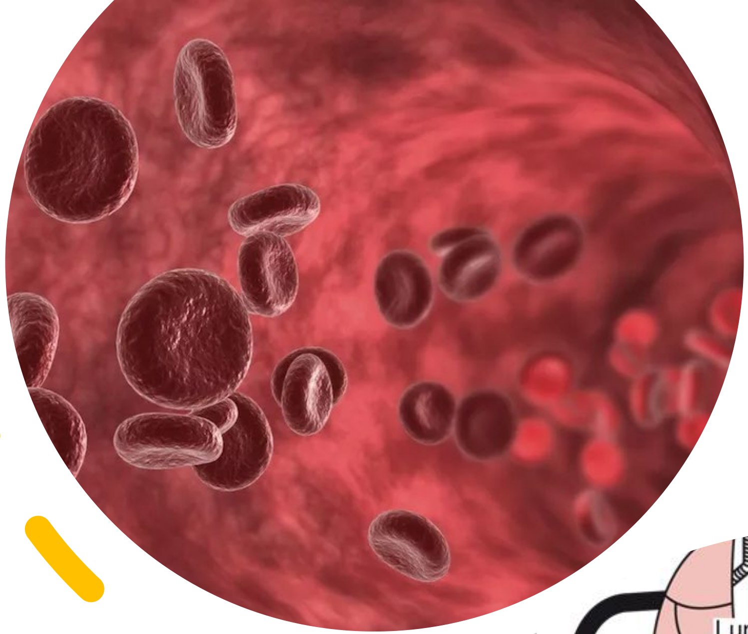
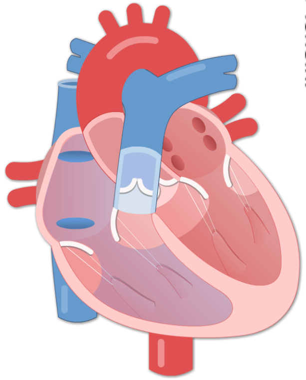
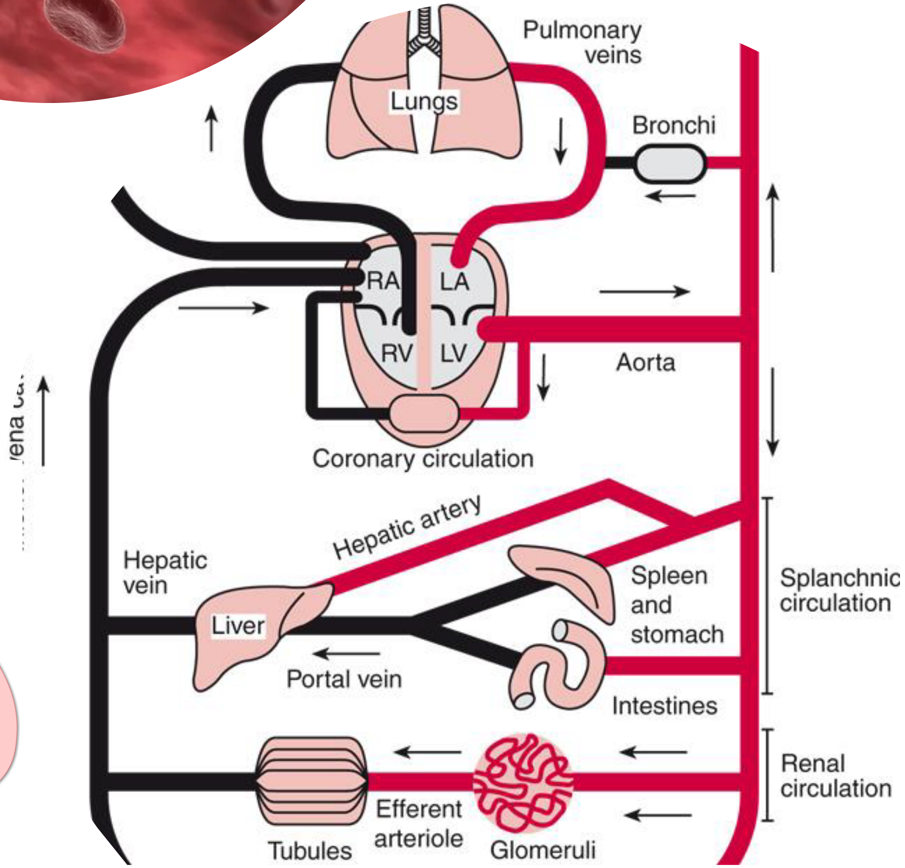
Why have a cardiovascular system?



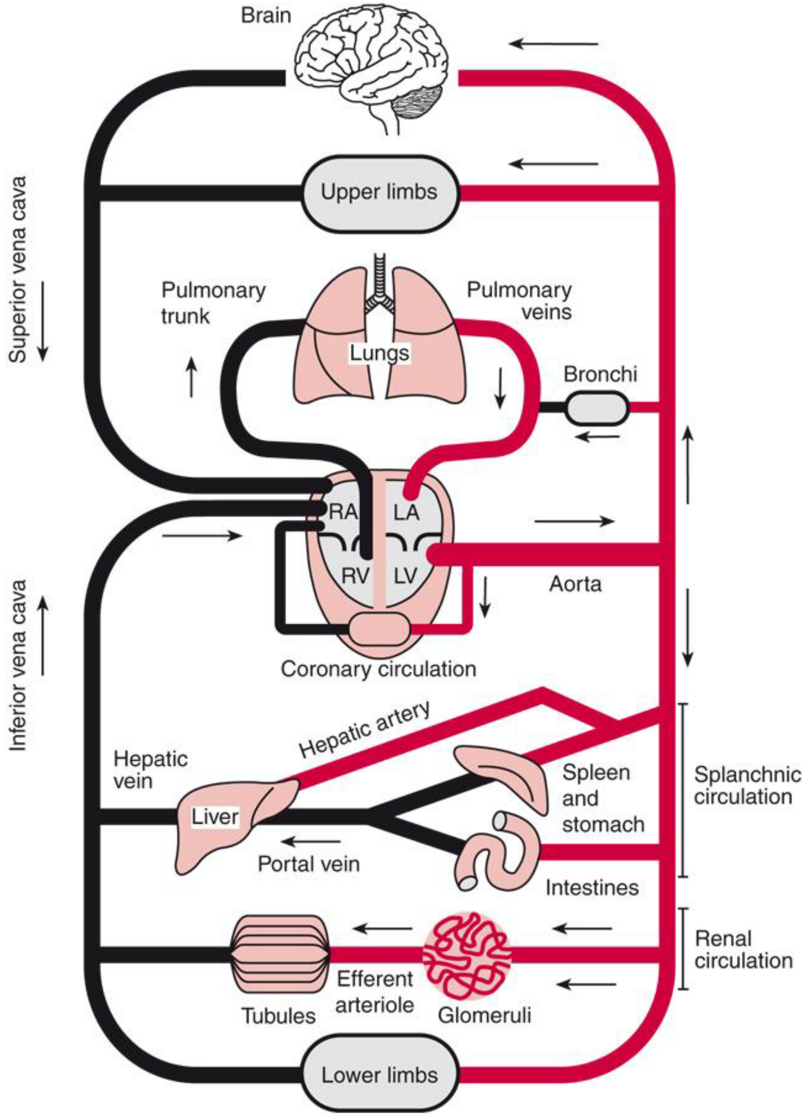
- The cardiovascular system is an elaborate transport network that distributes materials that are essential for the survival of body cells
- Plays a critical role in the exchange of molecules – delivery of substrates (e.g. oxygen and glucose) the tissues, and the removal of metabolic waste products from the tissues
- Distribution of messengers such as hormones to the tissues, also distribution of body defence mechanisms (immune cells)
- Role in temperature regulation → distribution of heat from the core of the body to the skin





Cardiovascular System

- The heart - the driving force
  propels blood around the body
- Arterial system
  the distribution channels
- The microcirculation
  the exchange vessels
- The venous system
  the blood reservoirs, return blood to the heart



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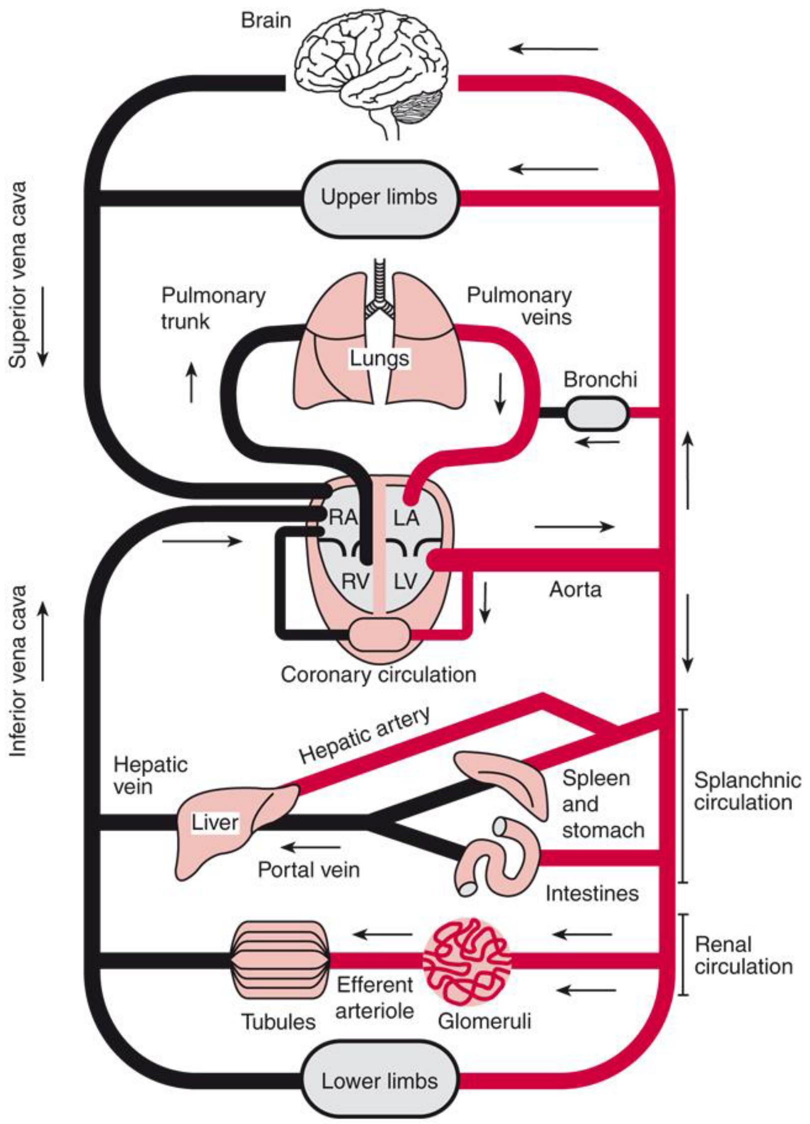

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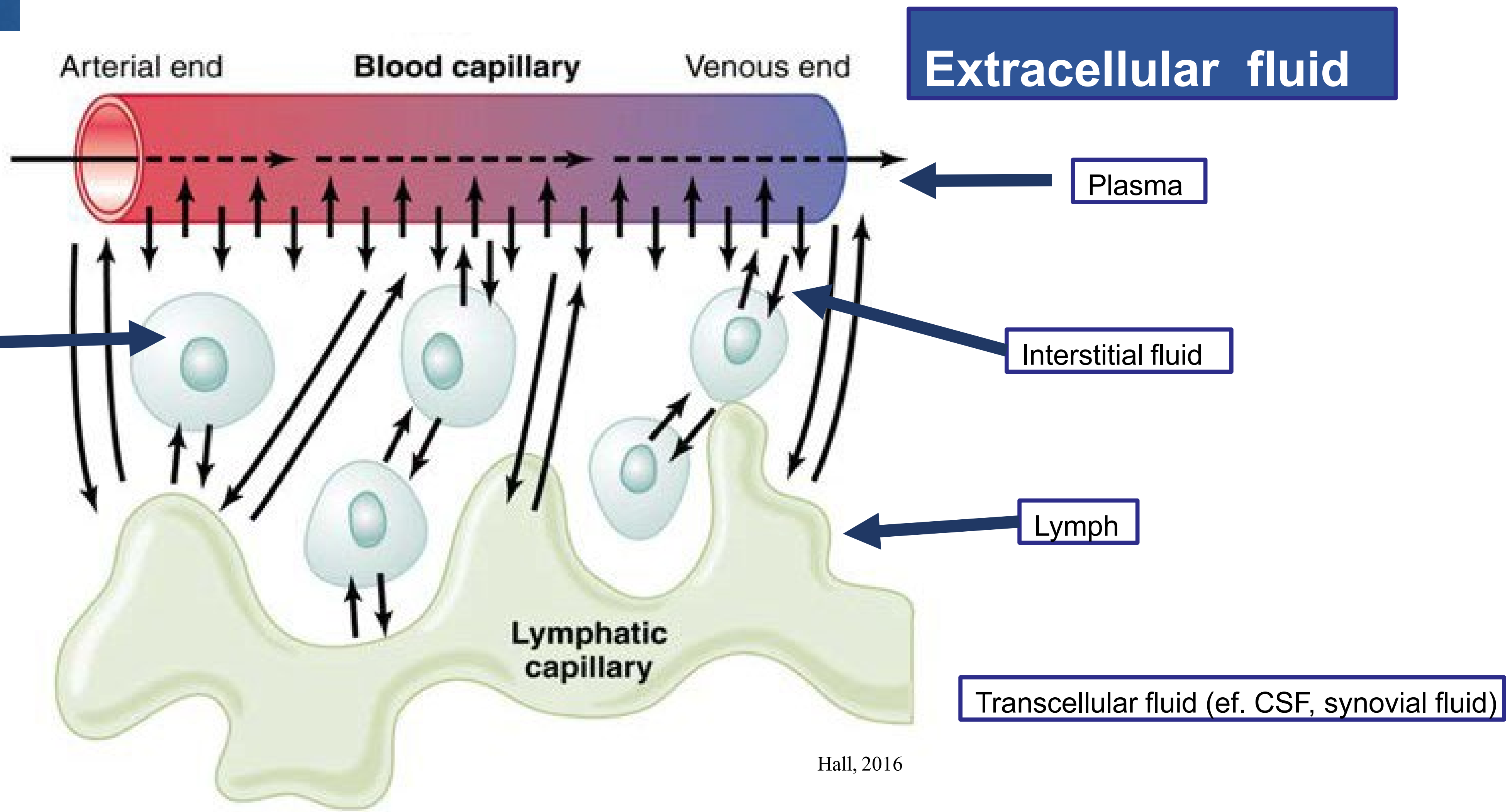
Body fluid compartments: overview



Hall, 2016

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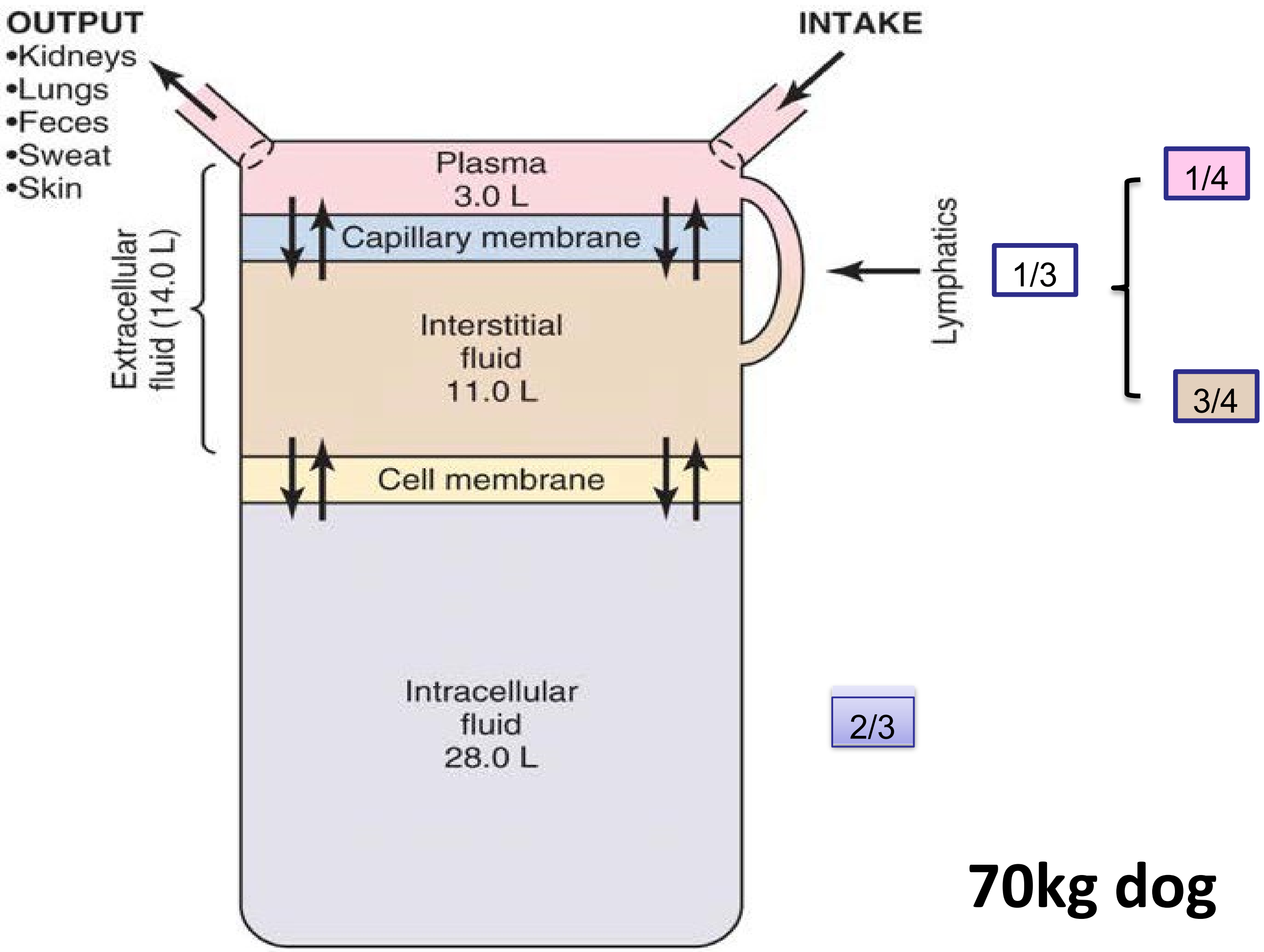
Body fluid compartments: ECF and ICF

- Total body water (TBW)
  - 60% of lean body weight
- 1/3 of TBW is extracellular
  - ¼ extracellular water = plasma
  - ¾ extracellular water = interstitial
  - Exchange of water, solutes, nutrients and gases occurs via diffusion and osmosis driven by hydrostatic and oncotic pressures
- 2/3 of TBW is intracellular
  - Water, solutes, nutrients and gases must cross the cell membrane
  - Simple diffusion and osmosis occurs for some molecules
  - Additional transport mechanisms are required for others – next lecture



70kg dog

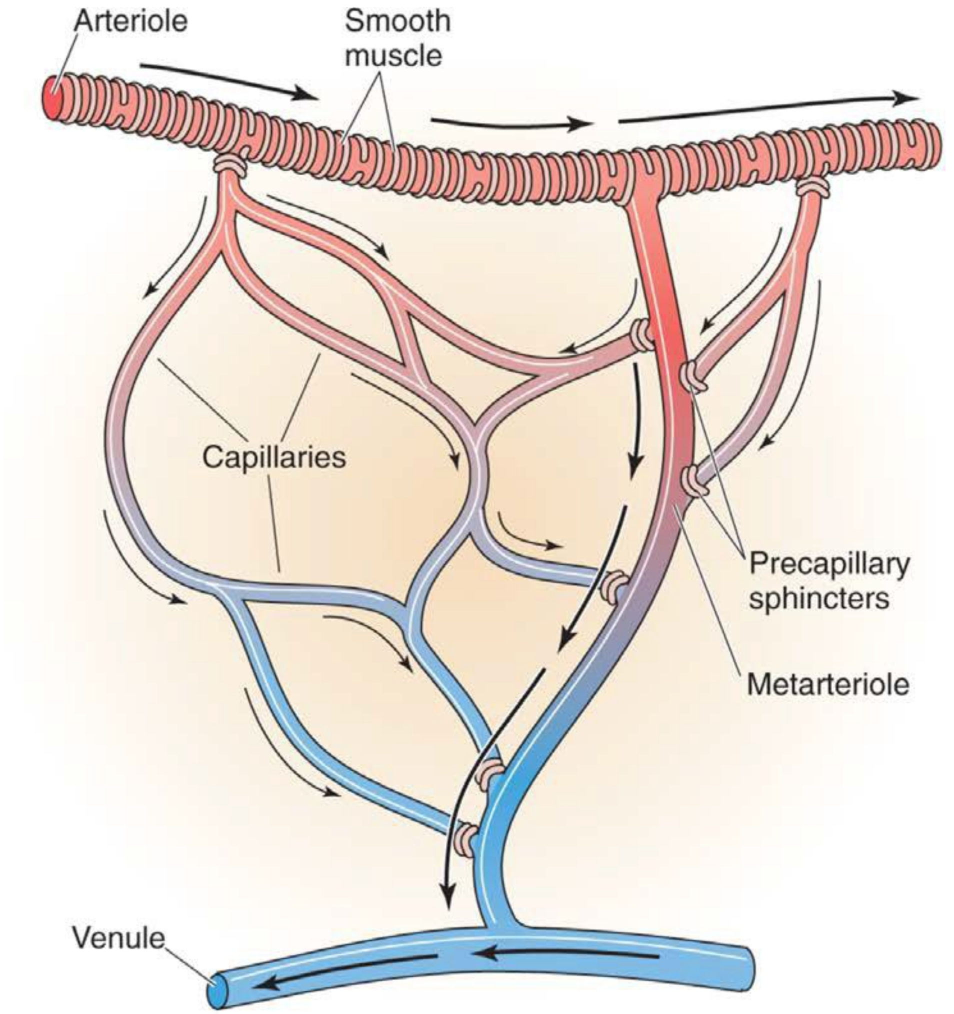
Guyton & Hall, 2007

Capillaries: sites of exchange

- Exchange of fluid (nutrients & metabolic products) between blood and interstitial fluid

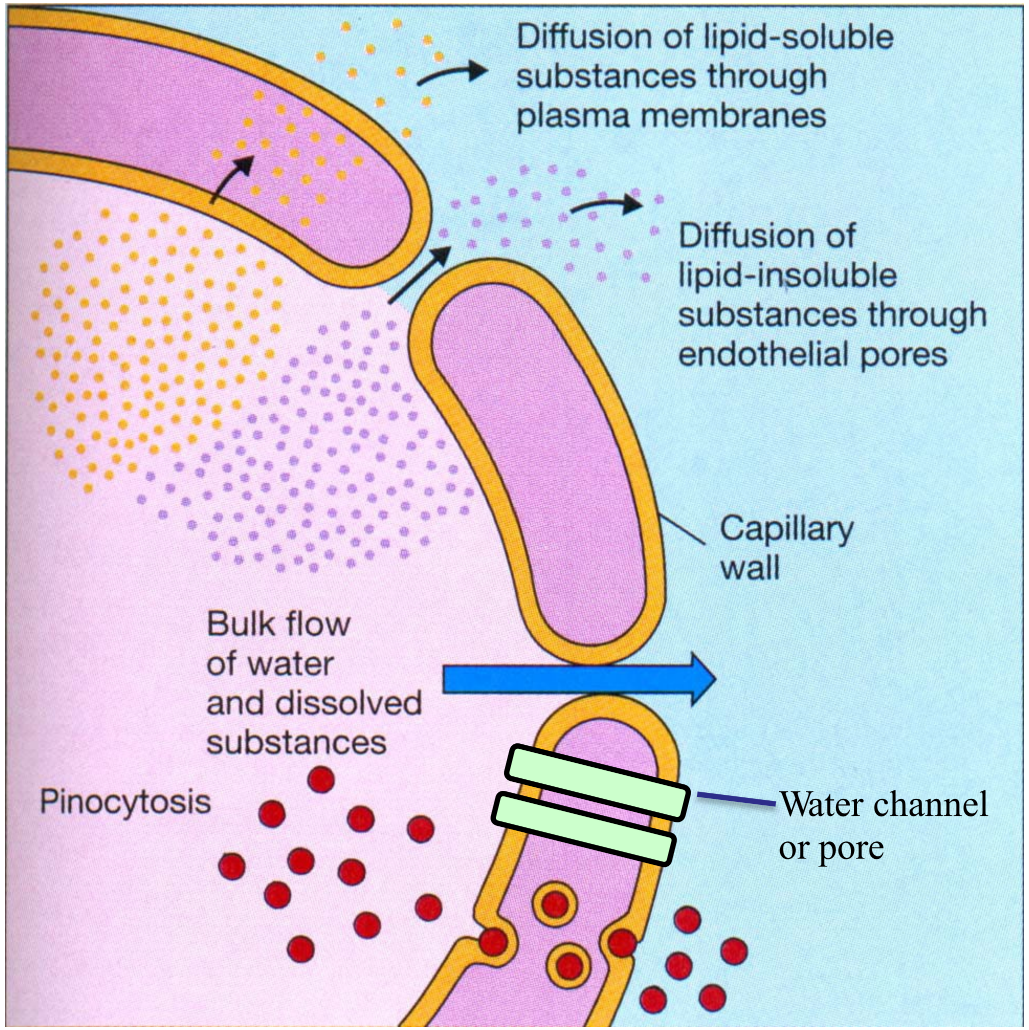
- Capillary walls are made up of a single layer of endothelial cells (~2μm thick)

- Capillaries are located close to every cell in body (30-100μm distance) → reduced diffusion distance = ↑ rate of diffusion (Fick's law)



Boron & Boulpaep, 2012

Movement of substances across capillary walls



Modified from Rhoades & Pflanzer 2003

1. Diffusion

- Lipid-soluble molecules cross EC membranes
- Lipid-insoluble molecules pass between ECs and through pores
- Rate of diffusion described by Fick's Law

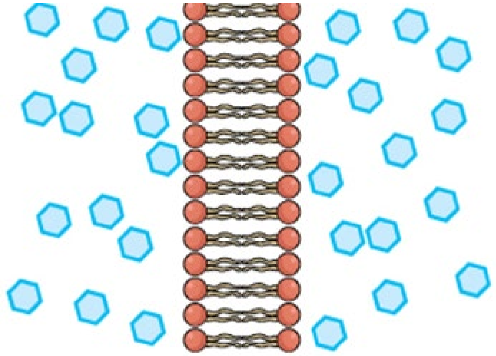
2. Transcytosis or pinocytosis

- Movement of macromolecules across ECs in vesicles

3. Bulk flow via Starling's Forces – driving force

- Bulk flow of fluid through channels in capillary wall – molecules moving together in bulk

Fick’s equation



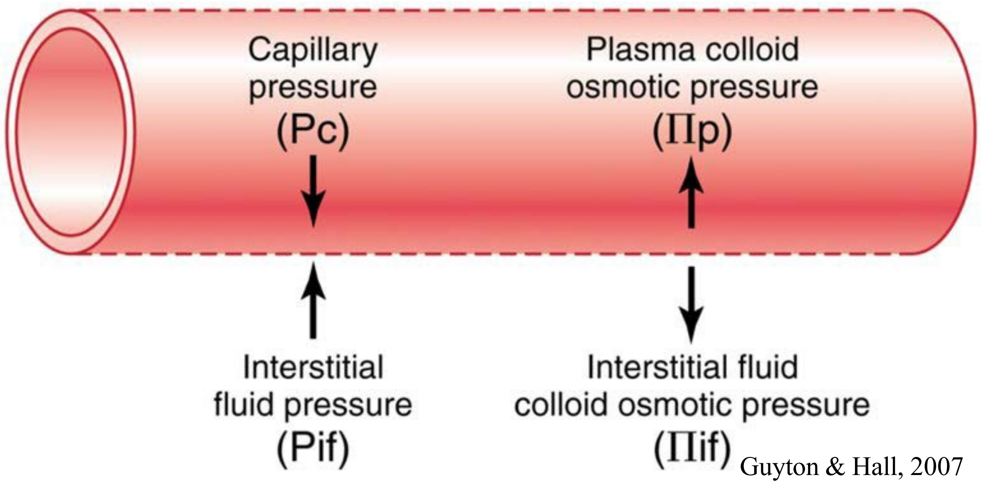
Fick’s equation describes factors that influence the rate of net diffusion across a membrane:

1. **Magnitude of concentration gradient**
   - Greater the difference in concentration, faster the rate of net diffusion
2. **Permeability of the membrane to the substance**
   - Greater the permeability, faster the rate of net diffusion
3. **Surface area of membrane available for diffusion**
   - Larger the surface area, faster the rate of net diffusion
4. **Molecular weight of substance**
   - Heavier the molecule, the slower the rate of net diffusion
5. **Distance of diffusion**
   - Greater the distance, the slower the rate of net diffusion

Forces influencing bulk flow: Starling's forces

Four forces influencing bulk flow:

1. Capillary blood pressure: hydrostatic pressure exerted on the capillary wall by the blood. Forces fluid out of capillary
2. Plasma colloid osmotic pressure (also known as oncotic pressure): force caused by plasma proteins which remain in plasma, which exerts an osmotic effect on water. Forces fluid into the plasma compartment
3. Interstitial fluid pressure: hydrostatic pressure exerted by the interstitial fluid on the outside of the capillary wall. Forces fluid into capillaries.
4. Interstitial fluid colloid osmotic pressure: the protein concentration in the interstitium is normally very low, and so this force is close to zero.



Guyton & Hall, 2007

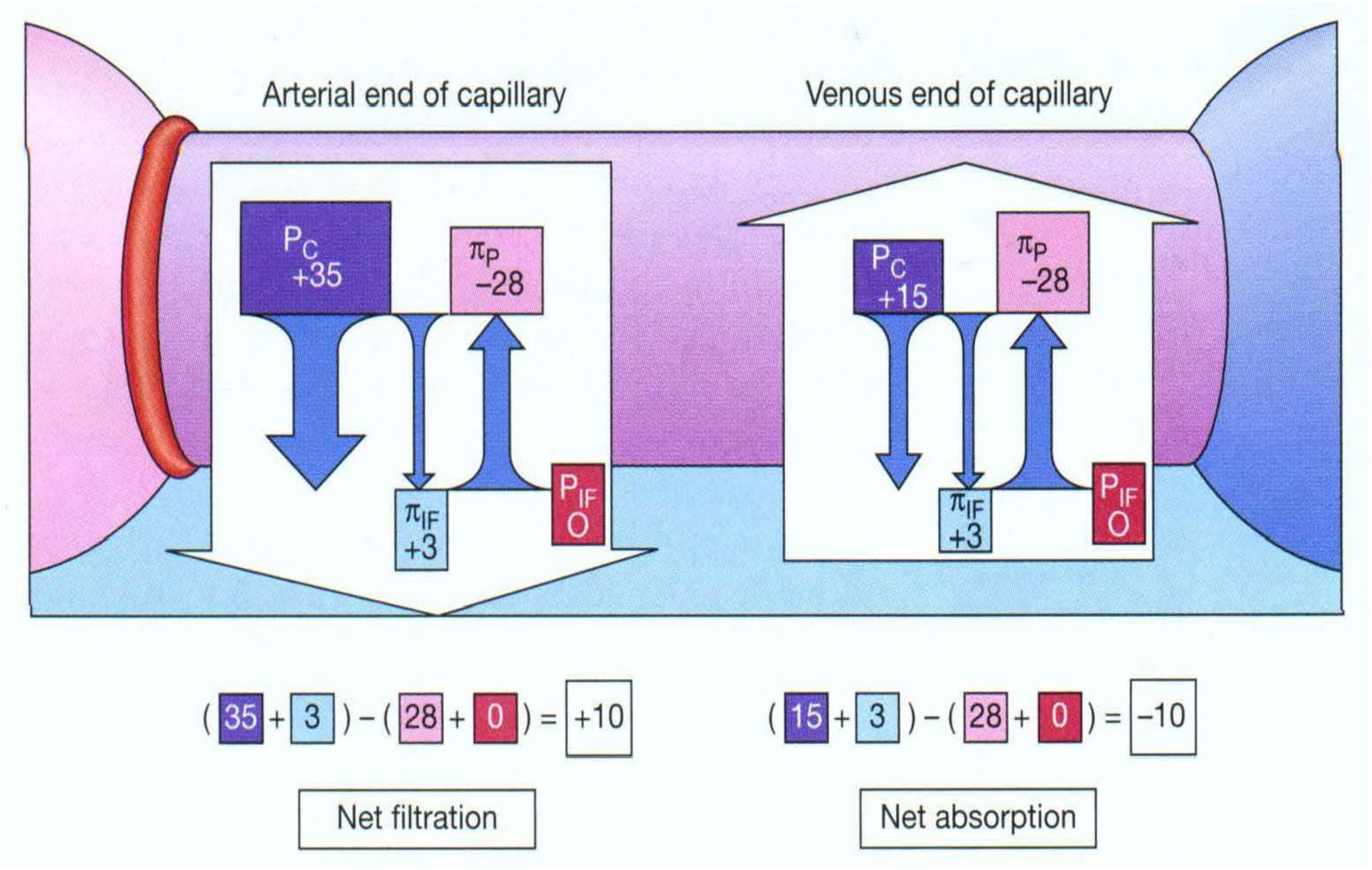
$$NFP = \underbrace{(Pc + \prod if)}_{\text{Filtration forces}} - \underbrace{(Pif + \prod p)}_{\text{Absorption forces}}$$

Filtration is greatest at the arterial end of the capillary

- Hydrostatic forces favouring filtration are greatest at the arterial ends of capillaries

- Oncotic osmotic pressure predominates at the venous ends of the capillaries ensuring 90% of the fluid is reabsorbed → this creates a filtration-absorption imbalance

- This excess fluid is collected by the **lymphatic system**



Rhoades & Pflanzer, 2003

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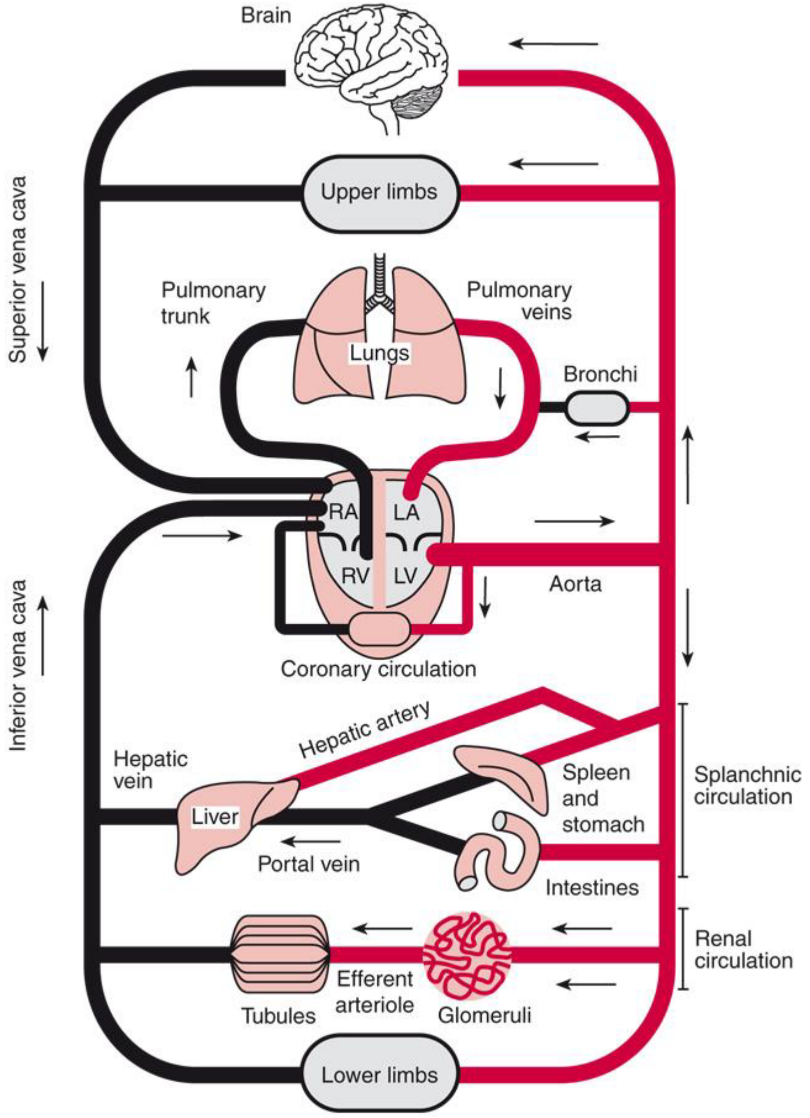

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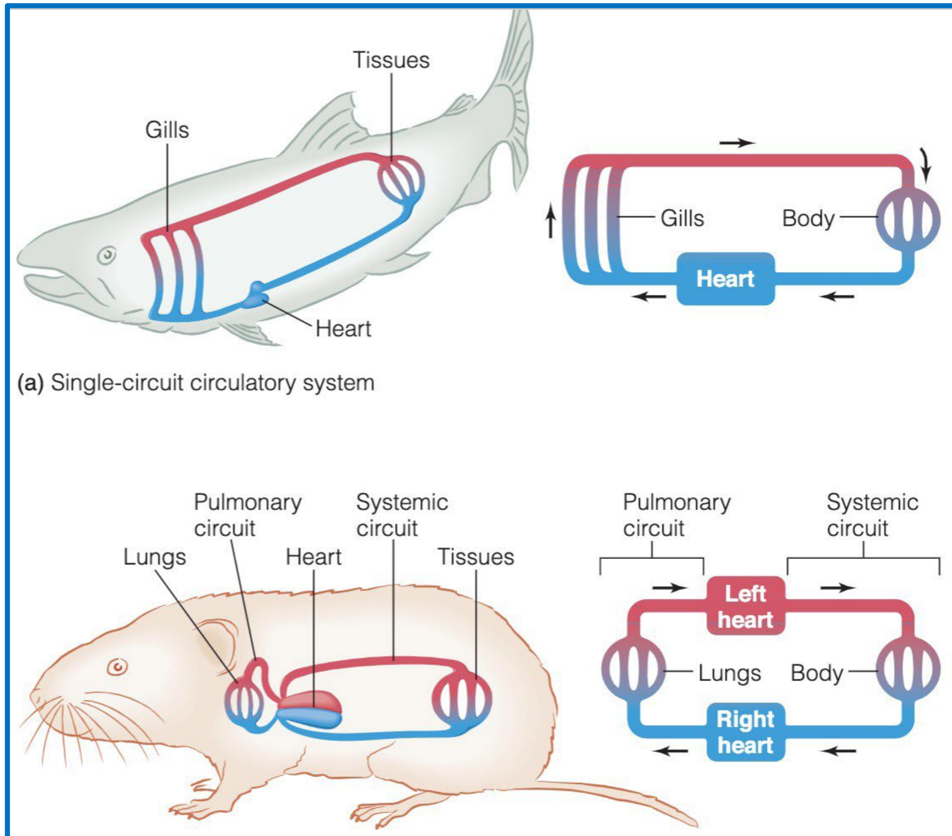
Single and dual circulatory systems



(a) Single-circuit circulatory system

(b) Double-circuit circulatory system

Figure 12 Vertebrate circulatory systems The structure of vertebrate circulatory systems varies depending on the respiratory strategy of the animal. **(a)** In water-breathing fish, blood travels from the heart through the aorta to the gills and then to the body tissues, and returns to the heart. **(b)** Air-breathing tetrapods have a double circulatory system with two pumps arranged in series. Blood travels through the left heart to the aorta which leads to the systemic circuit through the body, returning to the right heart that pumps the blood via the pulmonary artery through the pulmonary circuit through the lungs.

Single circuits:

Advantage:

Blood passing through the gills is fully oxygenated when it moves into the tissues.

Limitation:

In passing through the gills, blood loses much of its pressure developed by contraction of the heart.
This limits rate of oxygen delivery to the rest of the body.

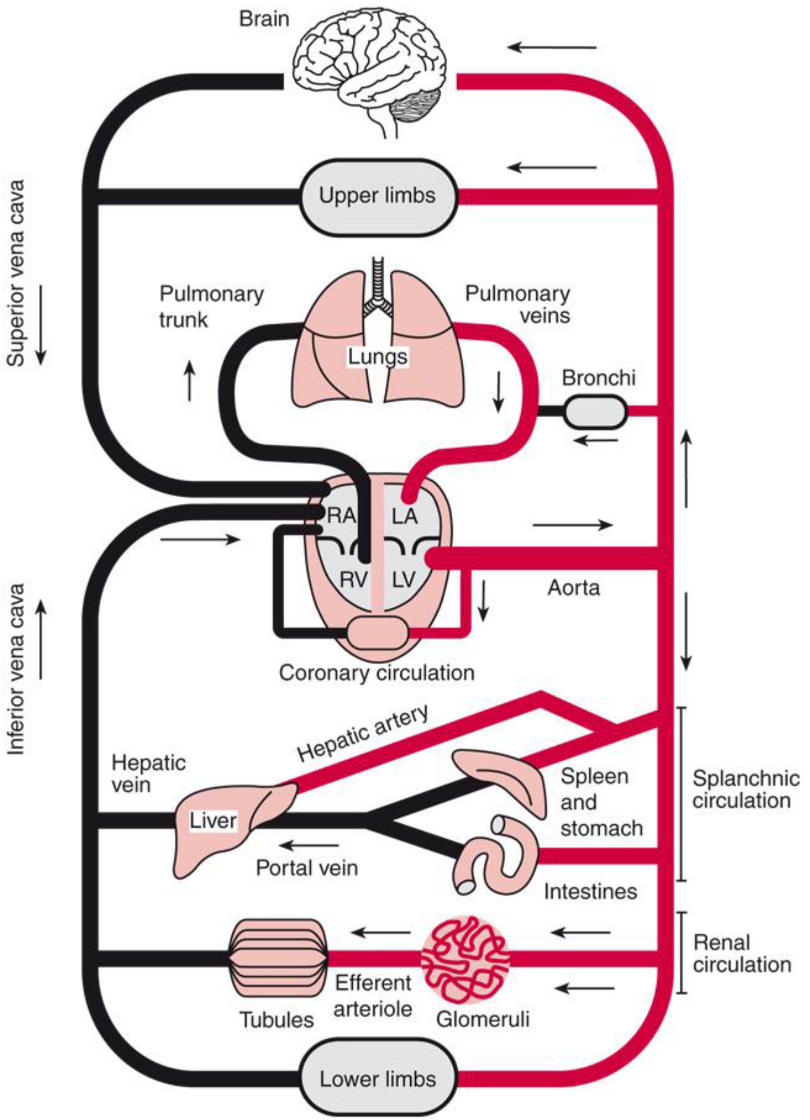
Dual circuits:

Effectively two heart pumps and two circulations
Flow must be matched in the two circulations

More efficient, higher rate of oxygen supply to tissues

Dual circulation

- The LEFT side of the heart pumps OXYGENATED blood to the SYSTEMIC circulation
- The RIGHT side of the heart pumps DEOXYGENATED blood to the PULMONARY circulation
- Two separate vascular loops – both originate and terminate at the heart



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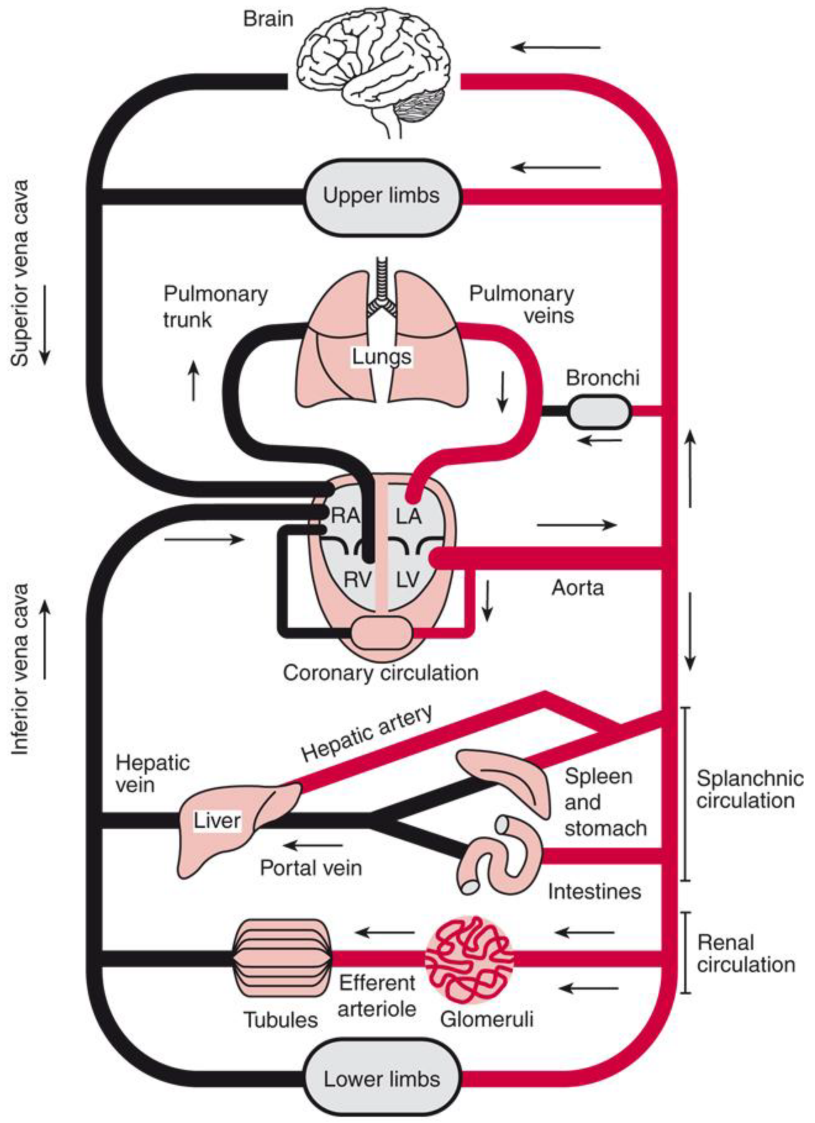
Blood flows in one direction!

Right ventricle	←	Right atrium
↓		↑
Pulmonary arteries		Systemic veins
↓		↑
Lungs		Capillary beds
↓		↑
Pulmonary veins		Systemic arteries
↑		↑
Left atrium	→	Left ventricle



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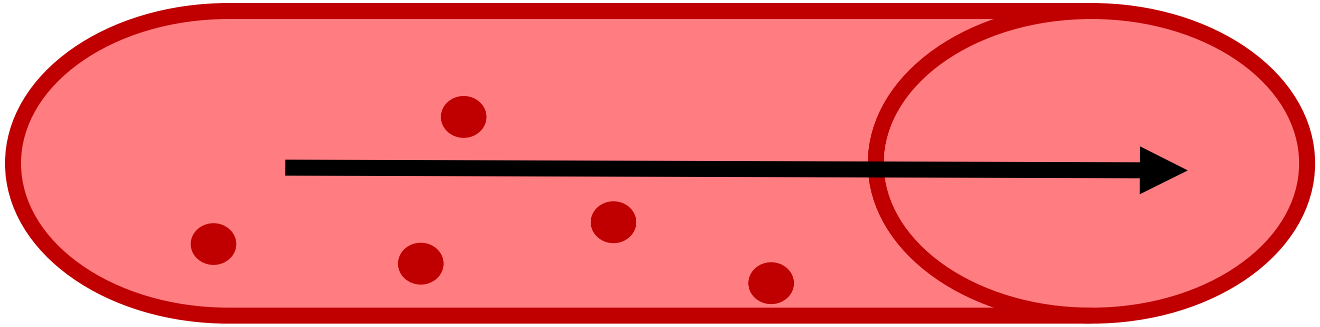
How does blood flow?

- Flow **through** a tube requires a pressure difference → fluid flows from high to low pressure
- Friction against blood vessels resists flow through blood vessels (tubes)

HIGH pressure  **LOW pressure**

- Force required to move a given volume of fluid through the tubes (in a specified period of time) is the vascular resistance

The basic flow equation

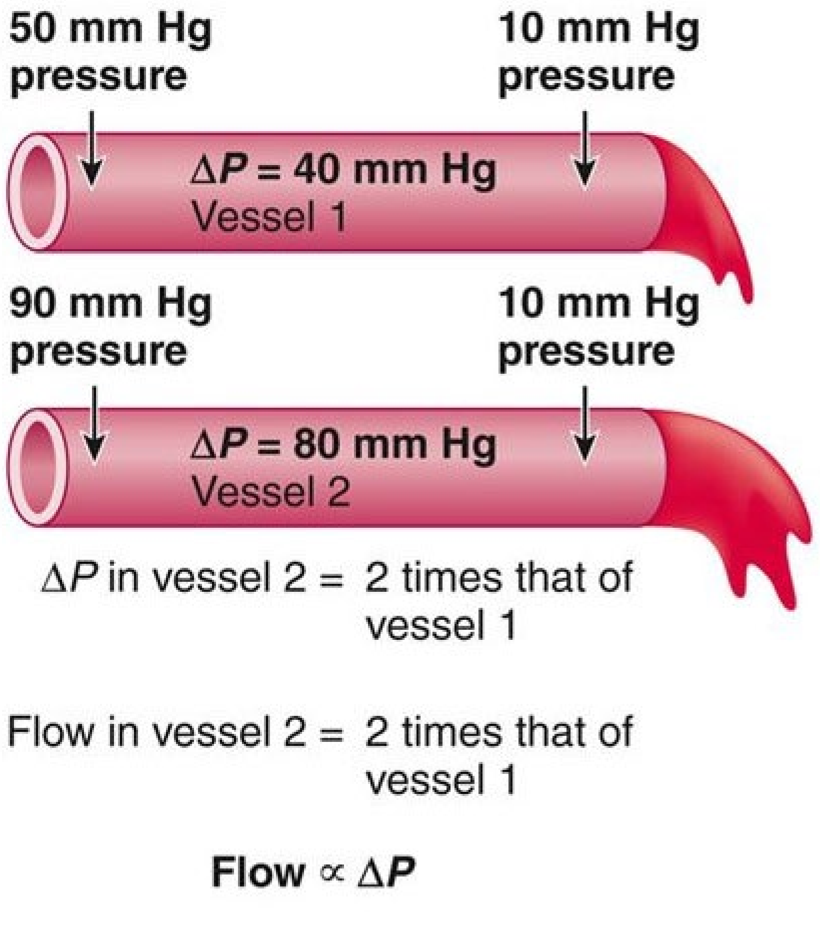
The basic flow equation:

$$\text{Flow} = \frac{\text{Pressure difference}}{\text{Resistance}} \quad \text{or} \quad Q = \frac{\Delta P}{R}$$

Q = flow rate; ΔP = Pressure difference; and R = resistance

Therefore, flow can be modified by:

- Changing pressure difference or
- Changing vascular resistance



(a) Comparison of flow rate in vessels with a different ΔP

As the difference in pressure between the two ends of the vessel increases, flow rate increases proportionately

Note: flow rate is not determined by the absolute pressures

Determinants of resistance

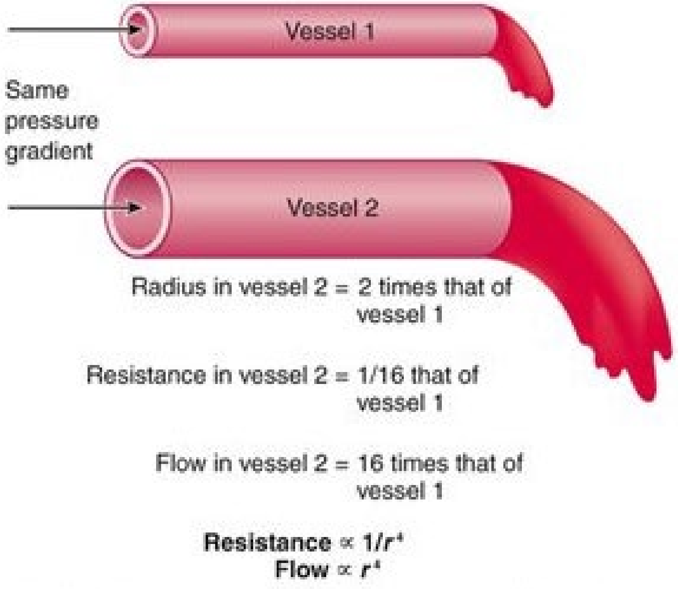
$$\text{Resistance} = \frac{8 \times \text{length} \times \text{viscosity}}{\pi \times (\text{radius})^4}$$

(classical Hagen-Poiseuille equation)

<u>Key message:</u> *Resistance is inversely proportional to the radius of the vessel*

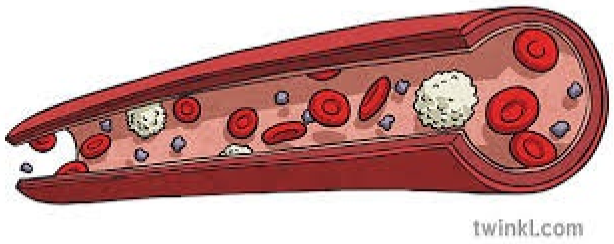
Therefore, as **vessel radius decreases, resistance increases**

(a) Comparison of contact of a given volume of blood with the surface area of a small-radius vessel and a large-radius vessel



(b) Influence of vessel radius on resistance and flow

Poiseuille's Law



$$Resistance\ (R) = \frac{8x\ length\ x\ viscosity}{\pi(radius)^4} = \frac{8LV}{\pi r^4}$$

$$Flow\ rate\ (Q) = \frac{\Delta P}{R} \longrightarrow Flow\ rate\ (Q) = \frac{\Delta P \pi r^4}{8LV}$$

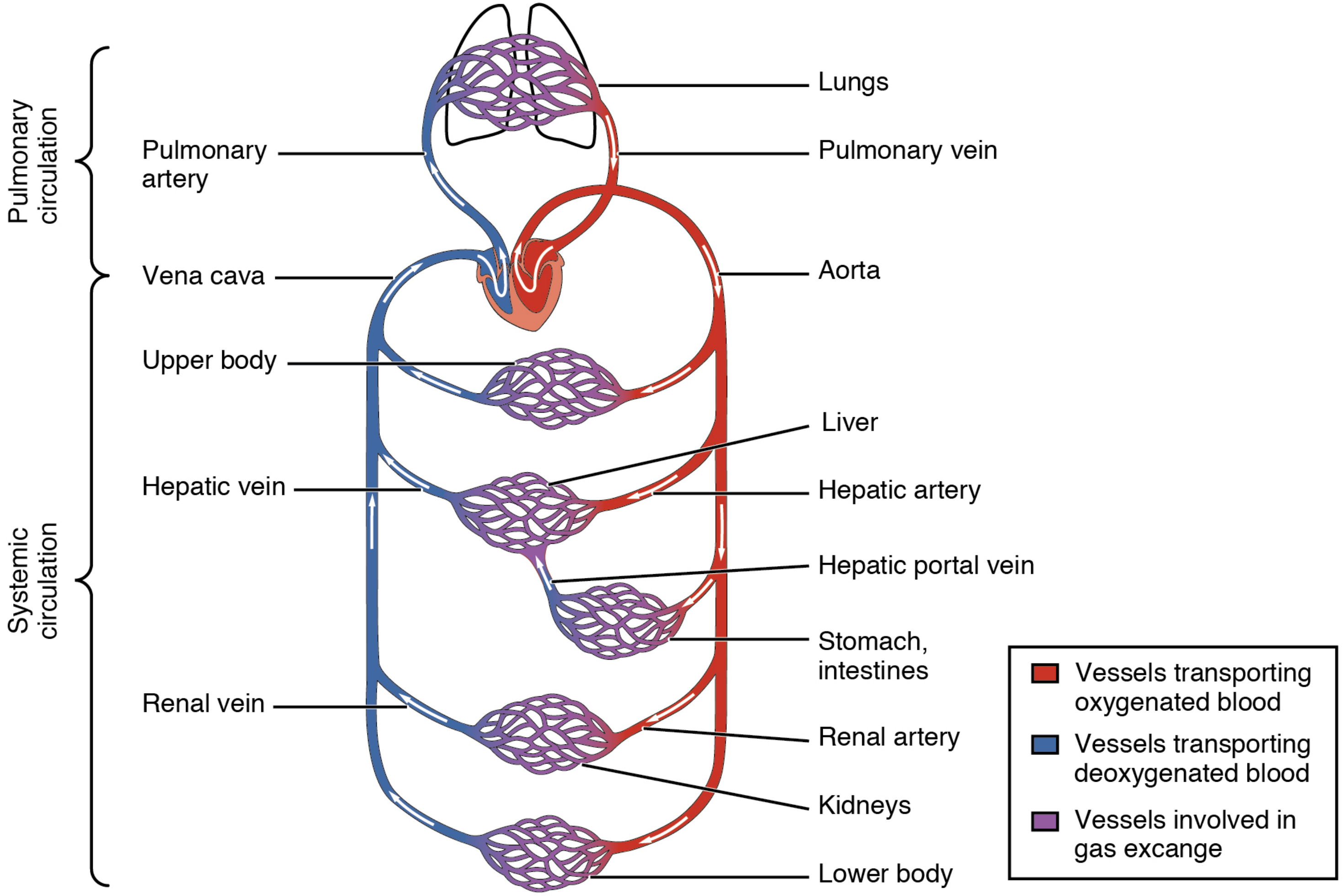
Basic flow equation

Inserting the determinants of resistance

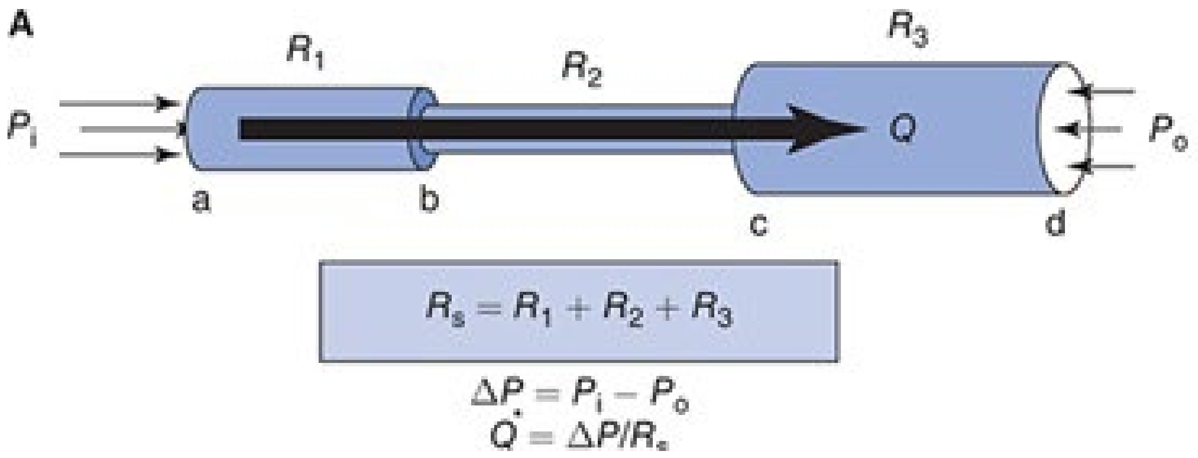
This is called Poiseuille's Law

Resistance in networks of vessels

Blood vessels are arranged in series and in parallel



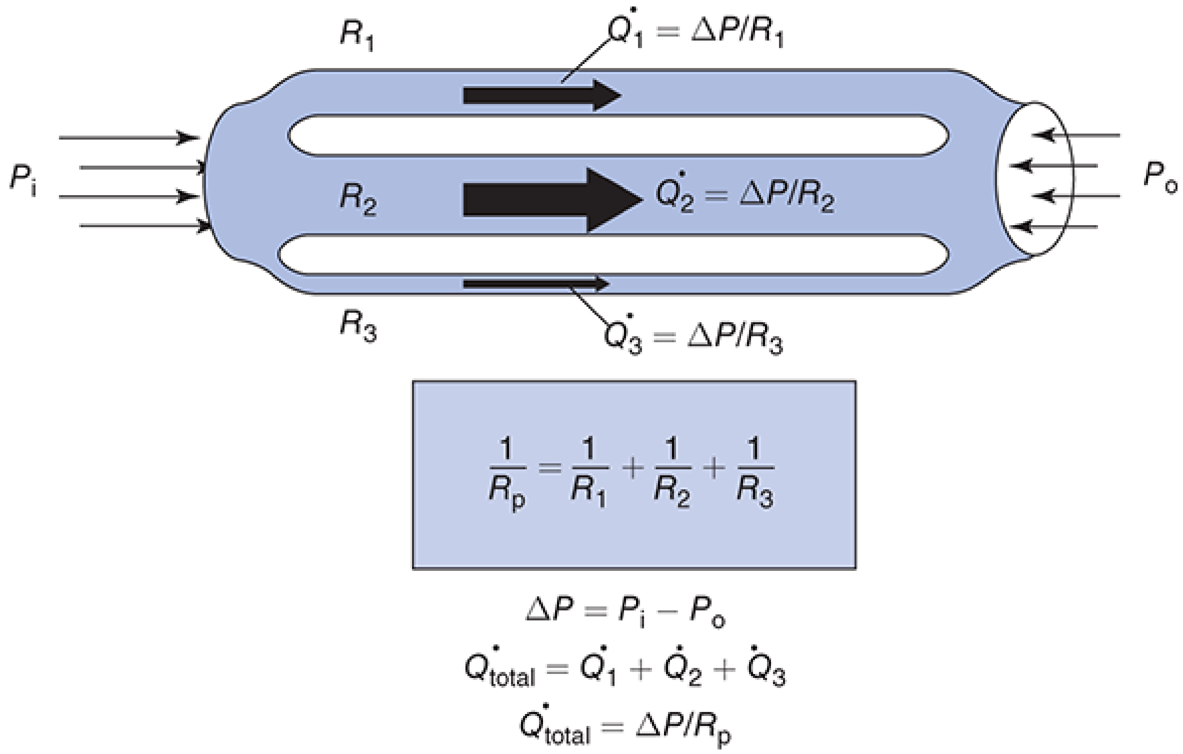
Resistance in networks of vessels: Series



Source: David E. Mohrman, Lois Jane Heller: *Cardiovascular Physiology*, 9e

Total resistance $(R_T) = R_1 + R_2 + R_3 \ldots$

Resistance in networks of vessels: Parallel



Source: David E. Mohrman, Lois Jane Heller: *Cardiovascular Physiology*, 9e

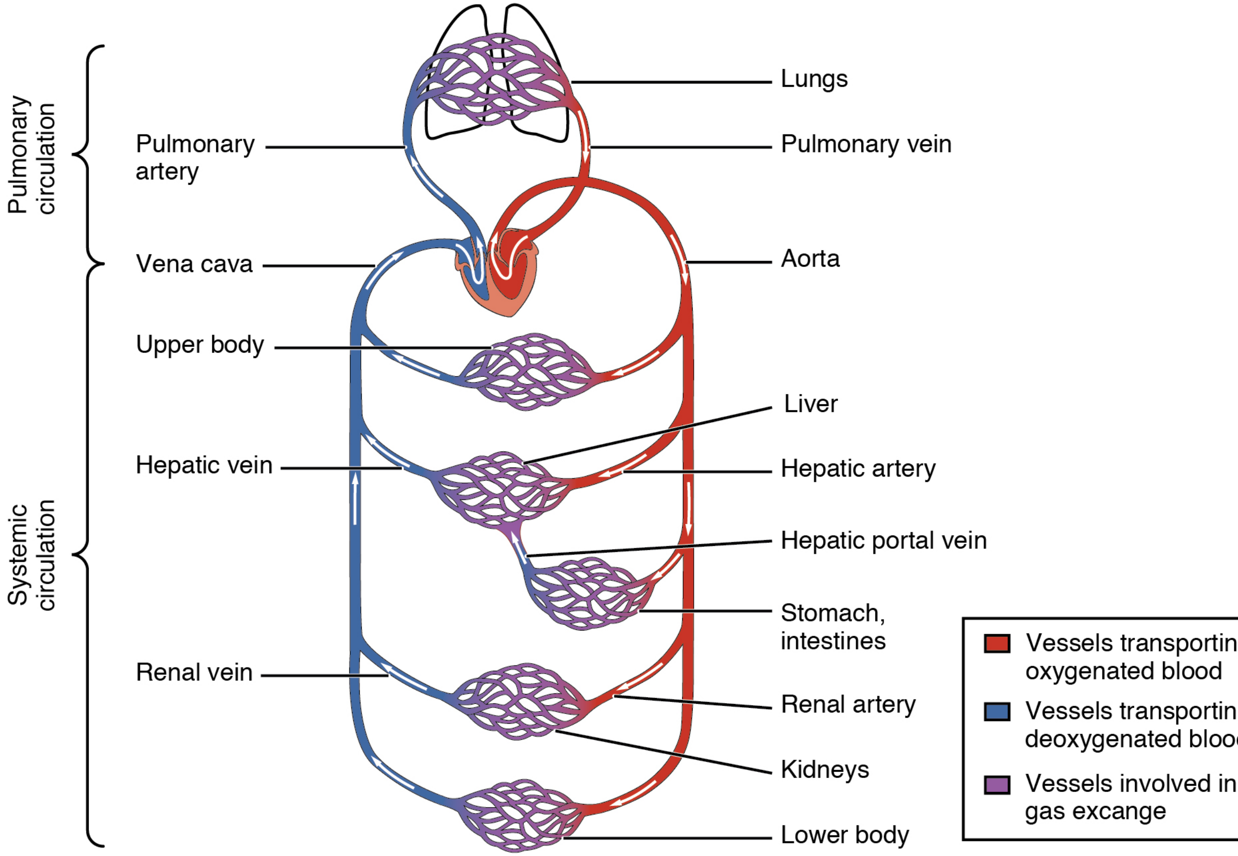
Total resistance for vessels in parallel: $1/R_T = 1/R_1 + 1/R_2 + 1/R_3$...

(this is called Ohm's law)

Resistance in networks of vessels

Key concepts:

- Total resistance in a series of blood vessels is equal to the sum of individual resistances of each segment
- Greatest pressure drop will occur in the segment with greatest resistance
- Vascular beds in organs often arranged in parallel
- In a parallel network, total resistance is lower than resistance in individual segments



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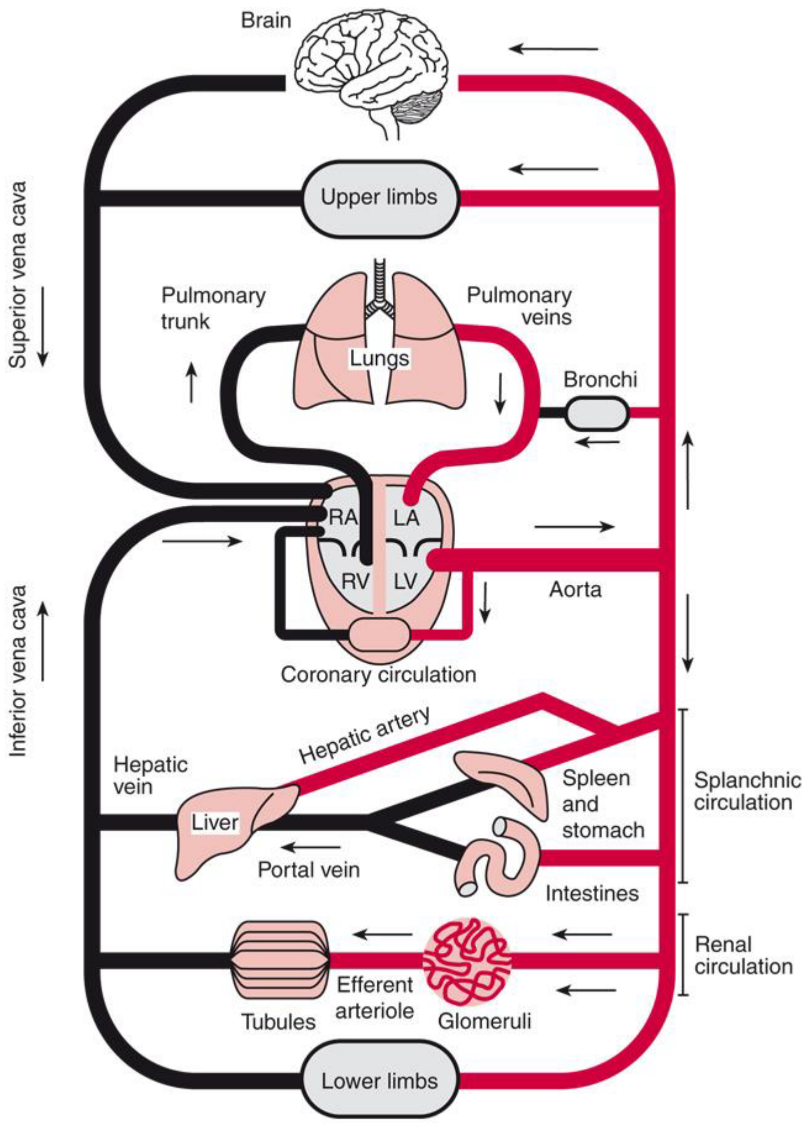
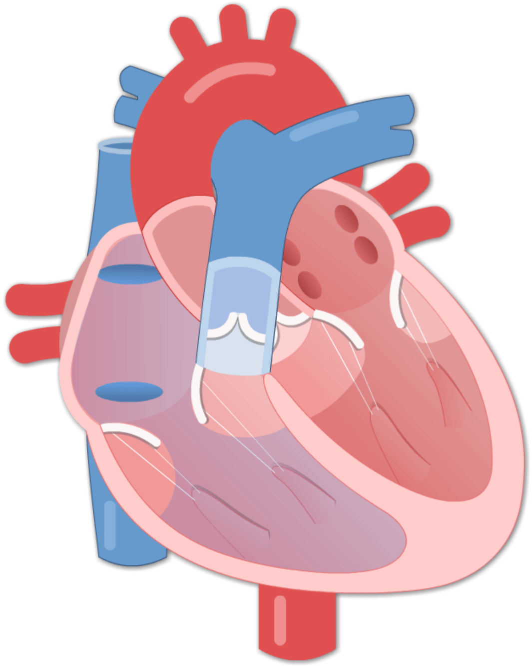
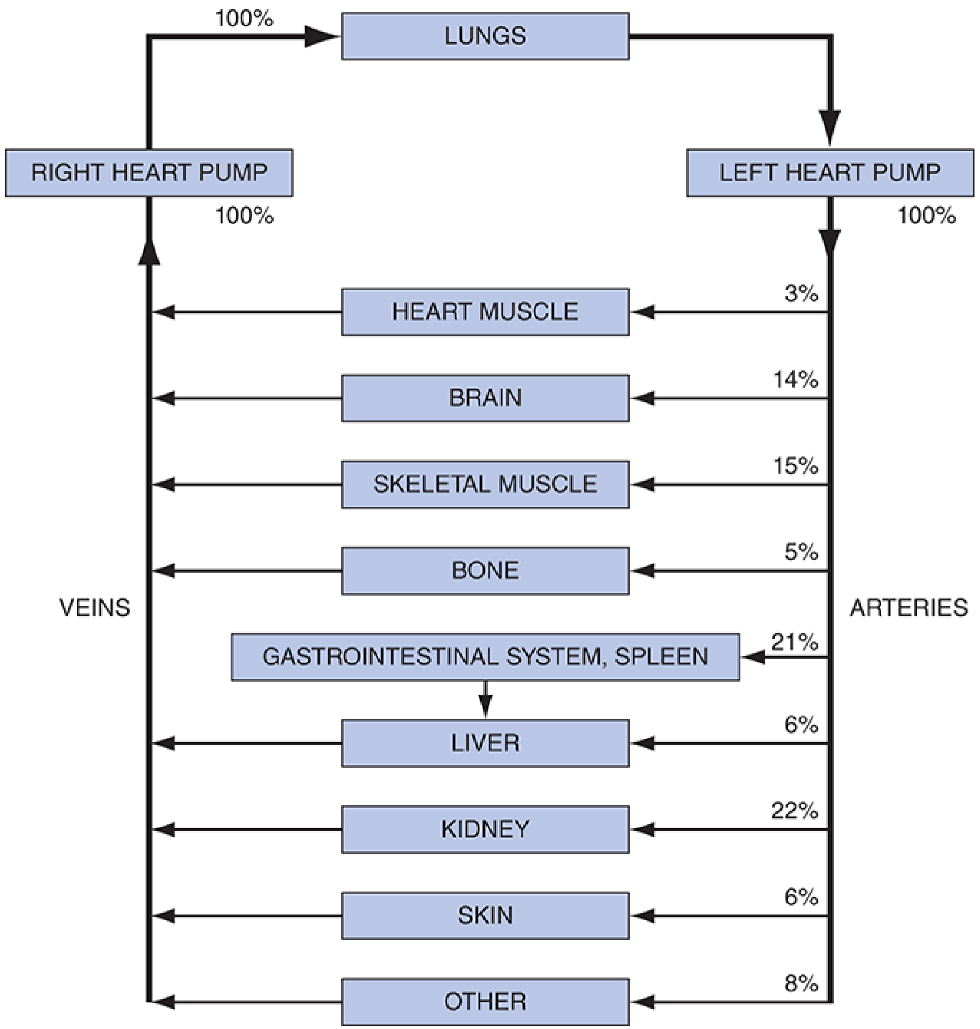


The pumping system: role of the heart

- The heart consists of two muscular pumps
- Blood flow through organs is passive
- Right heart pump provides energy to push blood through pulmonary vessels
- Left heart pump provides energy to push blood through the systemic organs

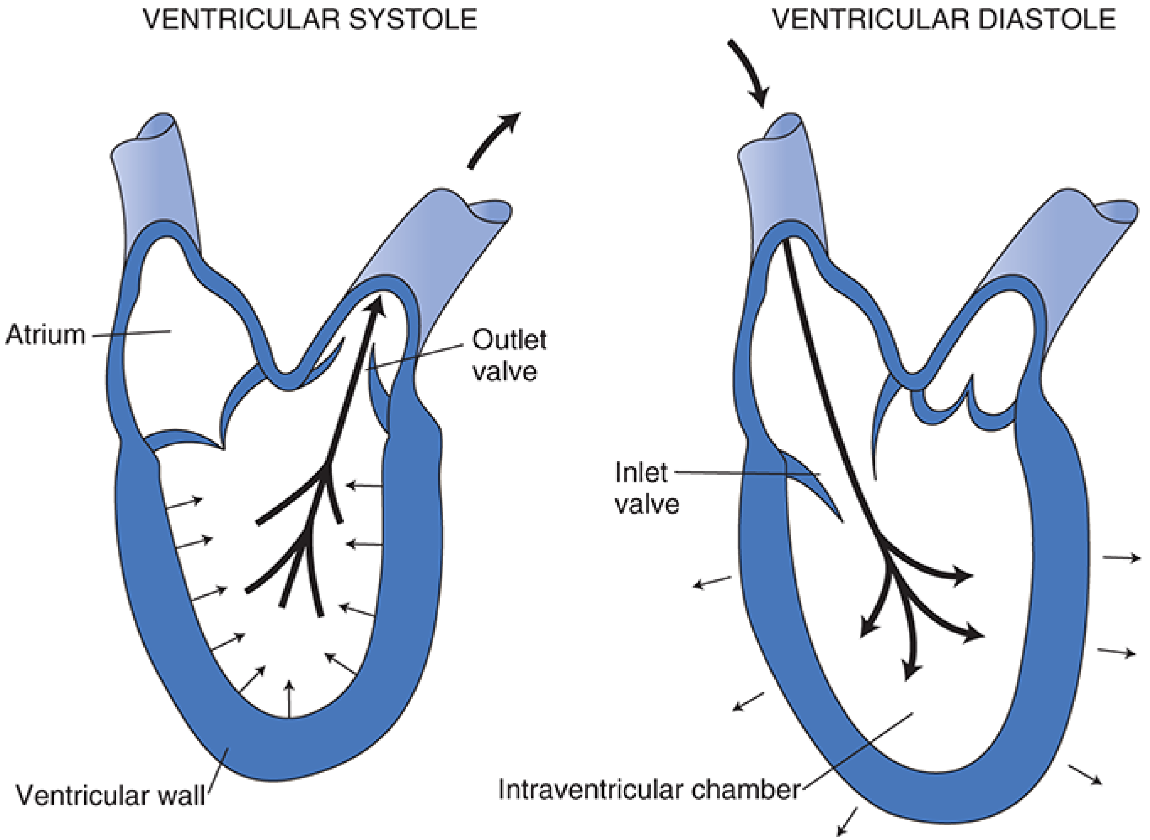




Source: David E. Mohrman, Lois Jane Heller: *Cardiovascular Physiology*, 9e

The pumping system: role of the heart

- Each side consists of two chambers: an atrium and a ventricle
- Heart valves allow flow of blood in one direction only
- Systole is the phase of the cardiac cycle when the muscle cells are contracting
- Diastole is the phase where muscle cells relax
- The left and right pumps are arranged in series



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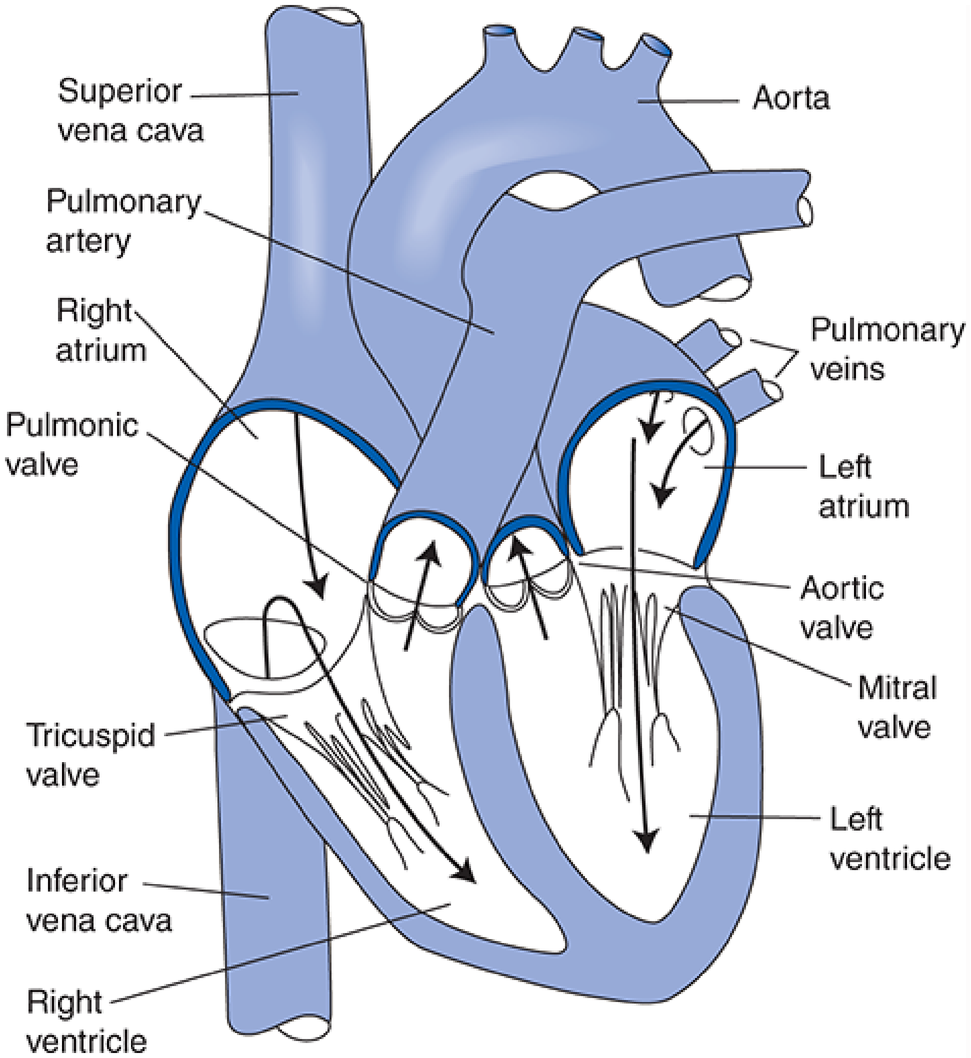
Pathway of blood flow through the heart



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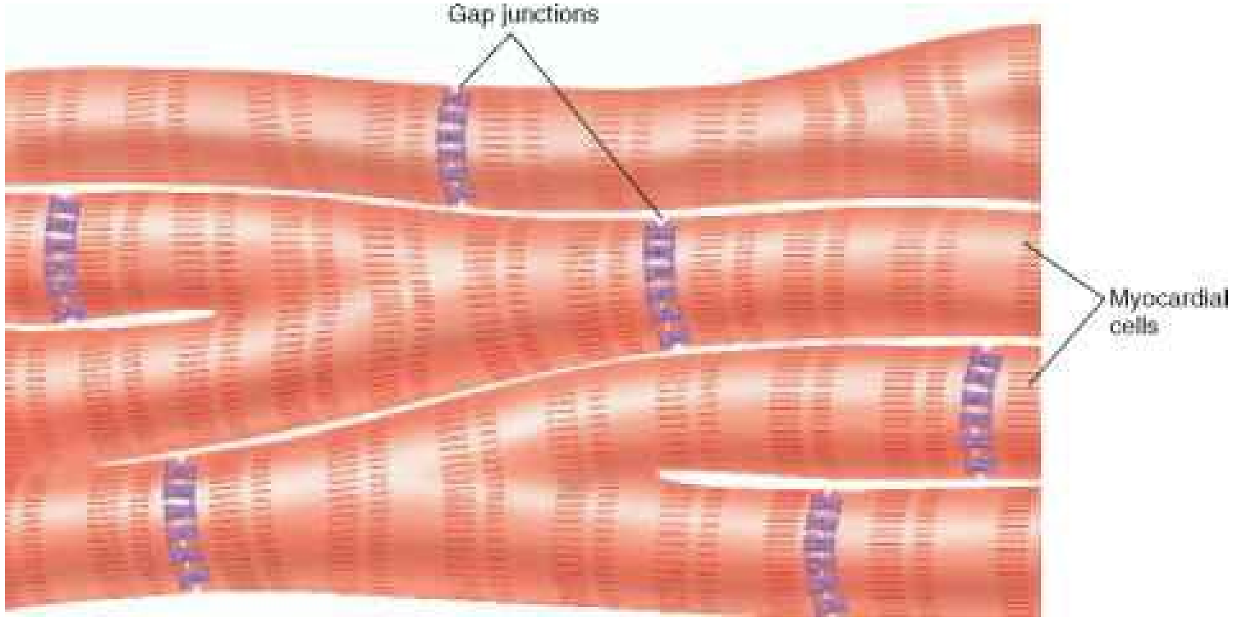
Coordinated pumping of the heart

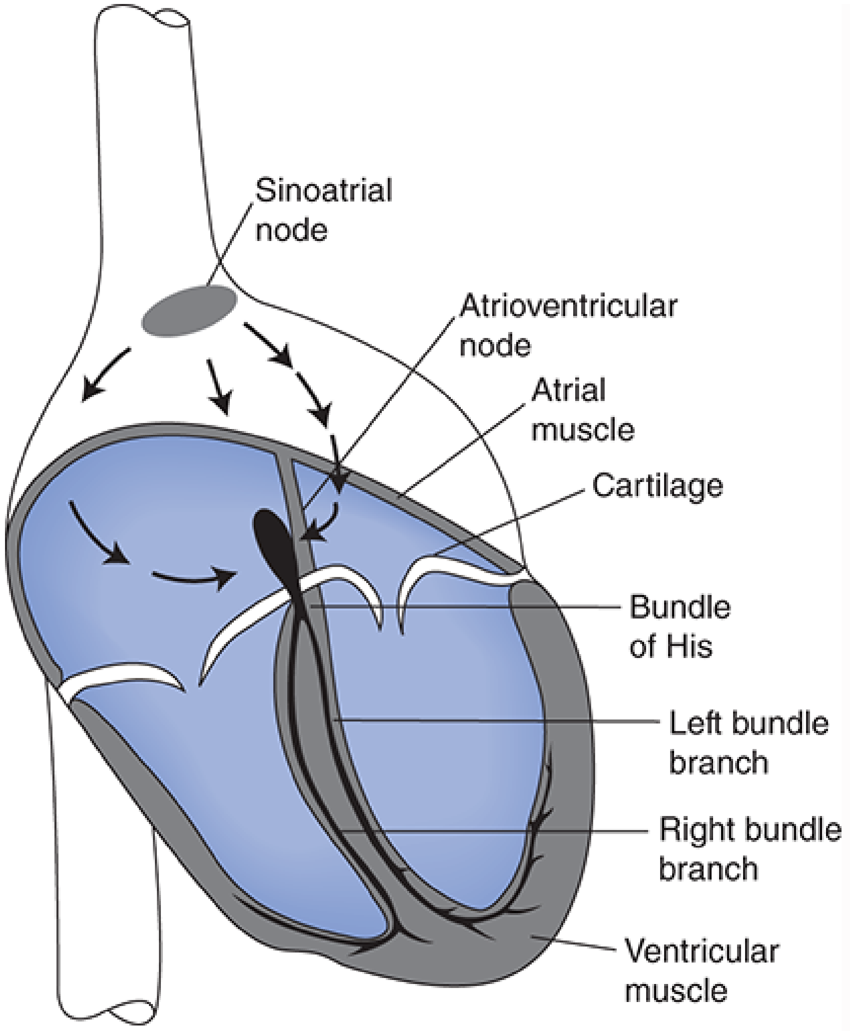
- Efficient pumping requires coordinated contraction of cardiac muscle cells
- Contraction is triggered when an *action potential* sweeps over the cell membrane
- Coordination is achieved primarily by conduction of action potentials between cells via gap junctions that connect cells



https://www.78stepshealth.us/human-physiology/cardiac-and-smooth-muscles.html

Coordinated pumping of the heart

- The heart has a specialised conduction system
- Sinoatrial node (SA) node is the pacemaker – it initiates the action potential
- Conduction system ensures that all of the cells work together to produce efficient pumping of the heart

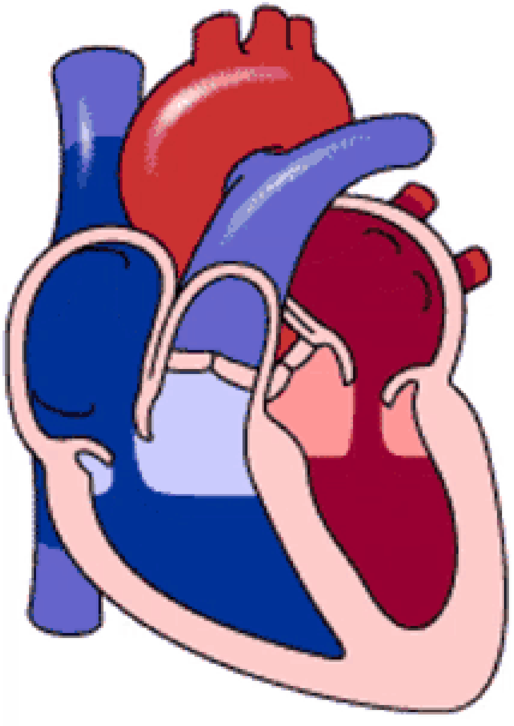


Source: David E. Mohrman, Lois Jane Heller: *Cardiovascular Physiology*, 9e

Coordinated pumping of the heart

Effective cardiac pumping requires:

- Regular, synchronised contractions
- Valves that open and close normally (no leakes)
- Adequate force of muscle contraction
- Adequate filling of ventricles



…… or there will be adverse consequences – stay tuned for the next chapter of this story!

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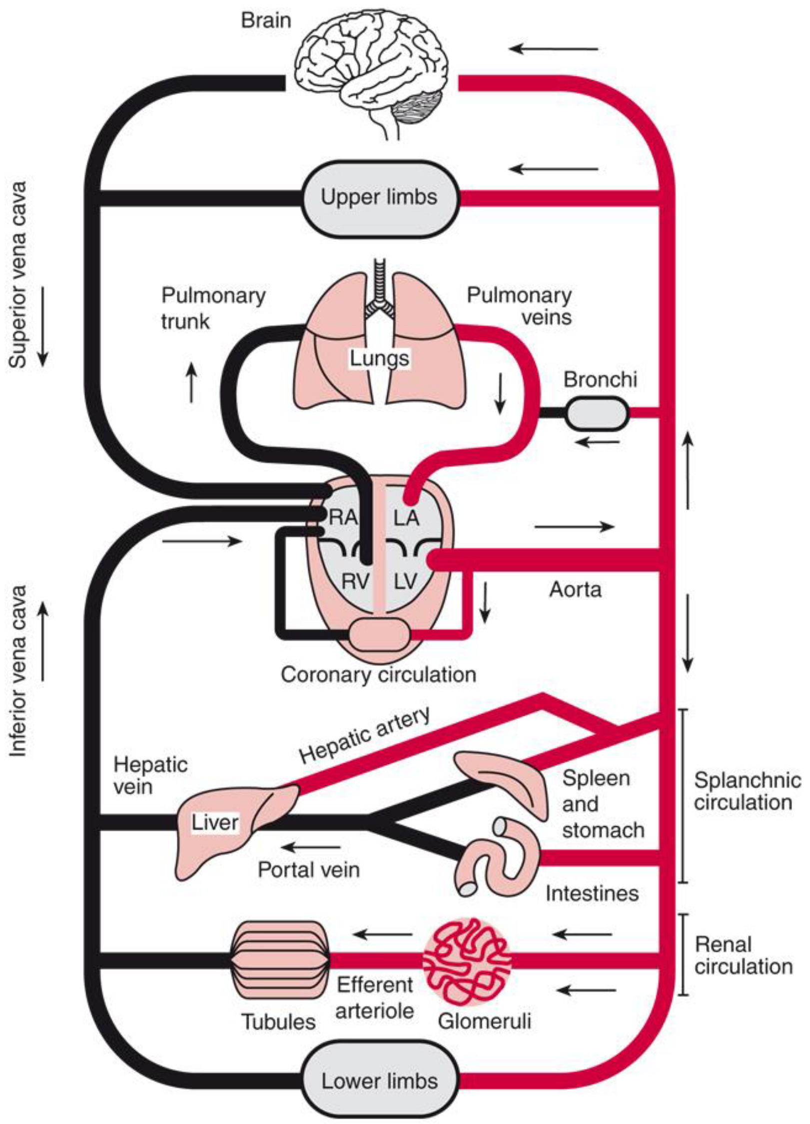

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