Principles of Hemodynamics

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Learning Objectives

- 1. Define pressure and its units.
- 2. Understand pressure in a fluid at rest and its variation with depth.
- 3. State Pascal's principle and discuss its implications in the human body.
- 4. Know the special considerations that apply to pressure in flowing fluids.
- 5. State Poiseuille's formula for blood flow and know the physical variables which determine the flow rate of a liquid through a tube. Explain why vessel diameter has such a significant impact on resistance to flow.

Learning Objectives

- 6. Understand the relation between volume flow rate and the velocity of flow and describe how the total cross-sectional area of the vascular system influences the velocity of flow.
- 7. Explain the factors that affect viscosity of blood.
- 8. Define laminar flow and turbulent flow. State Reynold's formula and understand the effect of turbulence on flow at a given pressure.

Hemodynamics

- ***Hemodynamics*** is the study of

fluid flow in the vascular system

Pressure

Pressure : Force/ Area F/A

Newton/ m^2 = Pascal = Pa

1 atm = 1.013×10^5 Pa

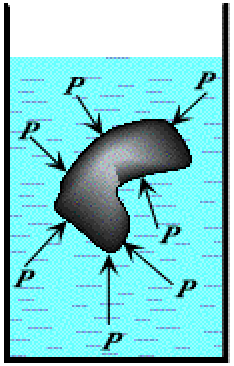
= 1.013 bar

= 760 torr

= 760 mm Hg

Pressure in a fluid at rest

- The magnitude of the force F exerted by the fluid on the surface divided by the surface area A is defined to be the pressure at that point.
- Fluid: A substance that can flow: gases and liquids



Basic Hydrostatic Laws which Apply to Incompressible Fluids

- 1. Fluid pressure is equal in every direction.
- 2. At different points in the same horizontal plane, pressures are equal.
- 3. Pressure increases with depth.

Variation of Pressure with Depth in an Incompressible Fluid

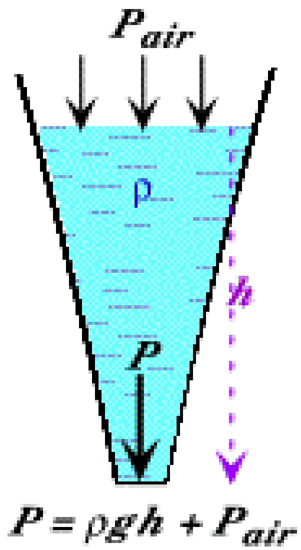
- Ph= h x d_w = ρgh
- d_w = weight density

  ρ = mass / volume,density of the fluid, kg / m^3

  g = acceleration due to gravity (9.8 m /sec^2)

  h=depth (m)
- P = Po + ρgh

  where Po is atmospheric pressure at sea level
- **The pressure at a given depth in a static liquid is a result the weight of the liquid acting on a unit area at that depth plus any pressure acting on the surface of the liquid.**



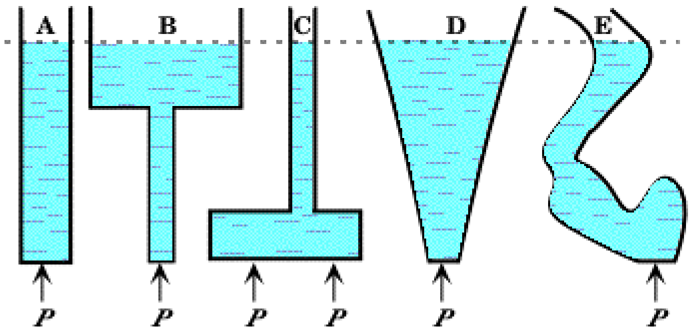
Pascal's Principle

- **Any external pressure applied to a fluid is transmitted as undiminished throughout the liquid and onto the walls of the containing vessel.**
- Exactly true for only stationary fluids

Pascal's Principle

- None of the body's fluids are strictly static or enclosed, as they are continually being replaced in a normally functioning body
- Body's enclosed fluids: cerebrospinal fluid, urine in bladder, fluid in the eyeball, amniotic fluid, synovial fluid

Pascal's Principle

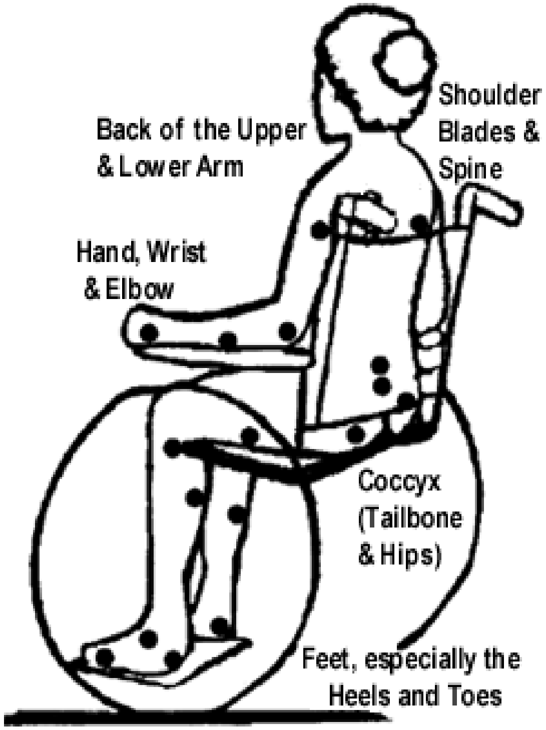


- The pressure at a point in a liquid is determined solely by the depth of that point below the surface. The volume of water or shape of container has no effect.

Clinical Applications of Pascal's Principle: Decubitus Ulcers

Chronically ill patients confined to an ordinary mattress for a long time tend to have bed sores. Bony projections not adapted to bear weight (buttocks, heels, shoulders). Weight supported on a small area. P〉 capillary P. Collapse of capillaries, prevent blood flow.

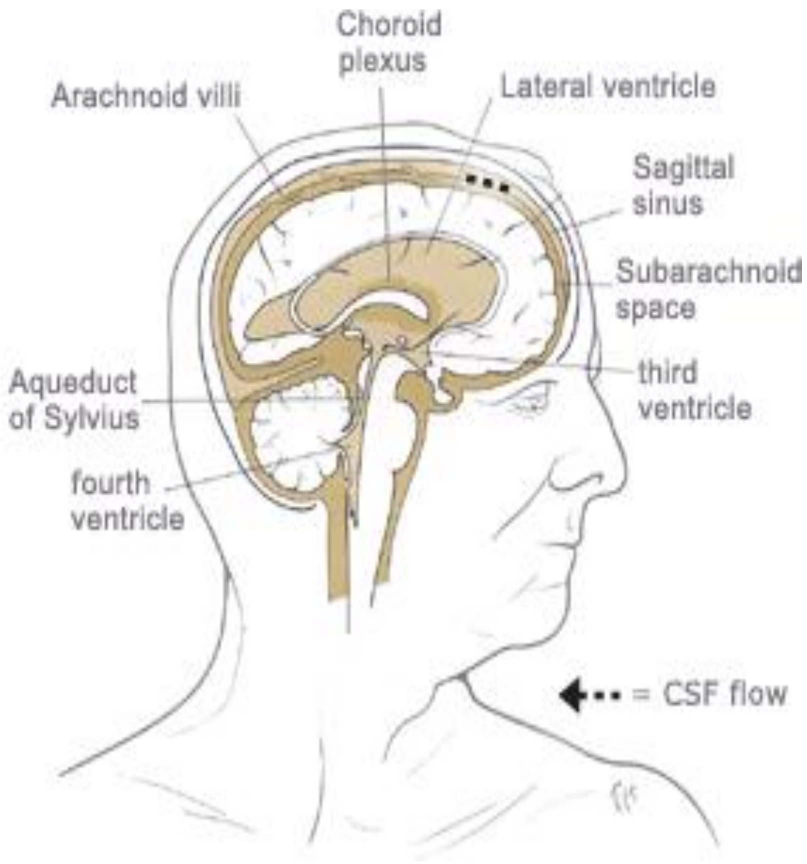
Use of an air or water mattress (closed fluid system) helps to prevent the formation of Decubitus Ulcers.



Clinical Applications of Pascal's Principle: Cerebrospinal Fluid

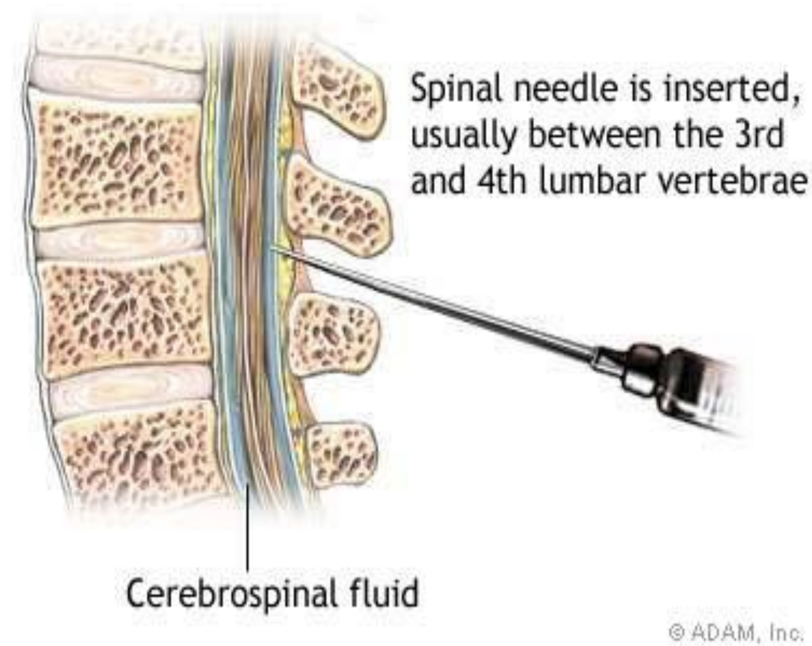
An increase in P in any part of the fluid will increase the P in all parts of the fluid.

- CSF is normally at a pressure of about 0.8 to 1.8 kPa (6 mm to 14 mmHg).



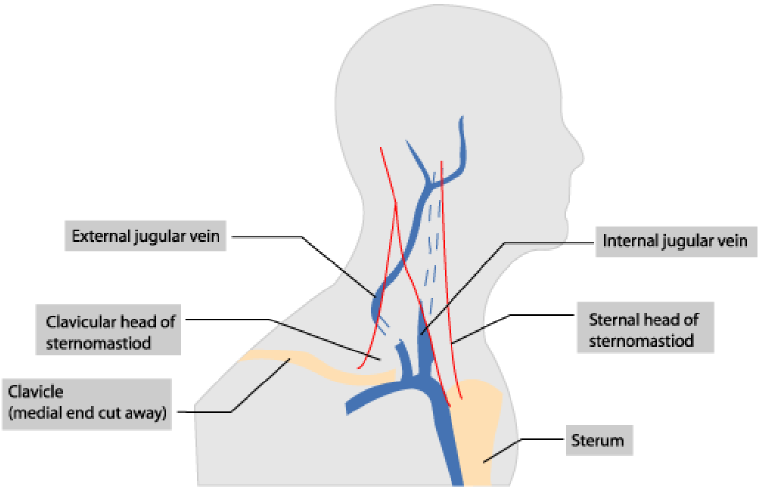
Clinical Applications of Pascal's Principle: Cerebrospinal Fluid

Brain tumors, inflamed meninges, haemorrhage or infection can increase the pressure of the CSF to between 3.9 and 5.9 kPa (30 to 45 mmHg). Pascal's principle can be used to determine if fluid flow in the spinal canal has been blocked: Queckenstedt's test



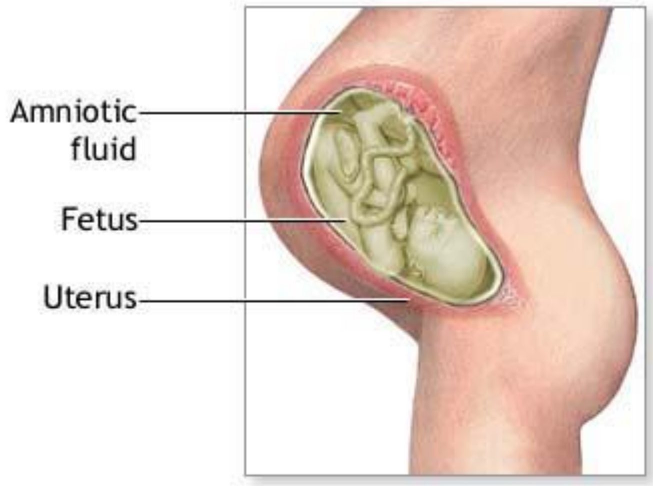
Clinical Applications of Pascal's Principle: Queckenstedt's Test

- If the jugular vein is squeezed, intercranial P increases. Transmitted to all parts of the fluid
- If spinal tap manometer unaffected, obstruction indicated



Clinical Applications of Pascal's Principle : Unborn Fetus

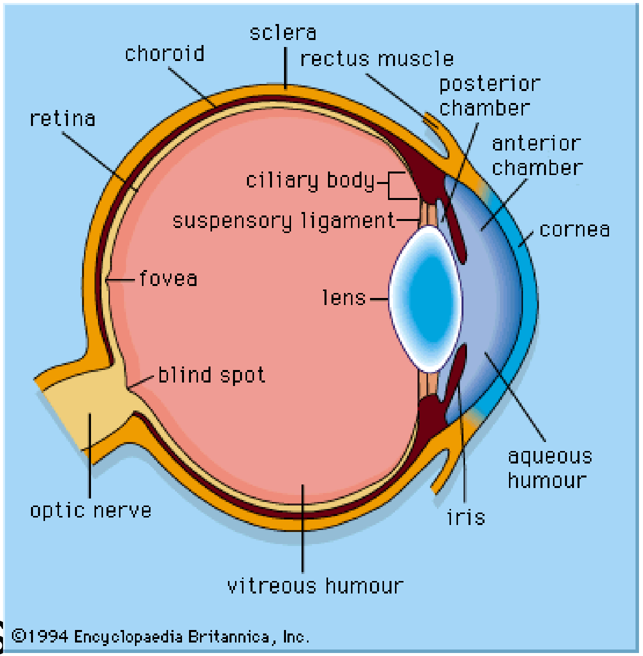
Amniotic fluid tends to distribute the effect of a force exerted on the abdominal area.



A.D.A.M.

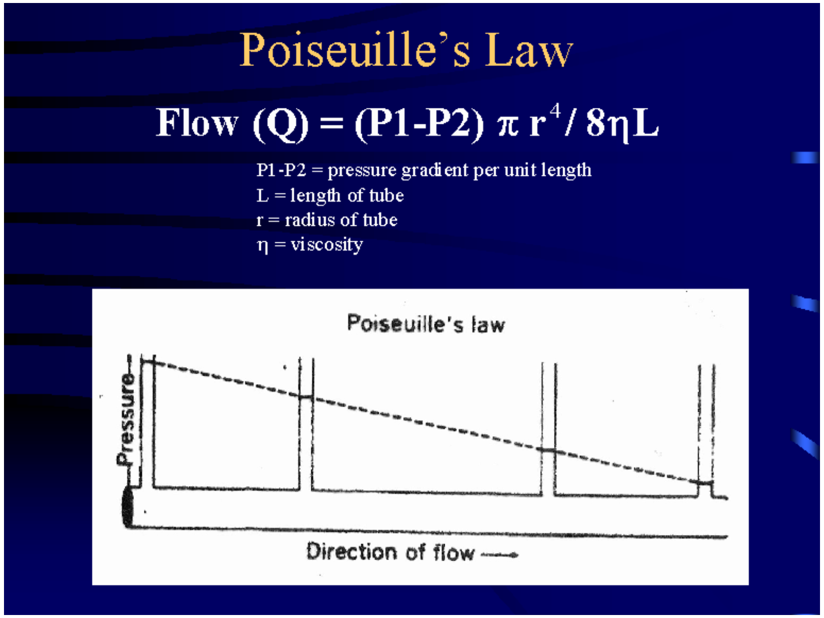
Clinical Applications of Pascal's Principle: Eye

- Contains enclosed fluid.
- Aqueous humor is at a P of about 2 kPa (15 mm Hg) but ranges from 1.3 to 4.0 kPa (10 to 30 mmHg).
- Eye pressure is measured by a tonometer. Glaucoma:increased pressure in the eye.
- Any blow to the front of the eye will transmit P to the back of the eye and harm delicate structures (blood vessels, retina, optic nerve).



Pressure of Flowing Fluids

- The pressure in flowing fluids depends on the details of the flow process in contrast to the case of the static liquid.
- When a liquid flows through a tube, there will be a pressure drop.
- Pressure drop per unit length= $\frac{P_1 - P_2}{L}$



Volume Flow Rate

- $\mathfrak{I}$ or Q volume flow rate

  $$\mathfrak{I} = \frac{P_1 - P_2}{R}$$

  Ohm's Law for fluid flow

  P_1= pressure upstream end

  P_2= pressure downstream end

  R= resistance to flow

- $$\mathfrak{I} = v \cdot A$$

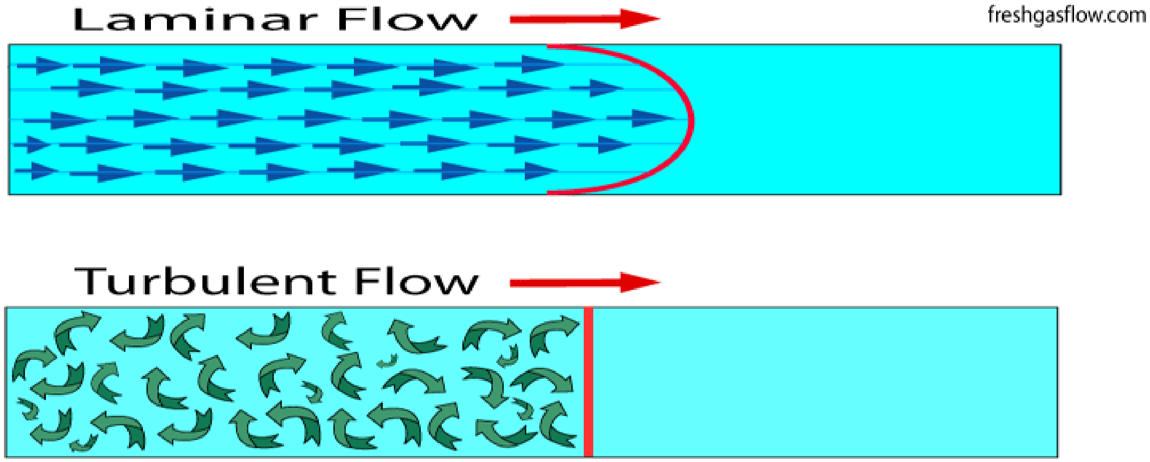
  $$\frac{\text{volume}}{\text{time}} \qquad \frac{\text{length}}{\text{time}} \cdot \frac{\text{volume}}{\text{length}}$$

Resistance to Flow

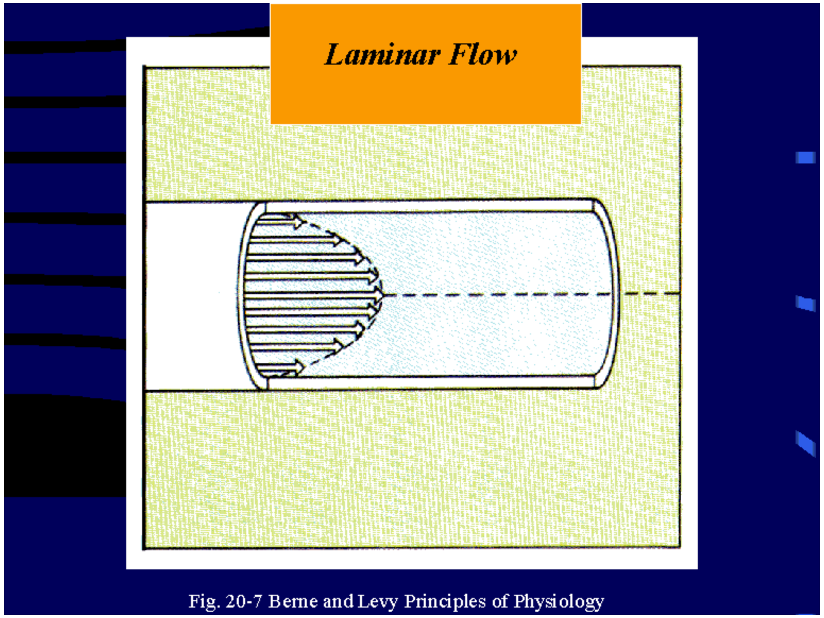
- fluids always flow from regions of high pressure to regions of lower pressure
- ***resistance*** to fluid flow is caused by friction between the molecules in the fluid and the walls of the tube
- ***frictional resistance always reduces flow***

Resistance

- **A.** ↓ with the diameter of the tube
  ↑ with the length of the tube
  ↑ with the viscosity of the fluid
- **B.** Flow pattern of the liquid: Laminar flow or/ turbulent flow

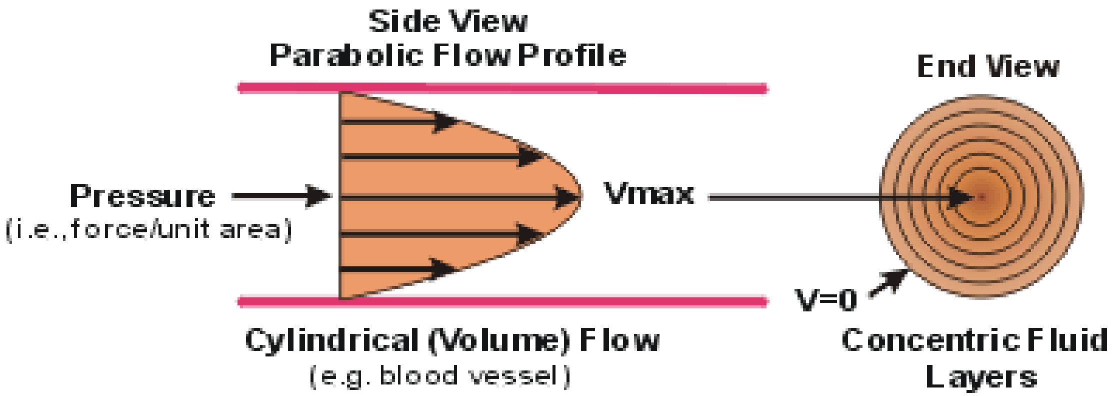


Laminar **Flow**



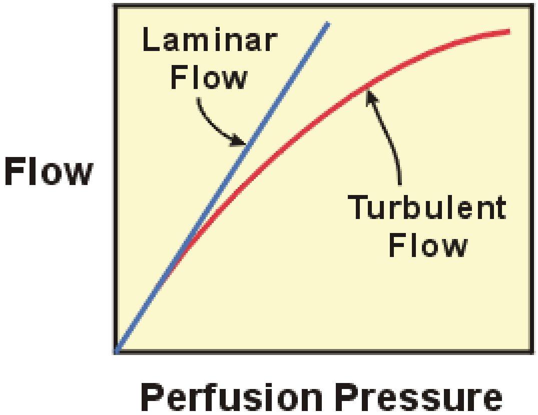
- Layered, streamline flow
- Velocity in each layer constant but less than that of the more axial layers; highest in the center
- Minimum energy loss

Laminar Flow



1999-2003 Richard E. Klabunde

Turbulent Flow



Effects of turbulence on pressure-flow relationship. Turbulence decreases flow at any given perfusion pressure.

- Caused by the momentum of the fluid
- Flow rate smaller than laminar flow, for the same P difference

Poiseuille's Law

- Applies to steady, laminar flow of Newtonian (ideal) fluids.
- $\Im = \dfrac{P_1 - P_2}{\Re}$ $\Re = \dfrac{8\,\eta\,L}{\pi\, r^4}$

η = viscosity

L = length of the tube

r = inside radius of the tube

$P_1 - P_2 = \Delta P$ = pressure gradient

- **UNITS :**

UNITS :	**I.U.**
P : dynes / cm^2	Pa
L : cm	m
$\Im$: cm^3 / sec	m^3 / sec
η : dyne-sec / cm^2	Pa - sec

Poiseuille's Law

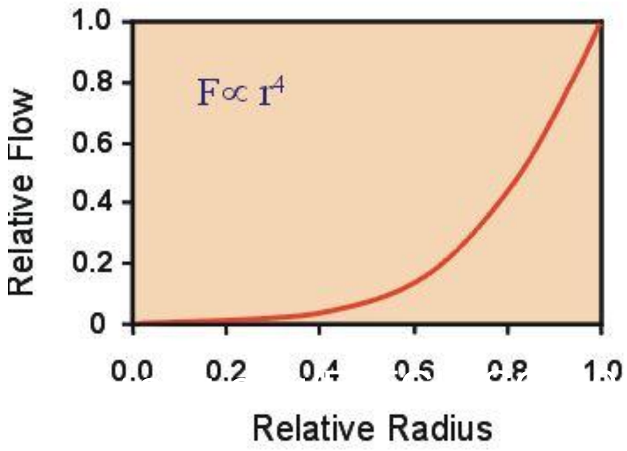
- $$\Im \;(\text{laminar flow}) = \frac{(P_1 - P_2)(\pi r^4)}{8 \eta L} = \frac{\Delta P (\pi r^4)}{8 \eta L}$$

$$\Im = A \bar{\upsilon} \quad \Rightarrow$$

$$\bar{\upsilon} = \frac{\Delta P r^2}{8 \eta L}$$

Jean-Louis Marie **Poiseuille**

Volume Flow Rate and Radius



Note that the volume flow rate depends upon the fourth power of the tubing radius

Relation between Flow Rate and Velocity

- $\Im = A\,v$

  If the pipe is rigid, the fluid that enters one end will be the amount that exits from the other end.

- Assuming the fluid incompressible

  $\boldsymbol{V} = A_1.L_1 = A_2.L_2$ $L_1 = v_1.t$ $L_2 = v_2.t$

- Therefore $A_1.\,v_1 t = A_2\,.v_2 t$

  $A_1\,.v_1 = A_2.\,v_2 = \text{constant}$

- $A \quad v = \quad \Im$

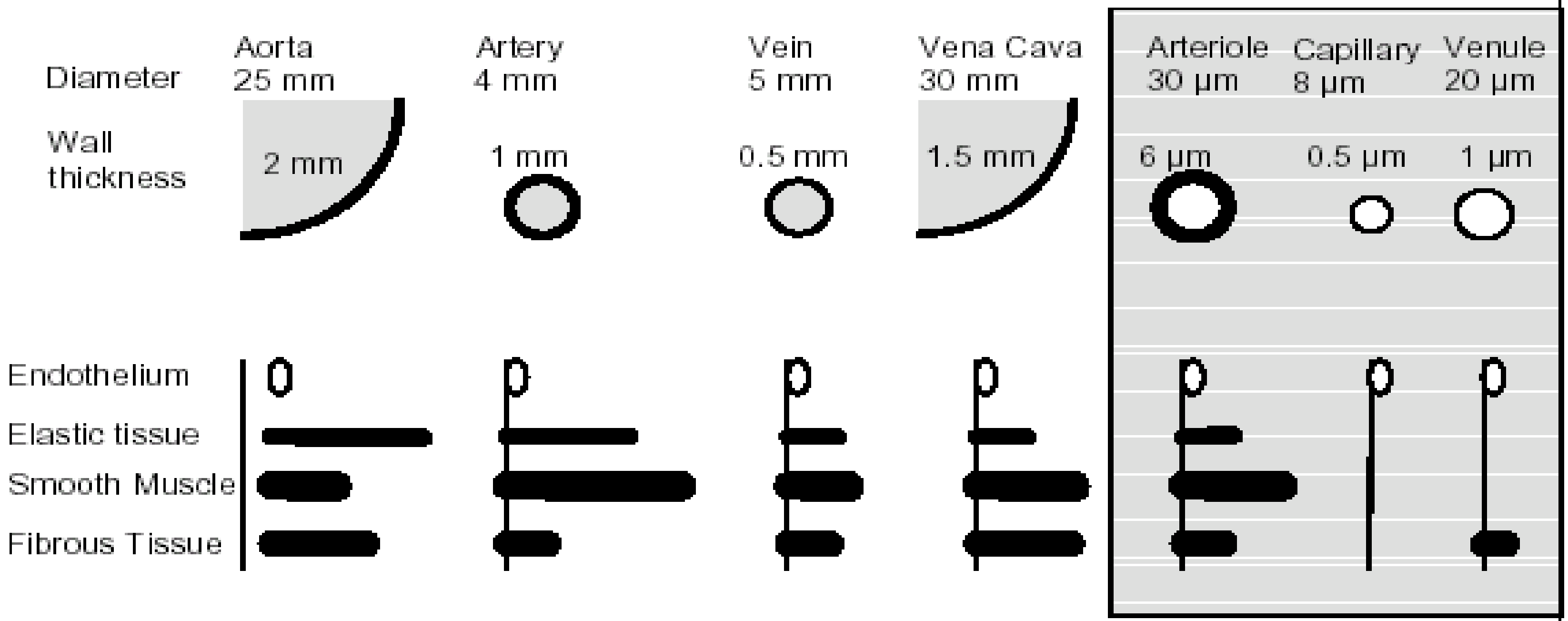
$$\frac{\boldsymbol{V}.\quad L}{L.\quad \text{time}} = \frac{\boldsymbol{V}}{\text{time}}$$

Flow rate and Velocity. Equation of Continuity

$$v_2 = \frac{A_1 v_1}{A_2}$$

- The velocity of the liquid is inversely proportional to the cross-sectional area of the pipe.
- This rule holds whether a given cross sectional area applies to a single large tube or to several smaller tubes in parallel.
- Equation of continuity holds where $\Im$ is the same everywhere in the pipe.

Circulation overview



Relative Velocities

- Velocity of blood:
- Aorta 30 cm/s
- Arterioles 1.5 cm/s
- Capillaries 0.04 cm/s
- Venules 0.5 cm/s
- Venae cavae 8 cm/s

- Artery 4 mm
- Aorta 25 mm
- Arteriole 30 μm
- Terminal arteriole 10 μm
- Vein 5 mm
- Capillary 8 μm
- Venule 20 μm
- Venacava 30 mm

Applicability of Pouiseuille's Law *in vivo*

- "The problem of treating the pulsatile flow of blood through the cardiovascular system in precise mathematical terms is insuperable" (Berne and Levy)
- - Blood is not Newtonian (viscosity is not constant)
- - Flow is not steady but pulsatile
- - Vessels are elastic, multibranched conduits of constantly changing diameter and shape.

Critical Velocity- Reynold's Number

$v_c = \dfrac{R\eta}{\rho r}$

η = viscosity
ρ = density
R = Reynold's number (experimental constant)

$R = \dfrac{r\,\bar{v}\,\rho}{\eta}$

η = viscosity
ρ = density of fluid
r = radius
$\bar{v}$ = mean velocity

- *R* is 1000 for water and slightly less for blood.
- *R* > 1000 ⇒ turbulence

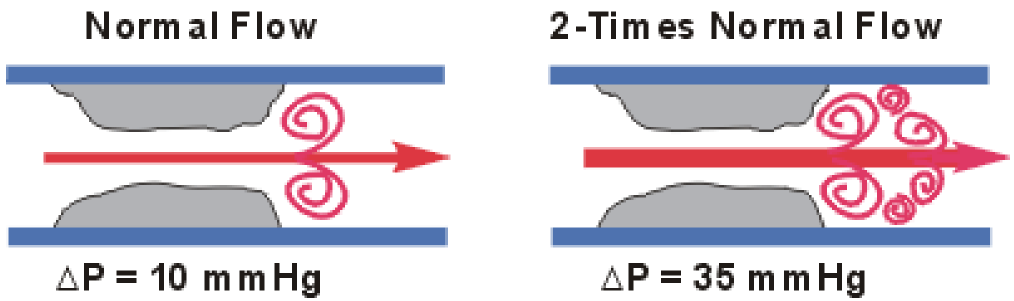
Critical Velocity

- In humans critical velocity is sometimes exceeded in the ascending aorta at the peak of systolic ejection.
- Turbulent flow   fluid of low viscosity

  velocity, relatively great

  develops first in large vessels
- Turbulence occurs more frequently in anemia

Turbulent Flow



- **In turbulent flow, some energy is dissipated as sound and some as heat.**
- Noise facilitates blood pressure measurements and makes possible the detection of some heart abnormalities.
- Example: heart and aorta of anemic patients. cardiac murmurs heard with the stethoscope
- Poiseuille and Reynolds experiments were for homogeneous fluids.
- Blood $\Rightarrow$ not homogeneous, flow is pulsatile, arteries are elastic

Changes in Blood Speed during Circulation

Speed maximum in the aorta, minimum in capillaries.

$\Im \Rightarrow$ 5 liters / min

$$\bar{\upsilon}_{aorta} = \frac{(5000\ cm^3 / min)\ (1 / 60\ min / sec)}{\pi\ (0.9\ cm)^2}$$

$$= 32.8\ cm / sec$$

Area of the pipes ↓ v (speed) ↑

Total area of the system must be used

Total area of the capillary system is ~ 1000 x as large as the aorta

Blood Distribution

- Velocities/Flows
  - Aorta: 300 mm/s
  - Capillaries: 0-3 mm/s or 5.5 hours/mm^3
- Blood mass: 8% of body mass
- Volumes (percent of total blood volume)
  - Systemic: 83%
    - Arteries: 11%
    - Capillaries: 5%
    - Veins: 67%
  - Pulmonary: 12%
  - Heart: 5%