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CHAPTER 5

A Review of Heart's Mechanics Through the Lens of Physics: Integrating Fluid Dynamics into Cardiovascular Health

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Abstract

The human heart, a complex biomechanical pump, operates with remarkable precision to sustain life. Through the lens of physics, this chapter explores the mechanics of the heart, focusing on the forces, pressures, and dynamics that drive its function. Cardiovascular disease remains the leading cause of death globally. This interdisciplinary approach fosters innovative techniques for normal functioning of the cardiovascular system, development of related diseases and its treatments, ultimately leading to improved health outcomes.

Keywords: Fluid dynamics, Hearts mechanics, Blood, Cardiovascular system

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Introduction

Physics forms the foundation of biology, as space, matter, energy and time are essential for the existence of living organisms, the core components of the universe. Physicist Richard Feynman noted that everything on Earth is composed of tiny particles called atoms, the basic units of matter that are constantly in motion. Biology is deeply rooted in physics, as it applies the laws of physics to study the biological processes of living organisms. This helps explain several phenomena such as how bats navigate in the dark, how insect wings enable flight and how whales communicate in the ocean. Physical laws often clarify biological processes on both macroscopic and microscopic scales. For instance, biomedical physics integrates physical principles to solve medical and biological challenges, revealing how fluid dynamics governs blood flow. Conditions such as hypertension (high blood pressure), atherosclerosis (narrowing of arteries), and heart diseases can be more effectively managed by applying these principles.

1. Cardiovascular System

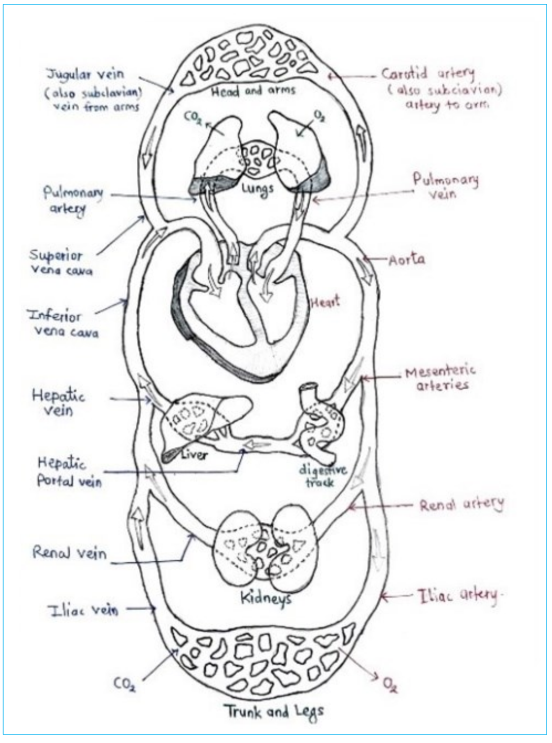

Fig. 1. Schematic view of circulatory system

The cardiovascular system, also known as the circulatory system, is the body's network responsible for transporting blood, nutrients, oxygen, and waste products to and from the cells. It consists of the heart, which acts as a pump, and a vast network of blood vessels, including arteries, veins, and capillaries following the laws of fluid dynamics. Key factors like blood pressure, resistance, viscosity, and vessel diameter influence flow, governed by different physical laws such as Poiseuille's law, which describes the flow of a fluid through a tube. The system delivers oxygen-rich blood from the lungs to

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tissues and organs and returns oxygen-depleted blood back to the lungs for oxygenation. Additionally, it plays a key role in maintaining body temperature, balancing fluid levels, and protecting the body from infections.

The blood circulatory system includes the heart, blood vessels and blood. It consists of systemic circulation (which delivers blood to the body) and pulmonary circulation (which sends blood to the lungs for oxygen).

1.1 Heart: The heart is a vital organ that pumps blood throughout the body, providing oxygen and nutrients to the body’s organ. It acts as a pump.

1.2 Blood: Blood is a fluid that circulates through the body, composed of plasma, RBCs, WBCs and platelets, transporting oxygen, nutrients, and waste products.

1.3 Blood flow: Blood flow refers to the movement of blood through the cardiovascular system (vessels), delivering oxygen and nutrients to tissues and removing waste products.

1.4 Vessels: In biology, a vessel refers to a tube-like structure that carries fluids such as blood, lymph, or sap. here are three main types of blood vessels:

- **Arteries**: Carry oxygen-rich blood away from the heart.
- **Veins**: Carry oxygen-depleted blood back to the heart.
- **Capillaries**: Tiny vessels where the exchange of gases, nutrients, and waste products occurs between blood and tissues.

1.5 Importance of Fluid Dynamics: Fluid dynamics is vital for understanding blood circulation as it explains how blood moves through the cardiovascular system. It helps analyse factors like blood pressure, flow rate, and vessel resistance, aiding in the diagnosis and treatments.

2. Blood as a Fluid

2.1 Fluid: A fluid is a substance that flows and can change shape to fit its container. It includes both liquids and gases and deforms continuously under the application of force. The properties of fluids include viscosity, density, pressure, flow rate, compressibility, surface tension, buoyancy, flow behaviour and diffusion.

2.2 Blood as a Fluid: Blood demonstrates its fluid nature through continuous flow, viscosity, denser than water and pressure adaptation. It flows easily through vessels, conforms to their shape, and adjusts to pressure changes, all of which are key properties of fluids.

2.3 Properties of Blood as a Fluid: Blood is a non-Newtonian fluid, meaning its viscosity changes under different flow conditions. Properties of blood as a fluid are:

1. **Viscosity (η)**: Viscosity is a degree of a fluid's resistance to flow. Mathematically, viscosity is the ratio of shear stress (τ) i.e. force per unit area to the shear rate (γ) i.e. (rate of change in velocity with respect to position).

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$$F = \eta A \frac{u}{y} \text{ or } \eta = \frac{\tau}{\gamma}$$

This is the measure of blood's thickness and resistance to flow. It varies with the concentration of cells and proteins in the blood, impacting how easily it moves through the blood vessels.

2. **Density (ρ):** The average density is defined as its mass (m) per unit volume (V).

   Blood is denser than water due to its cellular components and proteins.

3. **Pressure (P):** Pressure is defined as the ratio of normal force (F) per unit area (A).

   Blood pressure is defined as the force exerted by blood on the walls of vessels. It is vital for driving blood through the circulatory system and varies throughout the body.

4. **Flow Rate (Q)**: This refers to the volume of blood that flows through a vessel within a specific time. It is influenced by factors such as vessel size, blood pressure, and viscosity. Mathematically, $Q = (\text{Area}) \times (\text{velocity})$

5. **Compressibility (β)**: Blood is mostly incompressible, meaning its volume remains nearly unchanged under pressure. This property ensures stable blood flow and circulation.

6. **Flow Behaviour**: Blood can flow in a smooth, orderly manner (laminar flow) or in irregular way (turbulent flow), depending on conditions such as vessel diameter and flow rate.

7. **Surface Tension**: Although less relevant in blood compared to other liquids, surface tension affects blood's interaction with surfaces, particularly in processes like clotting.

8. **Buoyancy**: Although not a primary factor in the body, it can be relevant in laboratory analyses.

3. Methodology: Blood Flow Dynamics

The cardiovascular system works on some physical principles given below:

3.1 Fluid Dynamics Principles

3.1.1 Poiseuille's Law

Statement

Poiseuille's Law describes the flow of a viscous fluid through a cylindrical pipe and is used to understand how various factors affect the flow rate of the fluid. The law is mathematically represented as:

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

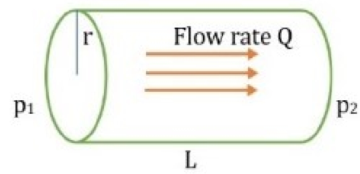

Fig. 2. Poiseuille's law

Where, Q: Volumetric flow rate of the fluid (in Liters per second).
ΔP: Pressure difference between the two ends of the vessel (in Pascals).
r: Radius of the cylindrical pipe or vessel (in meters).
η: Dynamic viscosity of the fluid (in Pascal-seconds or Poise).
L: Length of the cylindrical pipe or vessel (in meters).

Application

In the context of blood circulation, Poiseuille's Law helps explain how blood flow through blood vessels is influenced by various factors:

Vessel Radius: A small change in vessel radius significantly affects blood flow, as flow rate $Q \propto r^4$. Even small changes in radius have a significant effect on flow rate. For e.g. If the radius of a blood vessel is halved, the flow rate decreases to one-sixteenth of its original value.

Viscosity: Blood viscosity affects how easily it flows as $Q \propto \frac{1}{\eta}$. Higher viscosity increases resistance and reduces flow rate.

Pressure Difference: The greater the pressure difference, the higher the flow rate as $Q \propto \Delta P$, assuming other factors remain constant.

Vessel Length: Longer vessels create more resistance to blood flow, reducing the flow as $Q \propto \frac{1}{L}$.

3.1.2 The Navier-Stokes equation

It describes the motion of fluid substances such as liquids and gases. It is a fundamental equation in fluid dynamics, representing the conservation of momentum in fluid flow. The equation accounts for various forces acting on the fluid, including pressure, viscous (frictional) forces, and external forces.

In its general form, the Navier-Stokes equation is:

$$\rho\left(\frac{\partial v}{\partial t} + (v.\nabla)\, v\right) = -\nabla p + \mu \nabla^2 v + f$$

Where, ρ is fluid density, v fluid velocity vector, t is time, p pressure, μ is dynamic viscosity and f is the external forces (e.g., gravity).

Applications

The Navier-Stokes equations describe fluid motion and are applied to blood circulation to model how blood flows through the cardiovascular system. No-slip condition: Blood adheres to vessel walls, meaning zero velocity at the walls. Blood flow is pulsatile due to the rhythmic pumping of the heart.

3.1.3 Bernoulli's Principles

Statement

Bernoulli's Principle states that in a streamline flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or potential energy. In other words, this principle describes the conservation of energy of flowing fluids. It states that for an incompressible, non-viscous fluid, the sum of pressure energy, potential energy and kinetic energy is constant.

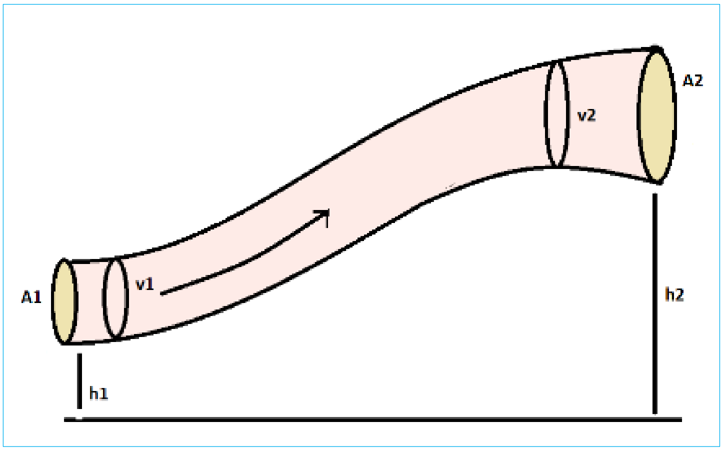

Fig. 3. Bernaulli's Principle

The principle is expressed as

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 = constant$$

Where, P is Fluid pressure (in Pa), ρ is Fluid density (in kg/m^3), v is fluid velocity (in m/s), g is Acceleration due to gravity (9.8 m/s^2) and h is height above a reference point (in m).

Application

Velocity and Pressure Relation or Energy Conservation: In blood circulation, this principle helps explain how blood flow behaves through narrowed or widened vessels. For example, when blood flows faster through a narrowed artery, the pressure drops, which can lead to clinical conditions like stenosis. Bernoulli's Principle is also applied in medical tools like Doppler ultrasounds to assess blood flow velocity and pressure changes, aiding in diagnoses of heart valve diseases and other cardiovascular conditions.

3.1.4 Continuity Equation

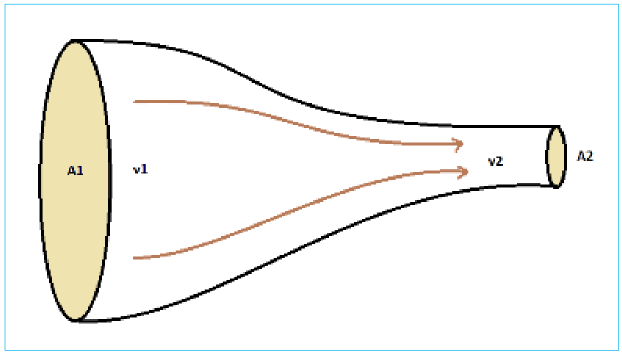

Fig. 4. Continuity Equation

Statement

The Continuity Equation is based on the conservation of mass for an incompressible fluid. It states that the product of cross-sectional area and velocity is constant along a streamline:

$$A_1 v_1 = A_2 v_2$$

Where, A_1 and A_2 are the areas of pipeline at two points 1 and 2 (in m²) and v_1 and v_2 are velocities at points 1 and 2 (in m/s).

Applications

In the circulatory system, the Continuity Equation explains how blood flow velocity changes in relation to the size of blood vessels: When blood moves from a wider artery to a narrower one, the velocity increases to maintain a constant flow rate. Conversely, as blood enters wider vessels, the velocity decreases. This principle explains why blood flows faster in the aorta compared to smaller arterioles.

3.1.5 Types of Blood Flow

Flow of fluid or blood is of three types as given below fig.5. Comparison between different types of flow is tabulated in table 1:

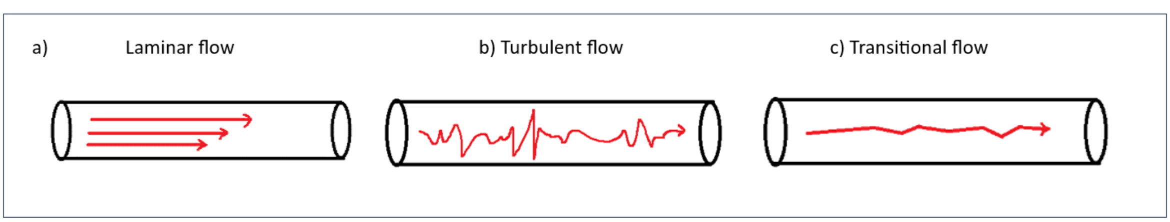

Fig. 5. Types of fluids flow

Table 1: Comparison of flow types

Laminar Flow	Turbulent Flow	Transitional Flow
Smooth flow.	Chaotic, irregular flow	Fluctuates flow between laminar and turbulent flow.
Layers of flow does not mix with each other and moves parallelly.	Layers of flow mixed with each other and flow gets disturbed.	Layers tending to mix with each other.
Damped due to high viscous forces.	Eddies and vortices forming, amplifies by inertia force.	Lies between laminar and turbulent flow
Low velocity gradient near walls of container.	High velocity gradient near walls of container.	Medium velocity gradient near the walls of container.
Reynold number < 2000	Reynold number > 4000	Reynold number lies between 2000 and 4000

3.1.6 Reynolds Number (Re)

Definition

The Reynolds number (Re) is a dimensionless value used in fluid dynamics to predict flow patterns in different fluid systems. It helps determine whether the flow of a fluid is laminar (smooth and orderly) or turbulent (chaotic and irregular). The formula for Reynolds number is:

$$Re = \frac{\rho v D}{\mu}$$

Where ρ is fluid density (in kg/m³), v is fluid velocity (in m/s), D is characteristic length or diameter of the vessel (in m) and μ is dynamic viscosity (in Pa s).

Applications: In blood circulation, the Reynolds number is used to analyse types of flow of blood i.e. whether blood flow is laminar or turbulent.

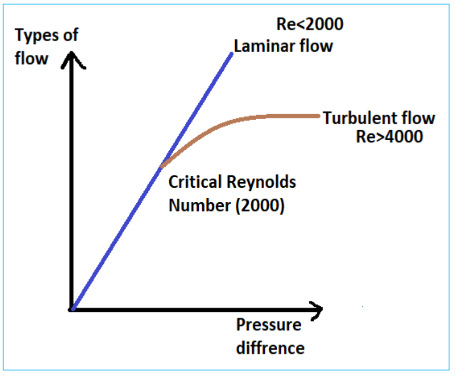

Fig. 6. Graphical Interpretation of Reynold Number

- **Laminar flow**: Re < 2000, occurs in normal, smooth blood flow through arteries and veins.

- **Turbulent flow**: Re > 4000, occurs in conditions like narrowed arteries (stenosis) or high blood flow rates, and can lead to complications like atherosclerosis or aneurysms. Turbulent flow can increase the risk of clot formation or vessel damage.
- **Transitional flow**: 2000 < Re < 4000, blood flow in medium-sized vessels or arteries during periods of increased activity or stress.
- **Clinical Relevance:** Reynolds number helps clinicians understand changes in blood flow dynamics and is used in diagnosing vascular conditions where blood turbulence may cause health risks.

3.2 Calculations (Cardiovascular Pressure and Flow)

The cardiovascular system relies on the interaction between blood pressure and blood flow to maintain proper circulation throughout the body. Blood flow is driven by pressure gradients created by the heart. The relationship between pressure, flow, and resistance is described by Ohm's Law for fluid flow:

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

Where, Q is blood flow (e.g. in L/min), ΔP is the pressure difference between two points (e.g. in mmHg) and R is the resistance to flow (e.g. in Hg-min)

3.2.1 Blood Pressure: Heart as a Pump

Blood pressure is the force exerted by circulating blood on the walls of blood vessels. It is highest in the arteries and decreases as blood moves through the arterioles, capillaries, venules, and veins. The cardiac cycle involves

- Systolic Pressure: The pressure during heart contraction.
- Diastolic Pressure: The pressure when the heart relaxes.

3.2.2 Factors Affecting Pressure and Flow

- **Vessel Diameter:** Smaller vessels increase resistance, reducing flow. Larger vessels reduce resistance and increase flow.
- **Blood Viscosity**: Thicker blood (increased viscosity) increases resistance and lowers flow.
- **Cardiac Output**: The amount of blood the heart pumps determine how much blood flows through the circulatory system.

The relation between diameter, cross sectional area and velocity of blood flow of different vessels is given in table 2. And the graphical interpretation of above numerical data is shown fig.7.

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Table 2: Comparison of types of vessels of blood circulation

Types of vessels	Diameter (mm)	Cross sectional A (cm^2)	Velocity of blood (cm/s)
Aorta	25	3-5	30-40
Arteries	04-06	20	20-30
Arterioles	0.02-0.2	400	10-15
Capillaries	0.005-0.01	4500	0.03-0.1
Venules	0.02-0.1	4000	01-02
Veins	5-10	80	10-20
Vena cava	30	08	10-15

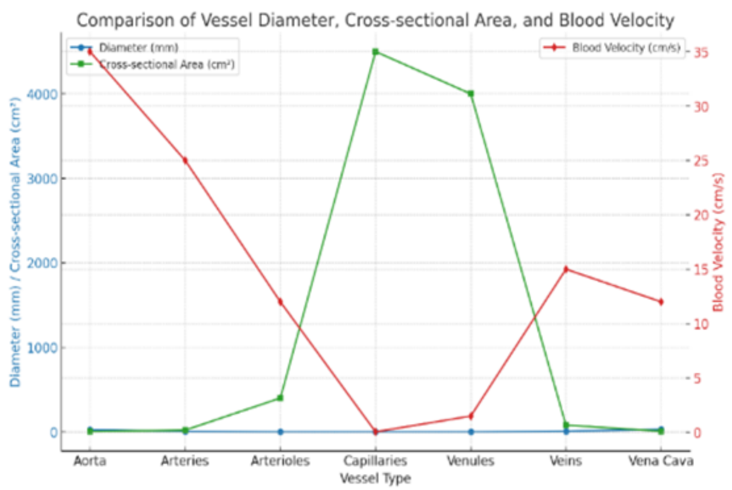
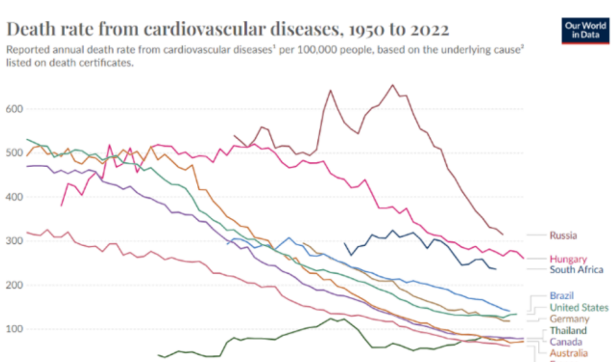
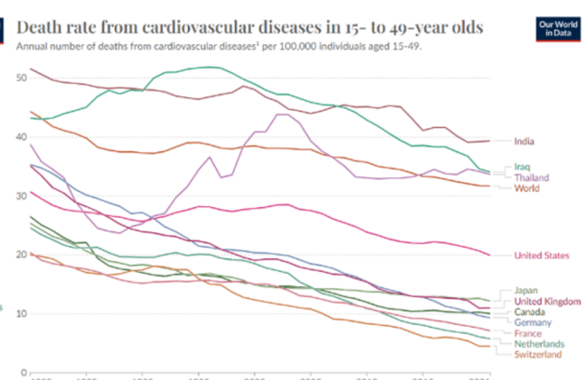


Fig. 7. Graphical Interpretation of vessels diameter, cross sectional area of vessels and velocity of blood flowing through vessels

4. Cardiovascular Diseases from Violations of Physical Laws & Treating Cardiovascular Disease with Fluid Dynamics





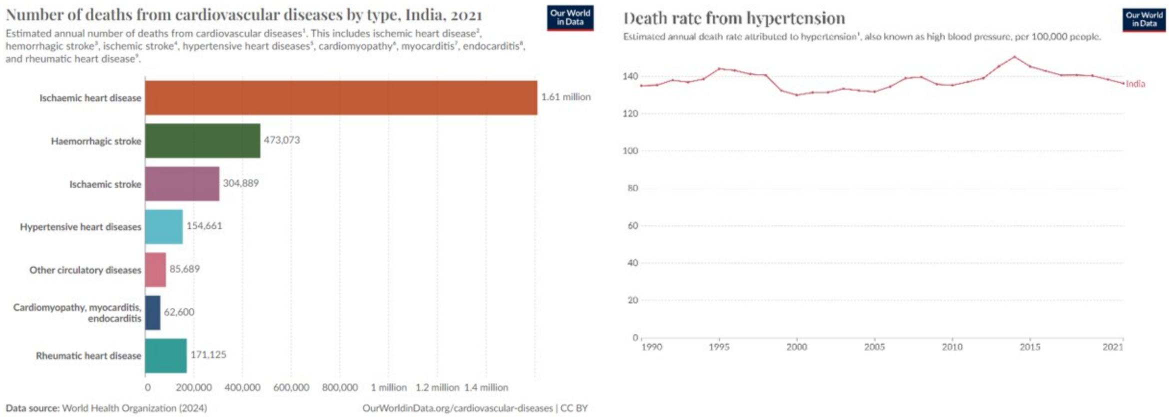


Fig. 8. Death rate from cardiovascular diseases
Source*:* WHO Mortality Database (2024), IHME, Global Burden of Disease
www.ourworldindata.org

Cardiovascular diseases often arise when the natural geometry of blood vessels or heart structures is altered, leading to violations of fundamental physical principles that govern blood flow. These disruptions create turbulence, increase resistance, or alter pressure dynamics, often resulting in serious health conditions. These diseases, including heart attacks, strokes, and hypertension, develop gradually with age, especially with risk factors like high blood pressure, smoking, and poor diet. They are the leading cause of death globally, with deaths rising from 14 million in 2000 to nearly 18 million in 2019.

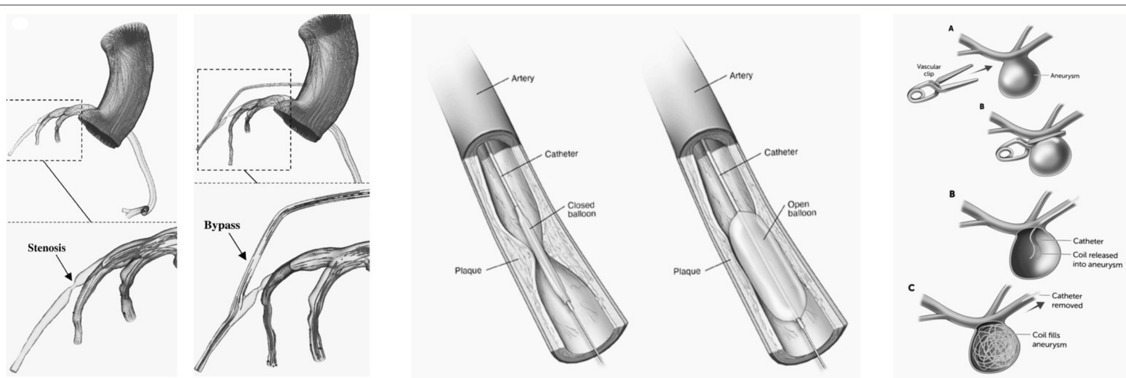


Fig.8: a) Stenosis and bypass
Source: Hiroki Kamada
b) Atherosclerosis and angioplasty
John Hospikins Medicine
c) Aneurysm and clipping, coiling
The Royal Children's Hospital, Melbourne

Controlling cardiovascular diseases through fluid mechanics involves restoring normal blood flow, reducing turbulence, and correcting pressure imbalances. The tabular representation linking cardiovascular diseases with the fluid dynamics principles and impacts are shown in below:

Table 3: cardiovascular diseases with the fluid dynamics principles, impacts and treatment

Sr. No	Cardiova-scular Disease	Cause or Description	Physical principle and its Violation	Impact	Treatment
1	Atherosclerosis	Plaque building in arteries leading to narrowing	**Poiseuille's law** $Q \propto \frac{1}{r^4}$ **Violation**: Narrowing drastically increases resistance, lowering blood flow.	Increase resistance and reduced flow, leading to heart attacks or strokes.	**Angioplasty** or **Stents**: Widens the artery to restore normal flow and reduce resistance.
2	Aneurysm	Bulging or weakening of vessel walls	**Bernoulli's Principle**: Pressure decreases in areas of high velocity. **Violation**: Bulging areas reduce pressure, increasing rupture risk.	High turbulence and risk of vessel rupture, leading to internal bleeding.	**Surgical Clipping** or **Endovascular Coiling**: Restores vessel geometry, balancing pressure according to Bernoulli's principle.
3	Stenosis	Narrowing of heart valves or vessels	**Bernoulli's Principle**: Blood velocity increases through narrowed regions, reducing pressure. **Violation**: Increased velocity causes low pressure.	Reduced blood supply downstream, increasing cardiac workload.	**Valve Repair or Replacement**: Restores valve geometry, ensuring normal flow and reducing turbulence.
4	Hypertension	High blood pressure due to narrow arteries or increased blood volume	**Ohm's Law for Fluids**: Flow $Q = \frac{\Delta P}{R}$ **Violation**: Increased resistance in narrow arteries.	Higher pressure damages blood vessels over time.	**Medications/Lifestyle Changes**: Reduce arterial resistance and pressure by managing stiffness and blood volume.
5	Thrombosis	Blood clots due to disrupted flow	**Reynolds Number**: Increase in Reynold number. **Violation**: High Reynolds number	Turbulent flow causes clots to form, obstructing circulation.	**Anticoagulants**: Promote smooth, laminar flow, reducing turbulence and clot risk.

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			leads to turbulence and clot formation.		
6	Varicose Veins	Enlarged veins due to valve failure	**Gravitational Forces & Pressure Gradients**: Valves prevent backflow. **Violation**: Valve failure allows pooling, increasing local pressure.	Impaired blood return to the heart, causing swelling.	**Compression Therapy**: Redistributes pressure and supports blood flow, counteracting gravitational pooling.
7	Heart Valve Disease	Defective heart valves, either stenotic or regurgitant	**Continuity Equation:** Disrupts flow **Violation**: Valve defects disrupt equal flow causing backflow and strain	Backflow and increased turbulence cause heart strain.	**Valve Replacement**: Restores valve function, ensuring smooth flow and pressure balance.
8	Coronary Artery Disease (CAD)	Blocked coronary arteries reduce oxygen supply	**Poiseuille's Law and Bernoulli's Principle:** Disturb. **Violation:** Reduced flow and pressure cause poor oxygen delivery.	Reduced oxygen delivery to the heart muscle leads to ischemia.	**Bypass Surgery or Angioplasty**: Restores normal flow and reduces resistance, improving blood and oxygen supply.
9	Pulmonary Embolism	Blood clots block pulmonary arteries	**Continuity Equation**: Obstructed flow violates the continuity of blood flow. **Violation**: Blockage disrupts flow continuity.	Reduced gas exchange and increased pressure in the lungs.	**Anticoagulants/Thrombolytics**: Dissolve clots, restoring flow continuity in pulmonary circulation.

This table illustrates how disruptions in fluid dynamics and the violation of fundamental physical laws contribute to various cardiovascular diseases, and how physics-based interventions can restore normal blood flow and pressure, leading to effective treatments.

5. Conclusion

In exploring the intersection of physics and cardiovascular system, we uncover a profound understanding of how fluid dynamics governs the complexities of blood flow and heart function. Principles such as Poiseuille's law, Bernoulli's principle, and Reynolds number provide essential insights into the behaviour of blood within the circulatory system, revealing how disruptions in these principles can lead to various cardiovascular diseases. By applying these physical principles, we can develop more effective treatments and interventions, from stents and valve replacements to advanced diagnostic tools. Embracing this interdisciplinary approach not only enhances our understanding but also drives innovation in medical technology, ultimately leading to better health outcomes.

As we continue to integrate fluid mechanics into cardiovascular care, the potential for groundbreaking advancements and improved patient outcomes remains vast. This synergy between physics and zoology is crucial for advancing our ability to prevent, diagnose, and treat cardiovascular diseases, paving the way for a healthier future.

6. Future Innovations for Cardiovascular Care

The future of cardiovascular medicine is set to benefit from advances in fluid dynamics. Enhanced modelling and simulations will lead to more personalized treatments, while innovations in medical devices will improve their effectiveness. Strengthening interdisciplinary collaboration will help translate research into practice. Personalized approaches and preventive strategies informed by fluid dynamics will enhance care, and better education for healthcare professionals will refine diagnostics and treatments. These efforts promise to significantly advance cardiovascular health and patient outcomes.

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