Haemodynamics of the Circulatory System

Haemodynamics is the study of the **forces and principles governing the movement of blood through the cardiovascular system**. It explains the relationship between **pressure, blood flow, resistance, velocity, viscosity and vessel diameter**.

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1. Basic Principles

Blood flows because of a **pressure gradient**:

$$Q=\Delta P R \boxed{Q=\frac{\Delta P}{R}}$$

Where:

- **Q** = blood flow
- **ΔP** = pressure difference between two points
- **R** = vascular resistance

Thus:

> **Blood flow is directly proportional to pressure difference and inversely proportional to resistance.**

For the systemic circulation:

$$CO=MAP-RAP SVR CO=\frac{MAP-RAP}{SVR}$$

Since right atrial pressure is usually small:

$$MAP \approx CO \times SVR \boxed{MAP \approx CO \times SVR}$$

Therefore, arterial blood pressure depends mainly on:

Cardiac output × systemic vascular resistance

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2. Blood Pressure and Pressure Gradient

Blood pressure progressively decreases as blood travels through the circulation.

Approximate pressures:

Site	Pressure (mmHg)
Aorta	~120/80
Large arteries	~120/80
Arterioles	Major pressure drop
Capillaries	~35 → 15
Veins	Low
Right atrium	~0–5

Important point

The **greatest fall in pressure occurs across the arterioles** because they provide the greatest resistance.

Therefore, arterioles are called the:

Resistance vessels

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3. Cardiac Output

Cardiac output is the volume of blood pumped by one ventricle per minute.

CO=HR×SV\boxed{CO=HR\times SV}

Normal resting values:

- Heart rate ≈ **70–75/min**
- Stroke volume ≈ **70 mL**
- Cardiac output ≈ **5 L/min**

Factors affecting cardiac output

Heart rate

↑ HR → ↑ CO, up to an optimum range.

Very excessive tachycardia → reduced ventricular filling → ↓ SV → potentially ↓ CO.

Stroke volume

Stroke volume depends mainly on:

1. Preload
2. Contractility
3. Afterload

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4. Poiseuille's Law

For flow through a cylindrical tube:

$$Q=\pi\Delta Pr48\eta L\boxed{Q=\frac{\pi\Delta P r^4}{8\eta L}}$$

Where:

- **r** = radius
- **η** = viscosity
- **L** = length

Therefore:

$$R=8\eta L\pi r4\boxed{R=\frac{8\eta L}{\pi r^4}}$$

The most important relationship is:

$$R\propto 1r4\boxed{R\propto\frac{1}{r^4}}$$

Significance

A small change in vessel radius produces a very large change in resistance.

For example:

If radius decreases by half:

$$R\rightarrow 16\times R \rightarrow 16\times$$

Thus **arteriolar diameter is a major determinant of systemic vascular resistance and blood pressure.**

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5. Vascular Resistance

The circulatory system contains many vessels arranged both in **series and parallel**.

Vessels in series

Total resistance:

RT=R1+R2+R3...R_T=R_1+R_2+R_3...

Vessels in parallel

1RT=1R1+1R2+1R3+...\frac{1}{R_T}= \frac{1}{R_1}+ \frac{1}{R_2}+ \frac{1}{R_3}+...

The systemic organs are largely arranged **in parallel**.

Advantage of parallel arrangement

Each organ receives blood from the arterial system independently, allowing regional regulation of blood flow.

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6. Laminar and Turbulent Flow

Laminar flow

Blood normally flows in layers.

- Central blood moves fastest.
- Blood near the vessel wall moves more slowly because of friction.

Velocity profile:

Parabolic

Maximum velocity occurs at the centre.

Advantages

- Efficient
- Quiet
- Low energy loss

Turbulent flow

Blood moves irregularly in different directions.

It is more likely when:

- Blood velocity is high
- Vessel diameter is large
- Blood viscosity is low
- There are irregularities or stenosis

Turbulence produces **vascular bruits and cardiac murmurs**.

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7. Reynolds Number

The tendency for turbulent flow can be expressed by:

$$\boxed{Re=\frac{\rho vd}{\eta}}$$

Where:

- ρ = blood density
- v = velocity
- d = vessel diameter
- η = viscosity

Turbulence is more likely when Reynolds number increases.

Therefore turbulence increases with:

- ↑ velocity
- ↑ vessel diameter
- ↓ viscosity

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8. Blood Velocity

Blood velocity is inversely related to the **total cross-sectional area**.

$$\boxed{v=\frac{Q}{A}}$$

Where:

- v = velocity
- Q = flow
- A = cross-sectional area

Cross-sectional area

Aorta → arteries → arterioles → capillaries

Total cross-sectional area becomes greatest at the **capillaries**.

Therefore:

Velocity is lowest in capillaries\boxed{\text{Velocity is lowest in capillaries}}

This is physiologically important because slow flow allows adequate time for:

- Oxygen exchange
- Nutrient exchange
- Removal of metabolic waste

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9. Compliance of Blood Vessels

Compliance is:

C=ΔVΔP\boxed{C=\frac{\Delta V}{\Delta P}}

It represents the ability of a vessel to accommodate changes in blood volume for a given change in pressure.

Veins

Veins are highly compliant and are therefore called:

> **Capacitance vessels**

They contain a large proportion of the circulating blood volume.

Arteries

Arteries have lower compliance and function primarily as:

> **Pressure reservoirs**

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10. Elasticity of Arteries

Large arteries contain abundant elastic tissue.

During ventricular systole:

LV contraction → aortic expansion → storage of elastic energy

During diastole:

Aortic recoil → maintains forward blood flow

This is called the:

Windkessel effect

It converts intermittent ventricular ejection into relatively continuous arterial flow.

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11. Pulse Pressure

PP=SBP−DBP\boxed{PP=SBP-DBP}

For BP 120/80:

PP=120−80=40 mmHgPP=120-80=40\ mmHg

Pulse pressure is influenced particularly by:

- Stroke volume
- Arterial compliance

Increased pulse pressure

Occurs with:

- Increased stroke volume
- Reduced arterial compliance, as in ageing

Reduced pulse pressure

May occur with:

- Reduced stroke volume
- Severe cardiac failure
- Hypovolemia

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12. Mean Arterial Pressure

Because diastole lasts longer than systole at normal heart rates:

MAP≈DBP+13(PP)\boxed{MAP\approx DBP+\frac{1}{3}(PP)}

For 120/80 mmHg:

MAP=80+403MAP=80+\frac{40}{3} MAP≈93 mmHg\boxed{MAP\approx93\ mmHg}

MAP is the major driving pressure for systemic tissue perfusion.

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13. Venous Return

Venous return is the amount of blood returning to the heart per minute.

In the steady state:

Venous Return=Cardiac Output\boxed{Venous\ Return=Cardiac\ Output}

Factors promoting venous return

1. Skeletal muscle pump

Muscle contraction compresses veins.

Muscle contraction → venous compression → one-way valves → blood toward heart

2. Respiratory pump

During inspiration:

Intrathoracic pressure ↓ → venous return ↑

3. Venous valves

Prevent backflow, particularly in the limbs.

4. Sympathetic venoconstriction

Venoconstriction decreases venous capacitance and shifts blood toward the heart.

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14. Capillary Haemodynamics

Capillaries are specialized for exchange.

Their walls consist mainly of:

- Endothelial cells
- Basement membrane

They have a very large total surface area and low blood velocity.

Functions

Exchange of:

- O_2
- CO_2
- Water
- Electrolytes
- Nutrients
- Hormones
- Metabolic products

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15. Starling Forces

Fluid movement across capillary walls depends on hydrostatic and colloid osmotic forces.

Main forces

1. **Capillary hydrostatic pressure (Pc)**
    - Pushes fluid out of capillary.
2. **Plasma colloid osmotic pressure (πc)**
    - Pulls fluid into capillary.
3. **Interstitial hydrostatic pressure (Pi)**
4. **Interstitial colloid osmotic pressure (πi)**

The modern Starling principle recognizes that fluid movement varies along the capillary and that lymphatic drainage is essential for maintaining fluid balance.

Clinical significance

Excess filtration or inadequate lymphatic drainage can produce:

Oedema\boxed{\text{Oedema}}

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16. Factors Affecting Tissue Blood Flow

Blood flow to an organ depends on:

$$Q=\Delta P R \boxed{Q=\frac{\Delta P}{R}}$$

Resistance can be altered mainly by changing **arteriolar radius**.

Vasodilatation

Radius ↑

→ resistance ↓

→ tissue blood flow ↑

Vasoconstriction

Radius ↓

→ resistance ↑

→ tissue blood flow ↓

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17. Autoregulation of Blood Flow

Many organs maintain relatively constant blood flow despite changes in perfusion pressure.

Mechanisms include:

Myogenic mechanism

Increased vascular pressure stretches vascular smooth muscle.

→ smooth muscle contracts
→ vessel constriction
→ flow is stabilized.

Metabolic mechanism

Increased tissue metabolism produces vasodilator substances such as:

- Adenosine
- CO_2
- H^+
- K^+
- Lactate
- Reduced O_2

→ arteriolar dilation
→ increased blood flow.

This is particularly important in the:

- Heart
- Brain
- Skeletal muscle
- Kidneys

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18. Important Relationships in Haemodynamics

Pressure–flow relationship

$$Q=\Delta P R \boxed{Q=\frac{\Delta P}{R}}$$

Resistance–radius relationship

$$R \propto 1 r^4 \boxed{R\propto\frac{1}{r^4}}$$

Velocity–cross-sectional area

$$v=Q A \boxed{v=\frac{Q}{A}}$$

Cardiac output

$$CO=HR \times SV \boxed{CO=HR\times SV}$$

Mean arterial pressure

$$MAP \approx DBP+13(SBP-DBP) \boxed{MAP\approx DBP+\frac{1}{3}(SBP-DBP)}$$

Compliance

$$C=\Delta V \Delta P \boxed{C=\frac{\Delta V}{\Delta P}}$$

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19. Clinical Applications

Haemodynamic change	Consequence
Arteriolar vasoconstriction	↑ SVR, ↑ BP
Arteriolar vasodilatation	↓ SVR, ↑ local flow

Increased blood viscosity	↑ resistance
Reduced vessel radius	Marked ↑ resistance
Atherosclerotic stenosis	↑ resistance, disturbed flow
Increased venous compliance	Venous pooling
Reduced arterial compliance	↑ pulse pressure
Reduced plasma oncotic pressure	Oedema
Increased capillary hydrostatic pressure	Oedema
Increased tissue metabolism	Increased local blood flow

Flow Summary

Cardiac pump

↓ generates

Pressure gradient

↓

Blood flow

$Q=\Delta P$$Q=\frac{\Delta P}{R}$

↓

Arterioles regulate resistance

$R\propto 1r4$$R\propto\frac{1}{r^4}$

↓

Capillaries provide low-velocity exchange

↓

Venules and veins return blood

↓

Venous return = cardiac output

Key Take-Home Points

1. **Pressure gradient is the driving force for blood flow.**
2. **Arterioles are the major resistance vessels.**
3. A small change in arteriolar radius produces a **large change in resistance** because resistance varies inversely with the fourth power of radius.
4. **Capillaries have the greatest total cross-sectional area and therefore the lowest blood velocity.**
5. **Veins are capacitance vessels** because of their high compliance.
6. **MAP is the principal driving pressure for systemic tissue perfusion.**
7. **Cardiac output = venous return** in the steady state.
8. Haemodynamics provides the physiological basis for understanding **hypertension, shock, oedema, heart failure, stenosis, aneurysm and circulatory failure**.