Blood as a fluid. Physics of flow and Pressure 1 (W1)

Physiology of circulatory system 1

- Main component is heart
- **Arteries** are vessels which go **away** from heart and **veins** are vessels which go **towards** the heart

What is the cardiovascular system?

- Tubes through which the blood flows: **blood vessels**
- Pump to produce blood flow: **heart**
- Fluid in the system: **blood**

The Heart and Circulation

- Average adult has a blood volume of 5-6 litres
- The heart (size of a fist) pumps ~**5.5 litres blood/min** (cardiac output)
- In exercise the Cardiac output **increases** to 25 L/min
- Purpose is to supply all tissues with oxygen and nutrients and to remove waste products

Heart (pump)

- Four chambers - two on the right
  - Right **atria** (RA)
  - Right **ventricle** (RV)
- Four chambers - two on the left
  - Left **atria** (LA)
  - Left **ventricle** (LV)
- **Vena Cava** - brings blood to heart, **Superior Vena Cava** (SVC) and **Inferior Vena Cava** (IVC)
- Blood leaves RV through the **Pulmonary Artery** (PA) towards lungs (deoxygenated)
- Oxygenated blood leaves LV through **Aorta** (A) and into the body
- Aorta and Pulmonary Arteries take blood away from the heart to body or lungs
- Pulmonary veins (PV) take blood back to the heart

Heart (valves)

- Four valves:
  - Atrioventricular valves are between the atria and ventricles.
  - Tricuspid valve on the right side
  - Mitral valve on the left hand side
- Aortic and Pulmonary valves are between the ventricles and the pulmonary arteries (Pulmonary valve) and the aorta (Aortic valve)

Hear Valves:

- Designed so when the pressure on one side increases blood flows across the valve into the next chamber
- Valves stop back flow of blood in the heart

Two circuits: Pulmonary and Systemic circulations:

Physics of Fluids 1

Fluid Flow

- Fluids (eg. Blood) flow from high pressure to low pressure
- Flow Rate: Q=deltaP / R, R = Flow resistance, P = pressure (volume of blood per unit time)

Fluid and Density

- **Liquids** and **gases flow**, and are therefore called **fluids**
- A **gas** can be any shape, is **easily compressed**
- A **liquid** has a **fixed volume**, **difficult** to **compress**
- **Density**, ρ, = mass(m) per unit volume (V) (ρ is greek letter rho)
- **Water** at 4 degrees C, ρ=**1000 kg/m^3**

Pressure - Definition

- A force applied over an area is pressure
- Pressure P is the force F per unit area A
- SI unit of pressure: pascal (Pa); 1 Pa = 1N/m^2
- 1 N = 1kg/(m/s^2) = SI unit of force: Newton (N)
- The same value of force can result in different pressures

Characteristics of Pressure in Fluids

Cases:

A: Open a hole in the container, what happens? Why?

- Flow starts **perpendicular** to container wall and then travels downwards due to gravity

B: Take an air-filled balloon to the bottom of a deep pool of water. What happens?

- Ball **keeps** its round **shape** unless diver squishes it

Conclusions:

- A: For a fluid at rest in a container, the Pressure acts perpendicular to the surface
- B: Pressure is the same in every direction in a fluid at a **given** depth

Pascal's Principle

- Squeeze part of a balloon, or a **heart chamber contracts.** What happens?
- If an external pressure is applied to a confined fluid, the pressure at every point within the fluid increases by that amount (Pascal's principle)

Does fluid pressure change with depth/height? Yes!

"Hydrostatic" Pressure in Fluids

- Why does the pressure increase with depth of fluid?
- Consider a liquid, density ρ, in a cylindrical container with cross-sectional area A. The bottom is *h* below the surface of the liquid
- The liquid in container pushes down on the water below it
  - Volume of liquid V=A*h*

- Force of bottom due to the weight of liquid on area A
  - W=mg = ρVg = ρA*h*g, g=9.8 m/s^2 = 9.8 N/kg
- Pressure P = F/A = W/A
  - **P = ρ*g*h**
  - P = Pa, h= metres
- Pascal's principle still applies even for hydrostatic pressure

A couple things to note:
- Hydrostatic - for system where a volume of a fluid is at rest
- The hydrostatic pressure equation **P = ρ*g*h** is valid for fluids whose density is constant and does not change with depth
- For example, gasses are very compressible and density can vary significantly with depth and the previous equation becomes **deltaP = ρ*g*deltaH**

Review questions
1. When you are standing, where is the **highest mean blood pressure**?
   - **TOES** (**lowest** part of body)
2. Why is an intravenous drip bag elevated?
   - **Hydrostatic pressure** is used to provide the pressure required to **drive** the **flow** of the fluid into the patients arm. Hence the bag has to be well above the level of the patient's arm

Measuring Pressure
- Blood pressure is monitored as an indicator of cardiac health
- Pressure is what drives fluid flow in most situations

Atmospheric Pressure
- Standard atmospheric pressure (at sea level) is 1.013*10^5 Pa or 101.3 kPa, also called 1 atmosphere (1 atm)
- This pressure does not crush us because the average pressure within the human body is close to 1 atm, pushing the other way. Minimal pressure difference between outside and inside

Gauge Pressure
- Devises to measure pressure include:
  - Tyre gauge, blood pressure monitor using a flexible diaphragm, open-tube manometer using mercury
- **Pressure gauges** measure the difference between two pressures, known as the gauge pressure Pg (subscript g)
- If the actual or absolute pressure inside the vessel is P, then the gauge pressure is Pg=P-Pa, where Pa is the outside, atmospheric, pressure
- eg. Your mean blood pressure is measured as 13kPa, it is **13kPa above the atmospheric pressure**

Measuring pressure - the manometer
- An open-tube manometer is a simple pressure gauge. A common way until recently to measure blood pressure (mercury sphygmomanometer) and pressure in respiration (in cm water)
- Atmospheric pressure, P sub a, acts at the open top end. The pressure P being measured causes the fluid on the left side to rise

- In equilibrium the pressures on both sides at the same height are equal: so, at the dotted line in the Figure, **P = P sub a + ρ*g*delta*h***
- Instead of calculating the lot, we can measure just the change in height, *deltah*
- 1mmHg ~ 133 N/m^2 = 133Pa
- Hg: **ρ**=13600 kg/m^3 (very dense)

<u>Measuring Blood Pressure (BP)</u>
<u>Sphygmomanometer</u>
- Air is pumped into the inflatable cuff until the pressure in the cuff (jacket) which is wrapped around the arm and squeezes
- In a typical blood pressure gauge, a flexible diaphragm response to difference in pressure from one side (atmosphere) to the other (the BP to be measured)
- Electronic sensors respond to how far the diaphragm has moved due to the pressure difference

<u>Step 1:</u> Pumped up inflatable cuff until the pressure in the cuff is greater than the pressure in the brachial artery, stopping the flow of blood
<u>Step 2:</u> Slowly release the cuff pressure until the maximum pressure produced by the heart is just enough to push some blood through. This is the maximum pressure- **systolic (120)**
<u>Step 3:</u> Keep releasing the cuff pressure until there is a steady flow of blood. This is the minimum pressure - **diastolic (80)**
- For males, normal BP = 120/80 (Maximum/Minimum)
- For females, BP = 110/70

Blood as a fluid. Physics of flow and Pressure 2 (W2)

Physiology 2

1. Atria = receive blood returning to the heart from the veins
   - RA = deoxygenated
   - LA = oxygenated
2. Ventricles = contraction generates the pressure to drive the flow of blood
   - RV = to lungs
   - LV = to body
3. Arteries = conduct blood to organs and tissues with little loss of pressure
   - Smallest arteries branch into arterioles. Control distribution flow
4. Capillaries = site substances exchange between the blood and cell of the body
5. Venules = collect blood from the capillaries
6. Veins = return blood to the heart

Cardiovascular System

- The system of blood vessels acts as a hydraulic filter converting pulsatile flow to steady flow
- Steady slow flow is needed in the capillaries to allow for the diffusion and transport of oxygen and other nutrients and waste products to and from the cells
- The pressure in fluids flowing through the system decreases with distance
- The arteries and arterioles have elastic walls so they distend (stretches) when blood is ejected from the heart (systole) and recoil during diastole. In this way the pulsatile flow is converted to a steady flow

Pulse Pressure

- The radial stretch of the aorta that results from the ejection of blood from the heart initiates a pressure wave which its propagated down the aorta and its branches
- This pressure wave can be detected as a pulse win the radial arteries and other distal arteries
- Pulse pressure is indicative of the volume of blood ejected by the heart (Stroke Volume)
- Pulse pressure can be increased in elite athletes who have an increase stroke volume and low heart rates
- Conversely in patients who have heart failure or who have suffered a haemorrhage the stroke volumes and pulse pressure will be reduced

Velocity of flow depends on total cross sectional area of blood vessels:

Blood flow is related to pressure differences and resistance of vessel wall

- Flow is always from region of high pressure to region of lower pressure
- It is the DIFFERENCE in pressure that is important, not the absolute pressure
- Flow is proportional to the pressure difference **$F \propto \Delta P$**
- Flow is inversely proportional to the resistance of the vessel wall **$F \propto 1/\Delta R$**
- Directly proportional if flow is **laminar** but sometimes flow can become **turbulent**

Viscosity

- Blood is thicker than water
- Blood - haematocrit (% volume of blood occupied by red blood cells)
- Haematocrit:
  - 45% in men
  - 42% in women
- Men have slightly higher other carrying capacity of their blood (more haemoglobin

- The electrolytes, proteins and other macromolecules increase plasma viscosity to 1.8x that of water
- The formed elements (blood cells, mainly RBCs) increase the viscosity to 3-4x that of matter
- Haematocrit 45% - viscosity 3x of water
- Haematocrit 60% - viscosity 7x of water
- Haematocrit 25% - viscosity 2x of water

Physics of Fluids 2 $Q = \Delta P / R$

Flow Rate

- Mass flow rate: Δm of fluid that passes per unit of time Δt
- Volume flow rate: ΔV of fluid that passes per unit time Δt
- Consider a cylinder of fluid with density ρ, cross sectional area A and length Δl, moving with a velocity v
- Hence, the mass flow rate is: $\mathbf{\Delta m/\Delta t = \rho A v}$ **kg/s**
- Volume flow rate is: **Q = Av m^3/s**

Flow Rate/Equation of Continuity:

- For constant flow, you can use these proportional equations
- $\mathbf{\rho_1 A_1 v_1 = \rho_2 A_2 V_2}$ (for mass flow)
- $\mathbf{A_1 V_1 = A_2 V_2}$ (for volume flow)
- This is called the equation of continuity

Viscosity

- Real fluids have some internal friction, called viscosity
- Friction = the resistance that one surface or object encounters when moving over another
- Viscosity = a frictional force between adjacent layers of fluids as the layers move past one another (such flow is called laminar flow)
- Viscosity of different fluids expressed by a **coefficient of viscosity, η** (eta)

Coefficient of Viscosity

- Viscosity = a frictional force between adjacent layers of fluids as the layers move past one another (laminar = in layers)
- Viscosity of different fluids expressed by a coefficient of viscosity **η**
- Model to derive discuss force F involved smooth (laminar) flow
- $\mathbf{F = \eta A * V/L}$
- Blood **η**= 0.004Pa s
- Water **η**= 0.0018Pa s
- Honey **η**= 2 Pa s
- Laminar flow is very well behaved

Laminar and Turbulent Flow

- If the flow of a fluid is smooth, its is streamline or laminar
- For a sufficienctly big obstacle, the flow becomes turbulent
- Turbulent flow has eddies (swirling motion of fluid)
- Low viscosities and high speeds
- Object in flow path can cause it
- Reynolds number $\mathbf{Re = \rho v L/\eta}$
- Transition form laminar to turbulent is $Re > 2000$ (very rough)

Turbulent Blood Flow

- Example - measuring blood pressure
- Flow through orifice can be quite laminar before orifice and turbulent after orifice

Bernoulli’s Equation - pressure, speed and height

- As a fluid flows it can change its **height**, y, **speed**, v, and **pressure**, P.
- These are related by Bernoulli’s equation for flow along a streamline (laminar)
- **P + 1/2ρv^2 + ρgy = constant**
- As speed increases, pressure decreases (for constant height)

Bernoulli’s Principle

- As speed increases, pressure decreases (for constant height)
- Pressure difference is enough to overcome the force of gravity
- Principle behind the wing, which allows airplanes to fly

Bernoulli’s Principle and Transient Ischaemic Attack (TIA)

- A person wth a constricted subclavian artery may suffer a temporary lack of blood flow to the brain - a TIA
- Blood speeds up to get past the constriction in the left artery. Higher v means reduce pressure
- Instead of fresh blood flowing up the left arterty, blood may flow from the brain down that artery
- This is known as subclavian steal syndrome
- This reduced supply to the brain may cause a TIA.

Flow in Tubes and Viscosity

- Viscosity produces a velocity gradient

A. Velocity is the same all across the tube
B. Velocity at the walls is zero; maximum at the centre of the tube
C. The shape of the Bunsen burner flame is due to velocity profile

- Without viscosity, a fluid could flow through a level tube or pipe (or human body) without a force being applied
- But viscosity acts like friction (resistance to flow)
- A pressure difference is needed for any steady flow
- Thus, the rate of flow depends on the pressure and viscosity
- Calculating the rate of flow can be complicated
- There is a simple formula for flow through a straight narrow tube. This formula is known as Poiseuille’s equation

Flow in Tubes - Poiseuille’s Equation

- The rate of flow of a fluid in a cylindrical tube depends on the viscosity of the fluid, the pressure difference, and the dimensions of the tube (assuming the tube has smooth internal surfaces)
- Volume flow rate, Q, in a cylindrical tube is:
  - Proportional to pressure difference **ΔP**
  - Inversely proportional to the length **L** of the tube
  - Inversely proportional to the viscosity, **η**
  - Proportional to the **fourth power** of the radius **r** of the tube
- Assumes laminar (not turbulent) and incompressible flow

Poiseuille’s Equation

- What happens to the volume flow Rate, Q, as parameters vary?
- If ΔP —> 2ΔP, Q=2Q
- If L —> 2L, Q=Q/2
- If η —> 2xη, Q=Q/2
- If r —> 2r, then Q —> 2^4 * Q = 16Q

Blood Flow and Poiseuilles Equation

- Restrictions in arteries have major eject on blood flow
- If the radius R is halved, the pressure ΔP has to increase by a factor of 2^4 = 16 to maintain the same flow rate, Q.

- As the body’s organs and muscles require a given blood flow; hence blood pressure increases in response to the heart

<u>Blood: Diffusion, Osmosis and Tonicity</u> (W3)

<u>Physiology</u>

<u>Body Fluid Compartments:</u>

<u>The Plasma Membrane:</u>

- Simple diffusion is movement of small molecules such as O2
- Passive transport is transport of ions through channel proteins in the direction of electrochemical gradient
- Primary active transport - against direction of electrochemical gradient and requires energy
- **Osmosis**: diffusion of a solvent such as water through a specific channel protein (aquaporin) through the lipid bilayer

<u>Diffusion and Osmosis</u>

- An **ideal semi-permeable membrane** is permeable only to solvent, usually water i.e. a water molecule is the only kind of particle that can penetrate, or pass through, the membrane
- A **selectively permeable membrane** is permeable to some substances and impermeable to others, i.e. certain particles other than water molecules may be able to penetrate such a membrane
- What determines net direction of H2O movement? H2O moves from region of high [H2O] to low [H2O]

<u>Diffusion</u>:

- **Solute** moves towards equilibrium. Membrane permeable to both solvent and solute
- **Both solute** and **solvent** (water) move until solute concentration equilibrium is reached

<u>Osmosis:</u>

- **Solvent** moves towards equilibrium. Membrane permeable to solvent but impermeable to solute
- **Only solvent** (water) moves until solute concentration equilibrium is reached

<u>Osmolarity and Tonicity</u>

- Osmosis is the flow of water across a semipermeable membrane from a solution with low solute concentration to a solution with high solute concentration
- Osmolarity of the solution may be defined as the number of solute particles in a solution
- Osmolarity allows us to predict if there will be H2O movement
- If a solution has **high [solutes]** —> high osmolarity —> strong tendency to **attract H2O** to move into that solution (from a solution of lower osmolarity
- If a solution has **low [solutes]** —> low osmolarity —> stronger tendency to **donate H2O** to move from that solution)to a solution of higher osmolarity)
- **Osmolarity** = total concentration of **all solute particles**
- **Tonicity** = total concentration of **non-penetrating solute particles**

1. Isotonic solution
   - Exact concentration of solutes inside of the red blood cell as outside
   - No net movement of water
2. Hypotonic solution
   - Higher concentration of solutes inside of the cell compared to outside
   - Swollen red blood cell
   - Water moves into cell in response to dilute solution outside of cell
3. Hypertonic
   - High concentration of solutes outside of the cell compared to inside