Cardiovascular System: Vessels

Over 60,000 miles of vessels per human body

Heart

Elastic Arteries

Muscular Arteries

Arterioles

Capillaries

Veins

Vessel Types:
1) Arteries (away from heart)
2) Capillaries
3) Veins (toward heart)

Blood Vessel Anatomy:

- Branch / diverge / fork
- Join / merge / converge

Pulmonary circuit
- Short, low pressure loop
- O₂-poor; CO₂-rich

Systemic circuit
- Long, high pressure loop
- O₂-rich; CO₂-poor

Function:
1) Circulate nutrients / waste
2) Regulate blood pressure

% / volume not fixed:
- Alteration of arteriole size
- Alteration of cardiac output
- Combination of two above
Blood Vessel Anatomy:

Vessels composed of distinct tunics:

1) Tunica intima
   - Endothelium (simple squamous epithelium)
   - Connective tissue (elastic fibers)

2) Tunica media
   - Smooth muscle / elastic fibers
   - Regulates pressure / circulation
   - Sympathetic innervation

3) Tunica externa
   - Loose collagen fibers
   - Nerves / lymph & blood vessels
   - Protects / anchors vessel

Vasomotor stimulation = vasoconstriction
Vasomotor relaxation = vasodilation

Cardiovascular System – Vessels

<table>
<thead>
<tr>
<th>Arterial/venous:</th>
<th>Hardening / stiffening of arteries</th>
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<tr>
<td>Arteries:</td>
<td>Major groups:</td>
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</table>
|                 | 1) Elastic Arteries: (conducting arteries):
|                 | a. Large, thick-walled (near heart)
|                 | b. Elastic fibers (pressure reservoir) |
|                 | D: 1.5 cm  T: 1.0 mm |
|                 | 2) Muscular Arteries: (distributing arteries):
|                 | a. Deliver blood to organs
|                 | b. T (smooth muscle) (vasoconstriction) |
|                 | D: 8.0 mm  T: 1.0 mm |
|                 | 3) Arterioles: Control blood into capillaries
|                 | a. Neural / hormonal / local controls |
|                 | D: 37.0 μm  T: 6.0 μm |

Relative tissue makeup:

Endothelium
Elastic tissue
Smooth muscle
Fibrous tissue

Cardiovascular System – Vessels

Blood Vessel Anatomy:

Capillaries:

1) Capillaries:
   - Location of blood / tissue interface
   - Stabilized by pericytes (smooth muscle cell)
   - D: 9.0 μm  T: 1.0 μm

Types of Capillaries:

A) Continuous
   - Found throughout body (most common type)

B) Fenestrated
   - Oval pores present
   - Located in high absorption / filtration regions (e.g., kidney)

C) Sinusoidal
   - Holes / ducts present
   - Allow passage of large molecules (e.g., liver)

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Marieb & Hoehn (Human Anatomy and Physiology, 8th ed.) – Table 19.1
Capillaries do not function independently – Instead they form intertwining networks called capillary beds.

• 10 - 100 capillaries / bed
  a) Vascular shunt
  b) True capillaries

Sphincters control blood flow through capillary bed

Not all capillaries are perfused with blood at all times...

• Sphincters control blood flow through capillary bed

Terminal arteriole
Postcapillary venule
Precapillary sphincters

Vascular shunt
b) True capillaries

Veins:

1) Venules:
   - Formed where capillaries unite
   - Extremely porous

2) Veins (capacitance vessels):
   - Large lumen; “volume” sink
   - Low pressure environment

Venous sinuses:
Specialized, flattened veins composed only of endothelium; supported by surrounding tissues

Capillaries
Vascular shunt
Terminal arteriole
Postcapillary venule
Precapillary sphincters

Leukocyte margination

D: 20.0 µm
T: 1.0 µm

D: 5.0 mm
T: 0.5 mm

Endothelium
Elastic tissue
Smooth muscle
Fibrous tissue

Marieb & Hoehn (Human Anatomy and Physiology, 8th ed.) – Figures 19.4

Marieb & Hoehn (Human Anatomy and Physiology, 8th ed.) – Figures 19.3 / 19.5
Blood Vessel Anatomy:

Vascular anastomoses: Regions where vessels unite, forming interconnections

Arteriovenous anastomoses:

1. Heart
2. Vascular anastomoses are common; vessel blockages rarely lead to tissue death
3. Great saphenous vein harvest

Arterial anastomoses provide alternative channels for blood to reach locations:

- Joints
- Abdominal organs
- Brain

Retina, spleen, & kidney have limited collateral circulation

Venous anastomoses are common; vein blockages rarely lead to tissue death

Heart

Pathophysiology:

Atherosclerosis:

Most common form of arteriosclerosis

Formation of atheromas (small, patchy thickenings) on wall of vessel; intrude into lumen

1) Endothelium injured
   - Infection / hypertension
2) Lipids accumulate / oxidize
   - LDLs collect on tunica intima
   - Foam cells: Macrophages engorged with LDLs, form fatty streaks

3) Fibrous plaque forms
   - Collagen / elastin fibers deposited around dying or dead foam cells

4) Plaque becomes unstable
   - Calcium collects in plaque
   - Vessel constricts; arterial wall thins / ulcerates (= thrombus)

Outcome:

- Myocardial infarctions
- Strokes
- Aneurysms

Statins: Cholesterol lowering drugs

Angioplasty / Stent: Bypass surgery

Hemodynamics:

To stay alive, blood must be kept moving...

Blood Flow:

Volume of blood flowing past a point per given time (ml / min)

The velocity of blood flow is not related to proximity of heart, but depends on the diameter and cross-sectional area of blood vessels

\[ v = \frac{Q}{A} \]

- \( v \) = Velocity (cm / sec)
- \( Q \) = Flow (ml / sec)
- \( A \) = Cross-sectional area (cm²)

Costanzo (Physiology, 4th ed.) – Figure 4.4
To stay alive, blood must be kept moving...

Blood Flow:
Volume of blood flowing past a point per given time (ml / min)

The velocity of blood flow is not related to proximity of heart, but depends on the diameter and cross-sectional area of blood vessels

\[ v = \frac{Q}{A} \]

Blood velocity is highest in the aorta and lowest in the capillaries

Cardiovascular System – Vessels

A man has a cardiac output of 5.5 L / min. The diameter of his aorta is estimated to be 20 mm, and the total cross-sectional area of his systemic capillaries is estimated to be 2500 cm².

What is the velocity of blood flow in the aorta relative to the velocity of blood flow in the capillaries?

\[ v_{\text{capillaries}} = \frac{5.5 \text{ L / min}}{2500 \text{ cm}^2} = 2.2 \text{ cm / min} \]
\[ v_{\text{aorta}} = \frac{5500 \text{ cm}^3 / \text{ min}}{3.14 \text{ cm}^2} = 1752 \text{ cm / min} \]

800x difference

Blood Pressure:
Force per unit area on wall of vessel (mm Hg)

- The magnitude of blood flow is directly proportional to the size of the pressure difference between two ends of a vessel
- The direction of blood flow is determined by the direction of the pressure gradient

Always moves from high to low pressure

Blood Flow (Q) = Difference in blood pressure (\(\Delta P\))

Hemodynamics:
To stay alive, blood must be kept moving...

Hemodynamics: Cardiovascular System – Vessels

Blood flow through a blood vessel or a series of blood vessels is determined by blood pressure and peripheral resistance.

Peripheral Resistance:
Amount of friction blood encounters passing through vessels (mm Hg/mL/min)

• Blood flow is inversely proportional to resistance encountered in the system.

\[
\text{Blood Flow (Q)} = \frac{1}{\text{Peripheral resistance (R)}}
\]

The major mechanism for changing blood flow in the cardiovascular system is by changing the resistance of blood vessels, particularly the arterioles.

Analogous to Ohm’s Law: \( V = IR \) or \( I = \frac{V}{R} \)

\[
\begin{align*}
\text{Blood Flow (Q)} &= \frac{\text{Difference in blood pressure (\( \Delta P \))}}{\text{Peripheral resistance (R)}} \\
&= \frac{\Delta P}{Q}
\end{align*}
\]

A man has a renal blood flow of 500 mL/min. The renal arterial pressure is 100 mm Hg and the renal venous pressure is 10 mm Hg. What is the vascular resistance of the kidney for this man?

\[
\text{Q} = \frac{\Delta P}{R} \\
R = \frac{\Delta P}{Q} \\
R = \frac{100 \text{ mm Hg} - 10 \text{ mm Hg}}{500 \text{ mL/min}} \\
R = 0.18 \text{ mm Hg/mL/min}
\]
Hemodynamics:

The factors that determine the resistance of a blood vessel to blood flow are expressed by Poiseuille's law:

\[ R = \frac{8L\eta}{\pi r^4} \]

1) Blood viscosity 2) Vessel Length 3) Vessel Diameter

\[ \text{viscosity} \rightarrow \text{resistance} \]
\[ \text{length} \rightarrow \text{resistance} \]
\[ \text{diameter} \rightarrow \text{resistance} \]

Hemodynamics:

The total resistance associated with a set of blood vessels also depends on whether the vessels are arranged in series or in parallel.

A) Series resistance:

Sequential arrangement (e.g., pathway within single organ)

The total resistance is equal to the sum of the individual resistances:

\[ R_{\text{total}} = R_1 + R_2 + R_3 + \ldots + R_n \]

B) Parallel resistance:

Simultaneous arrangement (e.g., pathway among various circulations)

The total resistance is less than any of the individual resistances:

\[ R_{\text{total}} < R_1 \]

Costanzo (Physiology, 4th ed.) – Figure 4.5

Hemodynamics:

To stay alive, blood must be kept moving…

Cardiovascular System – Vessels

Powerful relationship
Slight diameter change equals large resistance change

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Hemodynamics:

To stay alive, blood must be kept moving...

Cardiovascular System – Vessels

Ideally, blood flow in the cardiovascular system is streamlined

1) Laminar Flow: Characterized by parabolic velocity profile
   - Flow is 0 velocity at wall; maximal at center
   - Layers of fluid slide past one another
   
   Viscosity: Measure of the resistance to sliding between adjacent layers
   
   What would you expect to happen to blood viscosity as vessel diameter decreases?
   
   Fahraeus – Lindqvist Effect: Relative viscosity of blood decreases with decreasing vessel diameter (< 0.3 mm ~ 1.8x water)
   
   RBCs Exit to smaller vessels (∞)
   
   Hematocrit
   
   Plasma Skimming

2) Turbulent Flow: Blood moves in directions not aligned with axis of blood flow
   - More pressure required to propel blood
   - Noisy (stethoscope)

   Reynolds Number: Indicator of whether flow will be laminar or turbulent
   
   \[ \nu = \text{turbulence (}> 2000) \]

   Factors affecting Reynolds Number:
   1. Viscosity (↓ viscosity = ↑ Reynolds number)
   2. Velocity (↑ velocity = ↑ Reynolds number)

Compliance:
The capacitance of a blood vessel describes the volume of blood a vessel can hold at a given pressure

\[ \text{Compliance} = \frac{\text{Volume (mL)}}{\text{Pressure (mm Hg)}} \]

Compliance is high in veins (large blood volumes @ low pressure)

Compliance is low in arteries (low blood volumes @ high pressure)

Total blood volume = Unstressed volume + Stressed volume

Changes in compliance of the veins cause redistribution of blood between arteries and veins

Costanzo (Physiology, 4th ed.)
Hemodynamics:

As noted earlier, blood pressure is not equal throughout the system.

- High initial pressure:
  - Large volume of blood entering aorta
  - Low compliance of aortic wall

To stay alive, blood must be kept moving...

Although mean pressure is high and constant, there are pulsations of aortic (and arterial) pressure.

- Systolic Pressure: Pressure from ventricular contraction
- Diastolic Pressure: Pressure from ventricular relaxation

Dicrotic notch: Brief period following closure of aortic valve where pressure drops due to retrograde flow.

Pulse Pressure: Systolic pressure – Diastolic pressure
- Reflective of stroke volume

Mean Arterial Pressure: Diastolic pressure + 1/3 Pulse pressure

Why is it not + 1/2 pulse pressure?
Several pathologic conditions alter the arterial pressure curve in a predictable way.

**Arteriosclerosis**
- Compliance ↓ → Systolic pressure ↑

**Aortic stenosis**
- Stroke volume ↓ → Systolic pressure ↓

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Costanzo (Physiology, 4th ed.) – Figure 4.10

To stay alive, blood must be kept moving...

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Hemodynamics:

As noted earlier, blood pressure is not equal throughout the system:

1. Pressure remains high:
   - High elastic recoil of artery walls
   - Pressure reservoir

2. Dramatic drop in pressure:
   - High resistance to flow
   - Filtration of fluid out of capillaries

3. Pressure continues to drop:
   - Frictional resistance to flow
   - Loss of tone in arterioles

4. Energy consumed to overcome frictional forces

5. Blood return assisted by:
   - Lung tension (↓ resistance)
   - Valves
   - Muscular pumps

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Costanzo (Physiology, 4th ed.) – Figure 4.8

To stay alive, blood must be kept moving...
**Blood Pressure Regulation:**

Mean arterial pressure (P<sub>a</sub>) is the driving force for blood flow, and must be maintained at a high, constant level.

\[
\text{Mean Arterial Pressure (P<sub>a</sub>) = Cardiac Output (Q) \times Peripheral Resistance (R)}
\]

**Factors Affecting Blood Pressure:**

- **Blood Volume**
  - ↑ Blood Volume = ↑ BP
- **Cardiac Output**
  - ↑ CO = ↑ BP
- **Peripheral Resistance (R)**
  - ↑ R = ↑ BP
- **Blood Viscosity**
  - ↑ V = ↑ R = ↑ BP
- **Vessel Length**
  - ↑ L = ↑ R = ↑ BP
- **Vessel Elasticity**
  - ↓ VE = ↑ R = ↑ BP

**Note:** Equation deceptively simple; in reality, cardiac output and peripheral resistance are not independent of each other.

**System 1 - Baroreceptor mechanisms:**

- **Function:**
  - Mechanoreceptors (responsive to stretch)
  - ↑ P<sub>a</sub> = ↑ stretch = ↑ firing rate
  - Mechanoreceptors (responsive to pressure)
  - ↑ P<sub>a</sub> = ↑ pressure = ↑ firing rate

- **Location:**
  - Carotid sinus (increase in P<sub>a</sub>)
  - Glossopharyngeal nerve (IX)
  - Aortic arch (increase in P<sub>a</sub>)
  - Vagus nerve (X)

While sensitive to absolute level of pressure, they are most sensitive to rates of changes in pressure.
Blood Pressure Regulation:

Baroreceptor mechanisms are fast, neurally mediated reflexes that attempt to keep $P_a$ constant via changes in cardiac output and vessel diameter.

System 2

Renin-angiotensin II-aldosterone system is a slow, hormonally mediated response to keep $P_a$ constant via changes in blood volume.

Costanzo (Physiology, 4th ed.)
Blood Pressure Regulation:

Renin-angiotensin II-aldosterone system is a slow, hormonally mediated response to keep \( P_a \) constant via changes in blood volume.

![Diagram of the Renin-Angiotensin System]  

Blood Pressure Regulation:

Additional mechanisms aid in regulating mean arterial pressure

A) Peripheral chemoreceptors (carotid bodies / aortic arch)
- Respond to \( \downarrow P_{O_2} \) with vasoconstriction and increased heart rate

B) Central chemoreceptors (medulla oblongata)
- Respond to primarily \( \uparrow P_{CO_2} \) and \( \downarrow pH \)
  - Brain becomes ischemic
  - \( \downarrow P_{O_2} \) and \( \downarrow pH \)
  - Increased sympathetic outflow
  - Intense arteriolar vasoconstriction in peripheral capillary beds

C) Antidiuretic hormone (ADH)
  - (posterior pituitary)
  - Respond to an \( \uparrow \) serum osmolarity and \( \downarrow \) in blood pressure
  - Triggers vasoconstriction (V_1 receptors)

D) Atrial natriuretic peptide (ANP)
  - (atria)
  - Respond to an \( \uparrow \) in blood pressure
  - Triggers vasodilation and \( \uparrow H_2O \) excretion

Microcirculation:

Functions of the arterioles, capillaries, lymphatic vessels, and veins

- Exchange across capillary wall:
  - \( O_2 / CO_2 \)
  - Fluid / Solute
  - Directly through endothelium
  - Approaches cells between cells

- Simple diffusion drives exchange of gases and solutes
- Fluid transfer across membrane occurs via osmosis
  - Hydrostatic pressure
  - Oncotic pressure

![Diagram of Microcirculation]
Microcirculation:

Fluid movement across a capillary wall is driven by the Starling pressures across the wall.

\[ J_v = K_f [(P_c - P_i) - (\pi_c - \pi_i)] \]

- \( J_v \): Fluid movement (mL/min)
- \( K_f \): Hydraulic conductance (mL/min • mm Hg)
- \( P_c \): Capillary hydrostatic pressure (mm Hg)
- \( P_i \): Interstitial hydrostatic pressure (mm Hg)
- \( \pi_c \): Capillary osmotic pressure (mm Hg)
- \( \pi_i \): Interstitial osmotic pressure (mm Hg)

**Filtration** = Net fluid movement is out of capillary and into interstitial fluid (+ number)

**Absorption** = Net fluid movement is into capillary and out of interstitial fluid (− number)

In a skeletal muscle of an individual, the following Starling pressures were measured:

- \( P_c = 30 \) mm Hg
- \( P_i = 1 \) mm Hg
- \( \pi_c = 26 \) mm Hg
- \( \pi_i = 3 \) mm Hg
- \( K_f = 0.5 \) mL/min • mm Hg

What is the direction and magnitude of fluid movement across this capillary?

\[ J_v = 0.5 \times (30 - 1) - (26 - 3) \]
\[ J_v = 0.5 \times 26 \]
\[ J_v = 3 \text{ mL/min} \]

**Filtration** = 3 mL/min (filtration)
Microcirculation:

Fluid movement across a capillary wall is not equal along the length of a capillary.

\[ J_v = 0.5 \text{ (2)} \]
\[ J_p = 1 \text{ mL/min} \text{ (net filtration)} \]

What happens to the fluid not returned to the capillary?

Lymphoid system returns excess fluid to bloodstream.

Flow of Lymph:

- Originates as pockets
- Large diameters / thin walls
- One-way valves (vena contracta)

Lymph nodes filter fluids (99% purified)

Lymph node biopsy

Lymphatic vessels

Thoracic Duct:
- Begins inferior to diaphragm
- Empties into left subclavian vein

Right Lymphatic Duct:
- Empties into right subclavian vein

Cisterna chyli:
Chamber that collects lymph from abdomen, pelvis, and lower limbs

Cardiovascular System – Vessels

Marieb & Hoehn (Human Anatomy and Physiology, 8th ed.) – Figure 20.2

Randall et al. (General Animal Physiology, 5th ed.) – Figure 12.37
**Pathophysiology:**

**Cardiovascular System – Vessels**

**Edema (swelling)** results from an increase in interstitial fluid volume.

Forms when the volume of fluid filtered out of the capillaries exceeds the ability of the lymphatics to return it to circulation.

The equation for fluid balance in the interstitial space is:

\[ J_v = [K_f (P_c - P_i) - \pi_c + \pi_i] \]

**Causes:**

1. Increased capillary hydrostatic pressure
   - Arterial dilation
   - Deep vein thrombosis
   - Heart failure
2. Decreased capillary oncotic pressure
   - Severe liver failure (liver protein synthesis)
   - Protein malnutrition
3. Increased hydraulic conductance
   - Severe burn
   - Inflammation (leaky vessels)
4. Impaired lymphatic drainage
   - Removal / irradiation of lymph nodes
   - Parasitic infection

**Special Circulations:**

Blood flow is variable between one organ and another, depending on the overall demands of each organ system.

What about the lungs?

Interorgan differences in blood flow result from differences in vascular resistance.

Blood flow to specific organs can increase or decrease depending on metabolic demands.

Changes in blood flow to an individual organ are achieved by altering arteriolar resistance.

The mechanisms that regulate blood flow are categorized as local (intrinsic) control and neural / hormonal (extrinsic) control.

1) **Local control:**

   A) **Autoregulation**

      - Maintenance of constant blood flow in face of changing arterial pressure

      \[ Q = \Delta P / R \]

      **Myogenic Hypothesis:**

      When vascular smooth muscle is stretched, it contracts.

      \[ \Delta P = \uparrow \text{smooth muscle stretch} \Rightarrow \text{vasoconstriction} \]

      **ALTERNATIVELY**

      \[ \Delta P = \downarrow \text{smooth muscle stretch} \Rightarrow \text{vasodilation} \]
The mechanisms that regulate blood flow are categorized as local (intrinsic) control and neural / hormonal (extrinsic) control.

1) Local control:

   B) Active hyperemia
   • Blood flow to an organ is proportional to its metabolic activity

   C) Reactive hyperemia
   • Blood flow to an organ is increased in response to a period of decreased blood flow

**Metabolic Hypothesis:**
\[ \text{O}_2 \text{ delivery to a tissue is matched to O}_2 \text{ consumption by altering arteriole resistance} \]

- Tissues
- Back to resting...

**Blood flow to an organ is proportional to its metabolic activity**
- Blood flow to an organ is increased in response to a period of decreased blood flow

Local controls are most important mechanism for regulating coronary, cerebral, skeletal muscle, pulmonary, and renal circulation.

2) Neuronal / Hormonal controls:

   A) Neuronal
   • Sympathetic innervation of vascular smooth muscle

   B) Hormonal
   • Histamine
     - arteriodilator; vasoconstrictor
     - \( \uparrow P_c \) = local edema
   • Bradykinin
     - arteriodilator; vasoconstrictor
     - \( \uparrow P_c \) = local edema
   • Serotonin
     - local vasoconstriction
   • Prostaglandins
     - local vasodilators / vasoconstrictors

Sympathetic innervation of vascular smooth muscle

Circulatory shock refers to any condition in which the blood vessels are inadequately filled.

**Hypovolemic Shock**
- Large-scale blood loss
- Acute hemorrhage
- Severe vomiting / diarrhea
- Extensive burns

**Vascular Shock**
- Abnormal expansion of vascular beds due to extreme vasoconstriction
- Failure of ANS regulation
- Septicemia (infection)

**Cardiogenic Shock**
- Heart malfunctions
- Myocardial infarction