The Circulation

Dr. Adelina Vlad, MD PhD
The Cardiovascular System

- Integrates three functional parts
  - The heart, a pump that circulates a liquid, the blood,
  - through a set of containers, the vessels
The Vascular System

- On the basis of its anatomy, can be divided into:
  - **Systemic circulation** (greater circulation or peripheral circulation)
  - **Pulmonary circulation**

- It is a closed network of tubes that start and end at the heart:
  - **The arteries**, a distribution system that transports blood under **high pressure** *from the heart to the tissues*
  - **The microcirculation**, a diffusion and filtration system
  - **The veins** (and lymph vessels), a collection system that transports blood under **low pressure** *from tissues to the heart*
Physical Characteristics of the Vascular System

Mean linear velocity of blood flow is inversely proportional to aggregate vascular cross-sectional area:
- **21 cm/s** in the aorta
- **0.03 cm/s** in the capillaries, under resting conditions
- **14 cm/s** in venae cavae
Pressures Along the Vascular System

- **High pressure** zone: contracting LV → systemic arterioles
- **Low pressure** zone: systemic capillaries → right heart → pulmonary circulation → left atrium → LV in relaxed state

Normal blood pressures in the different portions of the circulatory system when a person is lying in the horizontal position:

- Pulsatile Mean value: 100 mmHg
- Average pressure 17 mm Hg
- LV

- Pulsatile Mean value: 16 mmHg
- Average pressure 7 mm Hg
- RV
HEMODYNAMICS

- Is the study of the physical laws of blood circulation

- Addresses the properties of
  - The container – blood vessels
  - The content – blood

- Blood flow is driven by a pressure head across variable resistances
Interrelationships Among Pressure, Flow, and Resistance

- **Blood flow** $F$ through a blood vessel is determined by two factors:
  - **pressure difference** $\Delta P$ of the blood between an upstream point and a downstream site = “pressure gradient” along the vessel, which is the **driving force** of the blood flow
  - **vascular resistance** $R$ between those two points, which is the **impediment** to blood flow through the vessel
- The analogous of Ohm’s law of electricity for direct current $I = \Delta V/R$, is the **Ohm’s law of hydrodynamics**: $F = \frac{\Delta P}{R}$
Blood Flow
Total Blood Flow in the Circulation

- Blood flow is the quantity of blood (ΔV) that passes a given point in the circulation in a given period of time (Δt):
  \[ F = \frac{ΔV}{Δt} \]

- The flow of blood delivered each minute by the heart, or the total mean flow in the circulation is the cardiac output
  \[ CO = SV \times HR = 5 \text{ liters/min at rest} \]

- \[ F = \frac{ΔP}{R} = \text{cardiac output (l/min or ml/min)} \]
- \[ ΔP = \text{pressure difference between Ao and VC (mm Hg), or between PA and PVs} \]
- \[ R = \text{total peripheral resistance (TPR) (mmHg/ml/min) in systemic or pulmonary circulation} \]
Flow – Velocity Relationship

- \( F \), is the quantity of blood (\( \Delta V \)) that passes a given point in the circulation in a given period of time (\( \Delta t \)): \( F = \frac{\Delta V}{\Delta t} \)

- \( \Delta V = A \times \Delta x \) if \( A \) is the cross-section area of the blood vessel and \( \Delta x \) the distance the blood bolus advances in \( \Delta t \) with a mean velocity \( v \); therefore:

\[
F = \frac{\Delta V}{\Delta t} = \frac{A \times \Delta x}{\Delta t} = A \times \frac{\Delta x}{\Delta t} = A \times \bar{v}
\]
Principle of Continuity

- In any steady-state process, the rate at which the mass enters the system must equal the rate at which mass leaves the system \( \Leftrightarrow \text{flow in} = \text{flow out} \)

- Hemodynamic applications
  - Two sets of vessels in series (systemic and pulmonary circulation) have the same flow \( \rightarrow \text{CO of the right and left heart must be equal} \)
  - The aggregate flow at any level of vascular arborization must be the same
    \[ F_{\text{Total}} = A_1 \cdot \bar{v}_1 = A_2 \cdot \bar{v}_2 = A_3 \cdot \bar{v}_3 = \ldots \]
    \( \rightarrow \) The mean linear velocity of blood flow is inversely proportional to aggregate vascular cross-sectional area
The aggregate cross-sectional area of each vascular territory and the blood velocity through it are mirror images of one another.
Vascular Parameters Vary with Arborization

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>AORTA</th>
<th>SMALL ARTERIES</th>
<th>ARTERIOLES</th>
<th>CAPILLARIES</th>
<th>VENA CAVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of units</td>
<td>1</td>
<td>8000</td>
<td>2 × 10⁷</td>
<td>1 × 10¹⁰ open (4 × 10¹⁰ total)</td>
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<tr>
<td>Internal radius</td>
<td>1.13 cm</td>
<td>0.5 mm</td>
<td>15 μm</td>
<td>3 μm</td>
<td>1.38 cm</td>
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<tr>
<td>Cross-sectional area</td>
<td>4 cm²</td>
<td>7.9 × 10⁻³ cm²</td>
<td>7.1 × 10⁻⁷ cm²</td>
<td>2.8 × 10⁻⁷ cm²</td>
<td>6 cm²</td>
</tr>
<tr>
<td>Aggregate cross-sectional area</td>
<td>4 cm²</td>
<td>63 cm²</td>
<td>141 cm²</td>
<td>2827 cm²</td>
<td>6 cm²</td>
</tr>
<tr>
<td>Aggregate flow</td>
<td>83 cm³/s (ml/s)</td>
<td>83 cm³/s</td>
<td>83 cm³/s</td>
<td>83 cm³/s</td>
<td>83 cm³/s</td>
</tr>
<tr>
<td>Mean linear velocity</td>
<td>21 cm/s</td>
<td>1.3 cm/s</td>
<td>0.6 cm/s</td>
<td>0.03 cm/s</td>
<td>14 cm/s</td>
</tr>
<tr>
<td>Single-unit flow</td>
<td>83 cm³/s (ml/s)</td>
<td>0.01 cm³/s</td>
<td>4 × 10⁻⁶ cm³/s</td>
<td>8 × 10⁻⁹ cm³/s²</td>
<td>83 cm³/s</td>
</tr>
</tbody>
</table>

Branching in a typical microcirculation (smooth muscle and submucosa of the intestine)
Poiseuille’s Law

- The flow can be predicted from the geometry of the vessel and the properties of the fluid with the Poiseuille-Hagen equation:

$$F = \Delta P \cdot \frac{\pi r^4}{8\eta \ell}$$

- In other words, the flow is:
  - Directly proportional to the axial pressure difference $\Delta P$
  - Increases with the fourth power of vessel radius $r$
  - Inversely proportional to both the length of the vessel $\ell$ and the viscosity of the fluid $\eta$

- The Ohm’s law applies to all vessels, whereas Poiseuille’s equation applies only to rigid, cylindrical tubes.
Poiseuille’s Law Requirements

- The fluid must be incompressible
- The tube must be straight, rigid, cylindrical, unbranched, with a constant radius
- The velocity of the thin fluid layer at the wall must be zero (no slippage)
- The flow must be laminar
- The viscosity of the fluid must be constant
- The flow must be steady (not pulsatile)
Laminar Versus Turbulent Flow

- **Laminar flow** – blood flows in streamlines, with each layer of blood remaining the same distance from the vessel wall.
- **Turbulent flow** - blood flows in all directions inside the vessel and mixes continuously.

- Occurs at high flow rates (beyond a critical velocity), when blood passes by an obstruction in a vessel or when it makes a sharp turn.
- A turbulent flow is not anymore proportional to $\Delta P$, but to roughly the square root of $\Delta P$ because $R$ increases → turbulence causes kinetic energy losses.
- Vortex formation during turbulence sets up murmurs.
Reynolds Number

- Is a parameter that determines **when flow becomes turbulent**

\[ Re = \frac{2\pi rv}{\eta} \]

- Tube radius, \( r \) – velocity, \( v \), density, \( \rho \), viscosity, \( \eta \)

- Turbulent blood flow occurs when
  - vessel radius (\( r \)) is large (**aorta**) or blood velocity (\( v \)) is high (**high cardiac output**); also, when local decrease in vessel diameter causes an increase in \( v \) (arterial **stenosis** or external **compression**)
  - viscosity (\( \eta \)) lowers (**anemia**); viscosity reflects the cohesive forces that tend to keep the layers well organized

- \( Re < 2000 \rightarrow \) laminar flow; \( Re > 3000 \rightarrow \) turbulent flow

- Murmurs occur in: vascular stenosis, shunts, cardiac valvular lesions
The Reynolds number gives a measure of the ratio of inertial forces to viscous forces:

- at low $Re$, viscous forces ($2r/v\eta$) are dominant $\rightarrow$ laminar flow characterized by smooth, constant fluid motion;

- at high $Re$, inertial forces ($v\rho$) are dominant, which tend to produce random eddies, vortices and other flow instabilities $\rightarrow$ turbulent flow.
Pressure Inside the Vessels
Pressure Inside the Vessels

- Is the force exerted by the blood against any unit area of the vessel wall, relative to the barometric pressure ($P_B$)
- Standard units of pressure:
  - $mm \ Hg$ or $cm \ H_2O$ for clinicians ($P = \rho gh$)
    - 1 mm Hg pressure = 1.36 cm $H_2O$ pressure
  - $Pascals$, $g/cm^2$, or $dynes/cm^2$ for physicists
Pressure Differences in the Circulation

- **Driving pressure** is the axial pressure difference and causes blood to flow from \( x_1 \) to \( x_2 \); in the circulation, it is the \( \Delta P \) between the arterial and venous ends of the systemic (or pulmonary) circulation.

- **Transmural pressure**, the \( \Delta P \) between \( r_1 \) and \( r_2 \), is the difference between the intravascular pressure and the tissue pressure.

- **Hydrostatic pressure**, the \( \Delta P \) between point \( h_1 \) and \( h_2 \) along the height axis, it exists even in the absence of any blood flow.
Factors that Generate Pressure in the Circulation

1. Compliance of the vessels
2. Gravity
3. Viscous resistance
4. Velocity (Bernoulli effect)
1. Compliance of the Vessels

- Is the volume of blood that can be stored in a given portion of the circulation for each millimeter of mercury pressure rise:

\[
\text{Vascular compliance} = \frac{\text{Increase in volume}}{\text{Increase in pressure}}
\]

- Low compliance increases the transmural pressure when the blood volume is increased (rigid vessels $\rightarrow$ high blood pressure)
2. Gravity

- Causes hydrostatic pressure when there is a difference in height:

\[ \Delta P = \rho g \Delta h \]

- In the cardiovascular system, the reference h level (zero height) is the level of the heart; here the pressure is unaffected by changes of body posture

- **Horizontal position:** relatively constant intravascular pressures along the body

- **Upright position:** intravascular pressure increases tremendously in the foot, and decreases in the head
The pressures are different between A and B, but the driving pressures ($\Delta P$) between arteries and veins are the same (separation between red and blue lines, violet background).
3. Viscous Resistance

- Blood viscosity, $\eta$, is the internal friction of blood layers.

- According to Poiseuille’s law:

  $$\Delta P = F \times \frac{8\eta l}{\pi r^4}$$

  an increase in blood viscosity generates a rise of blood pressure by increasing resistance.
4. Pressure – Velocity Relationship

- The heart imparts its energy in a pulsatile manner, with each heart beat → velocity varies during a cardiac cycle.

- Changes in velocity lead to compensatory changes in intravascular pressure:
  - The fluid pressure (potential energy, $p$) must decrease when velocity (kinetic energy, $\frac{1}{2} \rho v^2$) increases to satisfy conservation of energy or Bernoulli equation:
    $$p + \frac{1}{2} \rho v^2 + \rho gh = ct,$$
    and for horizontal fluid flows:  $$p + \frac{1}{2} \rho v^2 = ct$$

Or: Total energy = potential energy + kinetic energy = constant

→ trade-off between velocity and pressure
Bernoulli Effect

- Pressure decreases when the velocity of blood flow increases

\[ F = A_1 \times v_1 = A_2 \times v_2 \Rightarrow v_2 > v_1 \]
\[ P_1 + \frac{1}{2} \rho v_1^2 = P_2 + \frac{1}{2} \rho v_2^2 = ct \]
• Considering all these sources of pressure, we can state that the total pressure difference, instead of being given by Ohm's law of hydrodynamics ($\Delta P = F \times R$), is

$$\Delta P_{\text{total}} = \Delta P_{\text{gravity}} + \Delta P_{\text{compliance}} + \Delta P_{\text{viscous resistance}} + \Delta P_{\text{inertiance}}$$

**Inertia** is the resistance of any physical object to a change in its state of motion and reflects the trade-off between kinetic (velocity) and potential energy (pressure)

→ **inertiance** refers to Bernoulli effect in vessels where velocity changes due to cardiac cycle or pathological events
Vascular Impedance

- Both $P$ and $F$ through arteries are **pulsatile** during a cardiac cycle $\rightarrow$ an analogy with direct current circuits ($\Delta P = F \times R$) is not sufficient

- It is more accurate an analogy with alternating currents:
  \[ \Delta P = F \times Z, \text{ where } Z \text{ is mechanical impedance, that includes} \]
  - **Compliant impedance** that opposes volume change (compliance of the vessel)
  - **Viscous (or resistive) impedance** that opposes flow (shearing forces in the liquid); this term is the "$R$" of Ohm's law of hydrodynamics: $\Delta P = F \times R$ that applies to **steady** $P$ and $F$
  - **Inertial impedance** that opposes a change of flow (kinetic energy of fluid and vessels)

Conclusion: When $F$ and $P$ oscillate, $P/F = Z$ that depends not only on $R$, but on compliance and inertial properties of the vessels and blood as well
• Ohm's law for alternating current:

\[ E = I \times Z, \]

where \( Z \) is a complex quantity called the **impedance**;

• \( Z \) depends on the
  • electrical **resistance** \( R \) - hydrodynamic analogy = **viscous resistance**
  • electrical **capacitance** \( C \) - hydrodynamic analogy = **compliance**
  • electrical **inductance** \( L \) - hydrodynamic analogy = **inertiance**
Resistance to Blood Flow
Resistance to Blood Flow

- Is the impedance to blood flow in a vessel
- Can be expressed by rearranging the Ohm’s law of hydrodynamics

\[ R = \frac{\Delta P}{F}, \]

an approach independent of geometry, applicable to very complex circuits, such as the entire peripheral circulation

- Units of resistance:
  - PRUs (peripheral resistance unit): mm Hg/(ml/sec)
  - CGS (centimeters, grams, seconds) unit: dyne sec/cm\(^5\)

\[ R \left( \text{in} \frac{\text{dyne sec}}{\text{cm}^5} \right) = 1333 \times \frac{\text{mm Hg}}{\text{ml/sec}} \]
Conductance of Blood in a Vessel

- Conductance is a measure of the blood flow through a vessel for a given pressure difference

\[ C = \frac{F}{\Delta P} = \frac{1}{R} \]

- Unit measure: (ml/sec)/mm Hg
R is Inversely Proportional to $r^4$

- R derived from Poiseuille’s law is

$$R = \frac{8\eta \ell}{\pi r^4}$$

which states that for an individual unbranched, rigid vascular segment with a laminar blood flow the resistance increases tremendously with the decrease of the vessel radius.

For a constant $\Delta P$, a four fold decrease in vessel diameter decreases the flow (increases the R) as much as 256-fold.
Total R is Higher in Arterioles than in Capillaries

- In spite the smallest individual radius in the capillaries, total resistance in arterioles exceeds total resistance in capillaries.
- Why? Because the aggregate resistance of vessels of a particular order of arborization depends not only on $r$, but also on the number of vessels in parallel.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ARTERIOLES</th>
<th>CAPILLARIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal radius ($r_i$)</td>
<td>15 μm</td>
<td>4 μm</td>
</tr>
<tr>
<td>Individual resistance ($R_i$)</td>
<td>$\sim 15 \times 10^7$</td>
<td>$\sim 3000 \times 10^7$</td>
</tr>
<tr>
<td>Number of units</td>
<td>$1 \times 10^7$</td>
<td>$1 \times 10^{10}$</td>
</tr>
<tr>
<td>Total resistance ($R_{total}$)</td>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>
Many parallel blood vessels make it easier for blood to flow through the circuit because each parallel vessel provides another pathway for blood flow.

\[
\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \ldots \quad \text{or} \quad C_{\text{total}} = C_1 + C_2 + C_3 + C_4 \ldots
\]

The total resistance is far less than the resistance of any single blood vessel.

However, increasing the resistance of any of the blood vessels increases the total vascular resistance.
Vessels Connected in Series

- When blood vessels are arranged in series,
  - flow through each vessel is the same
  - the total resistance to blood flow \((R_{\text{total}})\) is equal to the sum of the resistances of each vessel:

\[
R_{\text{total}} = R_1 + R_2 + R_3 + R_4 \ldots
\]

- The overall resistance across a circulatory bed
  - results from parallel and serial arrangements of branches
  - is governed by laws similar to those for the electrical resistances of direct current circuits
Blood takes many parallel pathways from the left heart to the right heart.

In contrast, blood flow from the right heart to the left heart can only take a single pathway, across a single capillary bed in the lungs.

In still other cases, the blood flows through an arrangement of parallel and serial paths.

In most cases, blood flows through a single capillary bed...

Finally, some deoxygenated blood (which should have gone to the right heart) mixes with oxygenated blood bound for the systemic arteries.

...whereas in other cases, the blood flows through two capillary beds in series.
Viscous Resistance

- If the flow fulfills Poiseuille’s requirements, $R$ can be expressed in terms of vessel dimensions $(r, l)$ and viscous properties of the blood ($\eta$)

$$R = \frac{8 \cdot \eta l}{\pi r^4}$$

- **Viscosity** measures the **resistance to sliding** when layers of fluid are shearing against each other
  - Unit of viscosity: poise (P)
  - Whole blood viscosity = 3 cP
For a laminar flow

- The shearing laminae of the blood are concentric cylinders
- A very thin layer of blood close to the wall cannot move due to cohesive forces between the blood and the inner surface of the vessel wall
- The velocities increase from the wall to the center of the cylinder \( \rightarrow \) the velocity profile is a parabola with a maximum velocity at the central axis
Whole Blood Viscosity

- Depends on:
  1) Fibrinogen concentration
  2) Hematocrit
  3) Vessel radius
  4) Linear velocity
  5) Temperature

- At a fibrinogen concentration of 260 mg/dl, a hematocrit of 40% and a temperature of 37°C the whole blood viscosity is approx. 3.2 cP
1) **Fibrinogen**
   - Major plasma protein; key element in the coagulation cascade
   - Induces **erythrocyte aggregation**, which is thought to be caused by a non-specific binding mechanism $\rightarrow$ **increased whole blood viscosity** in the presence of fibrinogen

2) **Hematocrit**
   - It is the percentage of the blood that is cells (normal: 35 – 50%)
   - **Raising the hematocrit** increases the interactions among RBCs $\rightarrow$ **increases viscosity**
   - At hematocrits above 60%, cell-cell interactions deform the RBCs, leading to a steeper increase in viscosity
3) **Vessel radius**

- Viscosity **decreases** steeply at radii < 1 mm (Fahraeus-Lindqvist phenomenon) due to:
  - Axial accumulation of RBCs (plasma imparts a spin to peripheral RBCs) $\rightarrow$ plasma layer close to the wall, where the shearing forces are the greatest
  - Limited number of RBCs floating inside very small vessels (tank treading of RBCs, deformation of RBCs)
4) **Velocity of flow**
   - The tendency for RBCs to move to the center of the stream requires a certain flow → low velocities lead to increased viscosity

5) **Temperature**
   - Low temperature increases viscosity (intense cooling of the extremities), due to an increase of the cohesive forces between molecules
   - The presence of cryoglobulins (infections, autoimmune and lymphoproliferative disorders) that precipitate at less than 37°C can lead to vessel obstruction due to increased viscosity
Resistance and Vasomotion

- Vascular resistance depends critically on the action of vascular smooth muscle cells (VSMCs) that can change vessel $r$

- The terminal small arteries and arterioles is the major site of control of vascular resistance in the systemic circulation

- *Why?* Because the VSMCs in their walls are well represented (predominant) allowing up to four-fold variation in vessel diameter

- Lowering or increasing $r$ by arteriolar VSMCs contraction/relaxation under *humoral* or *nervous influences* can change $R$ as much as 100-fold
Pressure-Flow-Resistance Relationship

- Poiseuille’s law predicts a **linear pressure-flow relationship in rigid tubes**

- In real vessels an increase in pressure not only imparts a stronger impulse to the blood column (linear P - F relationship), but also **distends** the elastic arterial wall → **decrease of R** which further increases F → **nonlinear pressure-flow relationship in elastic vascular beds**

- An increase in active tension (VSMCs contraction after sympathetic stimulation) increases R and the stiffness of the walls, making the P-F relationship more linear and shifted to the right
PLOT

Flow (ml/min) vs. Driving pressure (mm Hg)

- No sympathetic stimulation
- Rigid tube
- Moderate sympathetic stimulation
- High sympathetic stimulation
In conclusion, in elastic vascular beds:

- $R$ decreases as $P$ increases due to vascular distension.
- Flow increases due to a lower $R$.
- $P$ and $F$ exhibit phasic oscillations that cannot be interrelated only by viscous resistance, as in rigid tubes.

→ A more complex term is needed for defining $P/F = \text{mechanical impedance}$, that depends on viscous resistance, as well as the compliance and inertial properties of vessels and blood.
Vascular Distensibility and Functions of the Arterial and Venous Systems
Vascular Distensibility

- Expresses the elastic properties of blood vessels
- Is a property of great functional value because
  - Influences the pressure-resistance-flow relationship
  - Smoothens the intravascular variation in pressure between systole and diastole
  - Influences the volume of blood that can be accommodate by a vessel

\[
\text{Vascular distensibility} = \frac{\text{Increase in volume}}{\text{Increase in pressure} \times \text{Original volume}} = \frac{\Delta V/V_0}{\Delta P}
\]

\( V_0 \) – the unstretched volume of the blood vessel
Vascular Distensibility

- Depends on the structural particulars of each type of vessel (elastic arteries, muscular arteries, veins):
  - arteries are 8 times less distensible than the veins in systemic circulation
  - pulmonary arteries are about 6 times more distensible than systemic arteries
Structure of Vascular Wall

- The wall of blood vessels has three layers: intima, media, adventitia; exception – capillaries have only intima
- The vascular wall has four major components whose relative abundance varies along the vascular circuit: endothelial cells, elastic fibers, VSMCs and collagen fibers

<table>
<thead>
<tr>
<th>Aorta</th>
<th>Medium artery</th>
<th>Arteriole</th>
<th>Precapillary sphincter</th>
<th>True capillary</th>
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</thead>
<tbody>
<tr>
<td>Internal radius: 12 mm</td>
<td>2 mm</td>
<td>15 µm</td>
<td>15 µm</td>
<td>3 µm</td>
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<tr>
<td>Wall thickness: 2 mm</td>
<td>1 mm</td>
<td>20 µm</td>
<td>30 µm</td>
<td>1 µm</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Venule</th>
<th>Vein</th>
<th>Vena cava</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µm</td>
<td>2.5 mm</td>
<td>15 mm</td>
</tr>
<tr>
<td>2 µm</td>
<td>0.5 mm</td>
<td>1.5 mm</td>
</tr>
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</table>
### Structure – Function Relationship

<table>
<thead>
<tr>
<th>Vessel Type</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>Pulse dampening and distribution</td>
</tr>
<tr>
<td>Large Arteries</td>
<td>Distribution</td>
</tr>
<tr>
<td>Small Arteries</td>
<td>Distribution and resistance</td>
</tr>
<tr>
<td>Arterioles</td>
<td>Resistance (pressure/flow regulation)</td>
</tr>
<tr>
<td>Capillaries</td>
<td>Exchange</td>
</tr>
<tr>
<td>Venules</td>
<td>Exchange, collection, and capacitance</td>
</tr>
<tr>
<td>Veins</td>
<td>Capacitance function (blood volume)</td>
</tr>
<tr>
<td>Vena Cava</td>
<td>Collection</td>
</tr>
</tbody>
</table>

- Elastic fibers dominance
- Collagen fibers dominance

*Image showing the structure and function relationship of blood vessels.*
Vascular Compliance or Capacitance

- Is the total quantity of blood that can be stored in a given portion of the circulation for each mm Hg pressure rise

\[
\text{Vascular compliance} = \frac{\text{Increase in volume}}{\text{Increase in pressure}} = \frac{\Delta V}{\Delta P}
\]

- Elastic rich arteries have a greater compliance than muscular arteries

- Although the compliance of veins seems to be high at a normal pressure range, their ability to accommodate large volumes of blood for each mm Hg is rather the result of a change in shape

Relative volume of 100% represents fully relaxed volume
In the arterial system a slight increase in volume causes a steep raise in pressure, proving that arteries have a moderate compliance, whereas veins can accommodate several hundreds ml of blood for an increase in pressure of only 3 – 5 mm Hg, acting as blood reservoirs.

**Sympathetic stimulation** decreases the arterial and venous capacitance by VSMCs contraction.

It is an important response for:
- redistribution of blood among vascular territories
- increasing venous return which eventually increases cardiac output (Frank-Starling law)
- maintaining blood pressure during hemorrhage
Delayed Compliance

- A vessel exposed to increased volume at first exhibits a large increase in pressure (immediate elastic distention), but the pressure returns back toward normal over a period of minutes to hours = stress-relaxation → the circulation can accommodate much extra blood when necessary.

- Delayed compliance in the reverse direction: the circulation automatically adjusts itself (minutes – hours) to diminished blood volume after a serious hemorrhage.

- **Stress-relaxation** and **reverse stress-relaxation**
  - are properties of smooth muscle
  - they allow a hollow organ to maintain about the same amount of pressure inside its lumen despite long-term, large changes in volume.
Arterial Pressure Pulsations

- With each beat of the heart a new surge of blood fills the arteries → pulsatile pressure variations during systole and diastole

- The blood pressure cycles between a maximal **systolic arterial pressure** that corresponds to the contraction of the ventricle and a minimal **diastolic arterial pressure** that corresponds to the relaxation of the ventricle
• The diastolic value is maintained at relatively high values despite the absence of any pressure head.
- Why?

During systole the pressure imparted by the heart to the blood column rises $\rightarrow$ dilation of the arterial wall that stores a volume of fluid $\rightarrow$ the flow rises gradually towards its maximal value.

During diastole the pressure generated by the ventricle falls to zero $\rightarrow$ the expanded vessel comes to the initial size, delivering its stored volume downstream $\rightarrow$ flow and an intravascular pressure that drops smoothly from the systolic value during diastole.
Effect of pulsatile pressure on flow through a compliant vessel
\[ P = F \times R \quad \rightarrow \text{in the circulation} \quad P = CO \times TPR \]
Pulse Pressure

- **Pulse pressure** is the difference between the systolic and the diastolic pressure.

- Major factors affecting the pulse pressure:
  1. the stroke volume output of the heart
  2. the compliance of the arterial tree

- Pulse pressure is determined approximately by the ratio of stroke volume output to compliance of the arterial tree.

Pressure pulsations at the root of the aorta
The spreading of the wave front of distention generated by LV ejection along the arterial walls is called transmission of the pressure pulse in the arteries.

- **Pressure pulse** - a moving wave of pressure that involves little forward total movement of blood volume.

- The greater the compliance of each vascular segment, the slower the velocity, because some of the energy of the pressure pulse goes into dilating the vessel:
  - 3 to 5 m/sec in the normal aorta
  - 7 to 10 m/sec in the large arterial branches
  - 15 to 35 m/sec in the small arteries

!!! The velocity of transmission of the pressure pulse is much higher than the velocity of blood flow.
Damping of the Pressure Pulses

- The intensity of pulsation becomes progressively less in the smaller arteries, the arterioles, and, especially, the capillaries.
- Damping of the pressure pulses is determined by:
  1) resistance to blood movement in the vessels
  2) compliance of the vessels (aggregate compliance increases in the periphery)

The degree of damping is almost directly proportional to the product of resistance times compliance.
Mean Arterial Pressure

- **Mean arterial pressure**
  - is the average of the arterial pressures measured millisecond by millisecond during one cardiac cycle
  - is determined about 60 per cent by the diastolic pressure and 40 per cent by the systolic pressure → mean arterial pressure < average of systolic and diastolic pressure

\[
\text{MAP} = \text{DBP} + \frac{1}{3}(\text{SBP} - \text{DBP})
\]
Pressure Profiles Along Systemic and Pulmonary Circulations

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>MEAN PRESSURE (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systemic large arteries</td>
<td>95</td>
</tr>
<tr>
<td>Systemic arterioles</td>
<td>60</td>
</tr>
<tr>
<td>Systemic capillaries</td>
<td>25 (range, 35-15)</td>
</tr>
<tr>
<td>Systemic venules</td>
<td>15</td>
</tr>
<tr>
<td>Systemic veins</td>
<td>15-3</td>
</tr>
<tr>
<td>Pulmonary artery</td>
<td>15</td>
</tr>
<tr>
<td>Pulmonary capillaries</td>
<td>10</td>
</tr>
<tr>
<td>Pulmonary veins</td>
<td>5</td>
</tr>
</tbody>
</table>

**Systemic circulation**
- Systolic pressure: 120 mm Hg
- Diastolic pressure: 80 mm Hg

**Pulmonary circulation**
- Systolic pressure: 25 mm Hg
- Diastolic pressure: 8 mm Hg
Cardiac outputs of the left and right hearts are the same, whereas the total resistance of the systemic circulation (1.1 PRU) is far higher than that of the pulmonary circulation (0.08 PRU) → higher driving pressure in the systemic circulation

Pulmonary vessels are wider and shorter and have thinner and less muscularly walls → low resistance, high compliance

Systemic pressure falls steeply (arterioles), while the pulmonary pressure drops rather uniformly (pulmonary arterioles are less muscularly and have a lower resistance)
Measuring Systemic Systolic and Diastolic Blood Pressures

- An accurate and direct method is by means of a catheter introduced in the vessel of interest - invasive, used only for special studies
- In clinics, the current approach for determining arterial systolic and diastolic pressure is the indirect, noninvasive auscultatory method; it usually gives values within 10% of those determined by direct catheter measurement
Auscultatory Method

The systolic pressure corresponds to the first tapping sound.

The diastolic pressure corresponds to the muffling of the sounds.