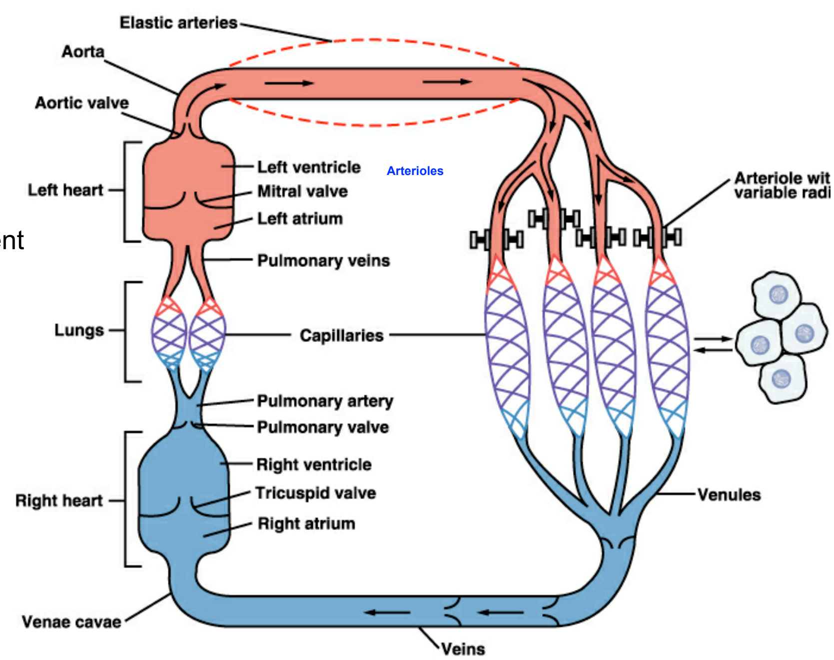
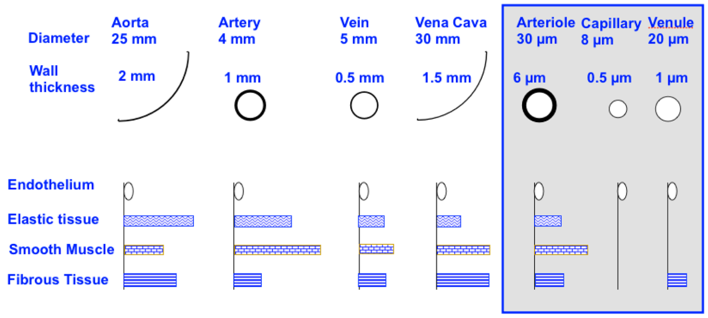
Hemodynamics

Overview and Terminology

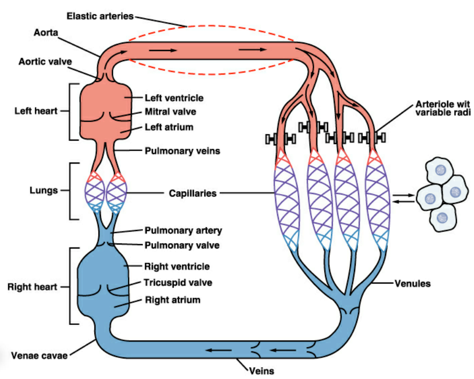
- Parameters
  - Pressure
  - Velocity
  - Flow
    - laminar vs. turbulent
  - Resistance
  - Viscosity
  - Energy
  - Area
  - Volume



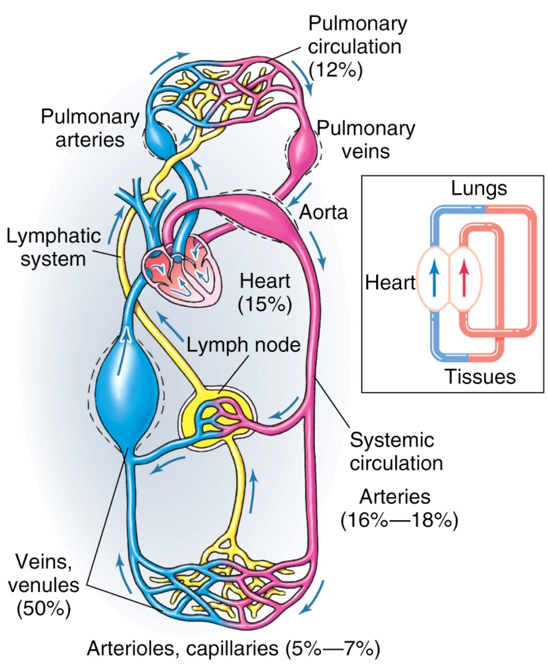
Structural Overview

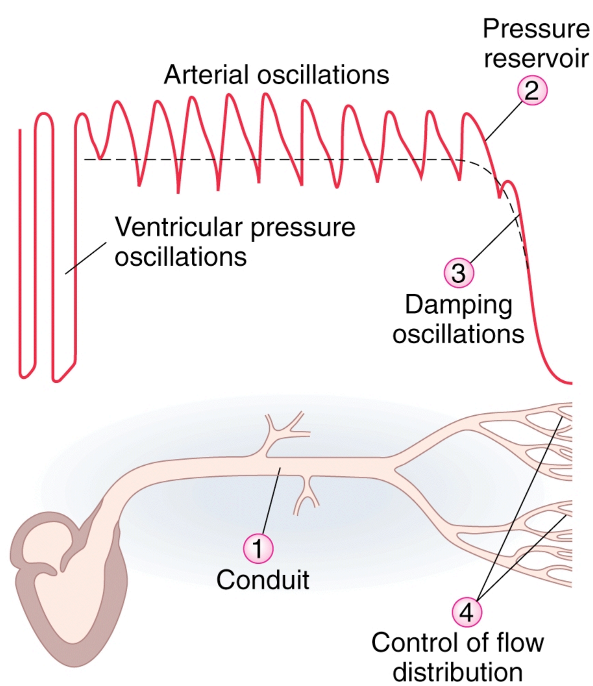


VESSEL TYPE	DIAMETER (mm)	FUNCTION
Aorta	25	Pulse dampening and distribution
Large Arteries	1.0 - 4.0	Distribution of arterial blood
Small Arteries	0.2 - 1.0	Distribution and resistance
Arterioles	0.01 - 0.20	Resistance (pressure & flow regulation)
Capillaries	0.006 - 0.010	Exchange
Venules	0.01 - 0.20	Exchange, collection, and capacitance
Veins	0.2 - 5.0	Capacitance function (blood volume)
Vena Cava	35	Collection of venous blood



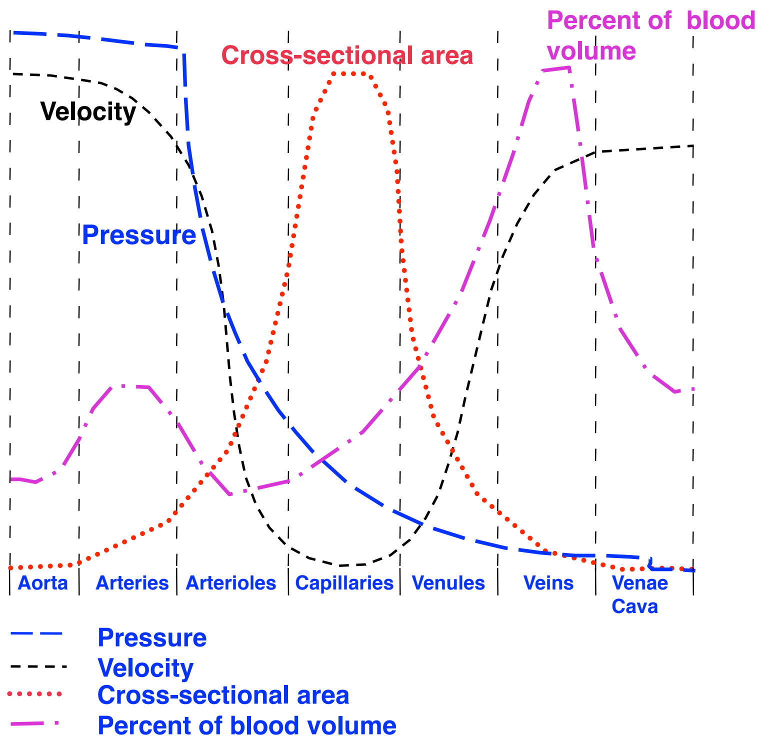
Functional Overview





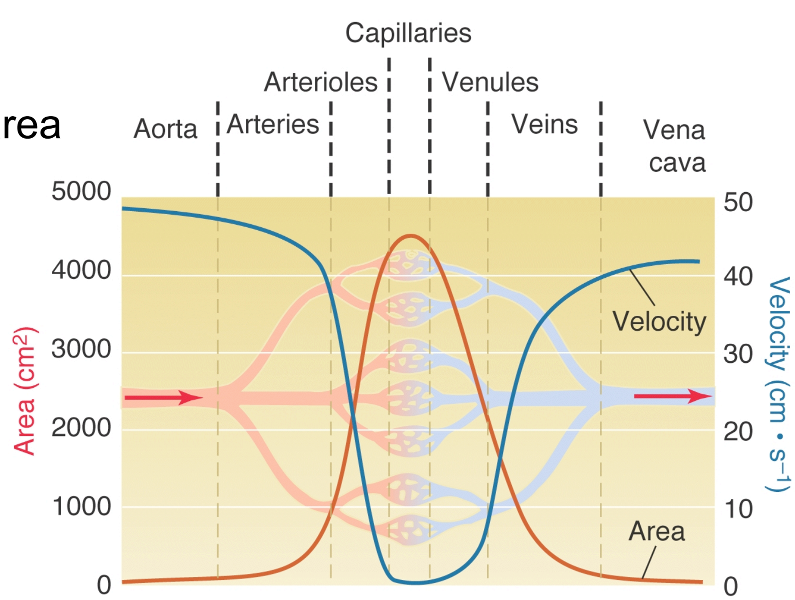
Blood Distribution

- Velocities/Flows
  - Aorta: 30-50 cm/s
  - Capillaries: 0-1 cm/s or 5.5 hours/mm3
- Blood mass: 8% of body mass
- Volumes (percent of total blood volume)
  - Systemic: 83%
    - Arteries: 11%
    - Capillaries: 5%
    - Veins: 67%
  - Pulmonary: 12%
  - Heart: 5%



Velocity vs. Area

- Flow is constant throughout
- Flow =∫velocity * area



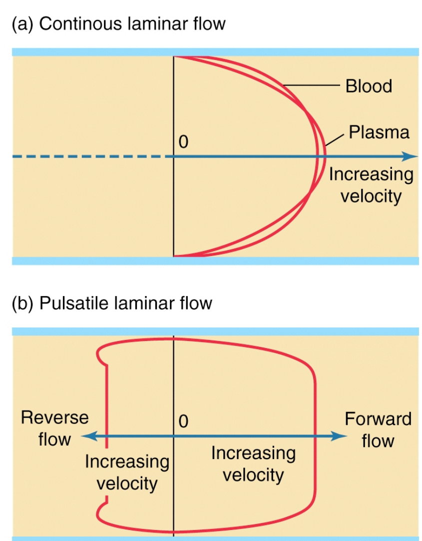
Hemodynamics Basics

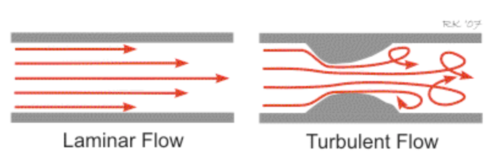
- "The problem of treating the pulsatile flow of blood through the cardiovascular system in precise mathematical terms is insuperable" (Berne and Levy)
  - Blood is not Newtonian (viscosity is not constant)
  - Flow is not steady but pulsatile
  - Vessels are elastic, multibranched conduits of constantly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

Laminar Flow and Turbulence

- Laminar flow
  - Parabolic profile
- Pulsatile laminar flow
  - Velocity changes
  - May reverse direction
- Turbulent flow
  - Nonaligned movement
  - Noisy (BP cuff)
  - Reynolds number
    - > 1000 = turbulence
    - > 200 = eddies possible
  - Rarely occurs in healthy vessels

Velocity Profiles



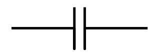


Hemodynamic Parameters

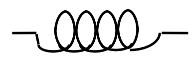
P = pressure V = volume $\dot{Q}$ = flow η = viscosity

- Resistance $$R = \frac{\Delta P}{\Delta \dot{Q}}$$

- Compliance $$C = \frac{\Delta V}{\Delta P}$$



- Inertance $$L = \frac{\Delta P}{\Delta \dot{Q} / \Delta t}$$



- Poiseuille's Law
  - laminar flow
  - Newtonian fluid
  - rigid tube
  - works for small arteries and veins

$$\dot{Q} = (P_1 - P_2)\frac{\pi r^4}{8\eta l}$$

$$R = \frac{8\eta l}{\pi r^4} \qquad (I = \frac{V}{R})$$

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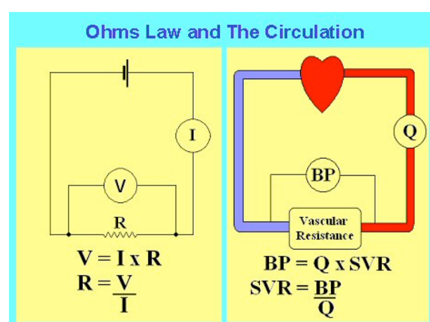

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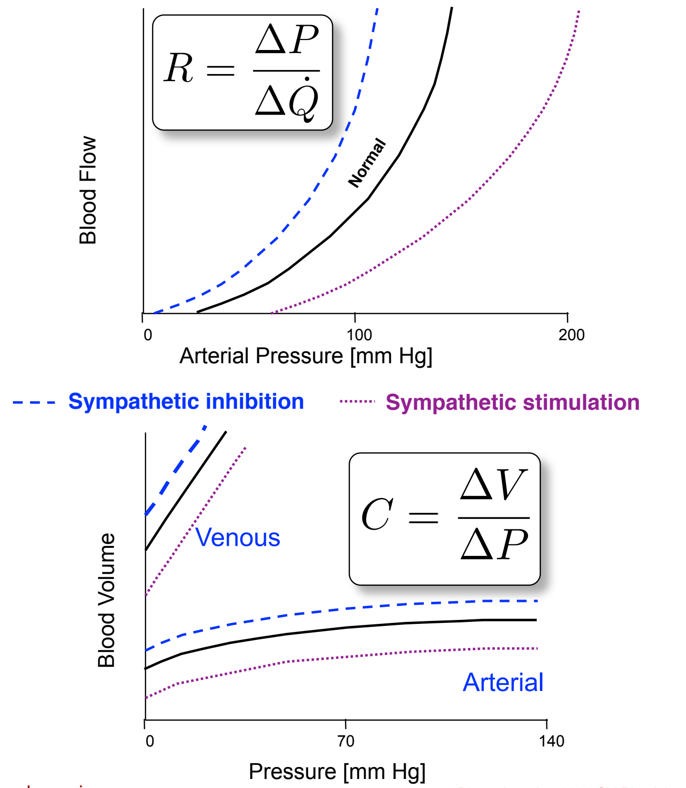
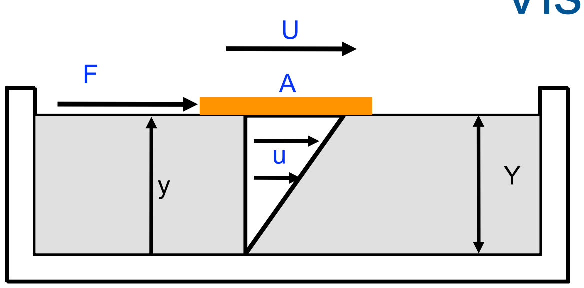
Resistance and Compliance

- Veins vs. arteries
  - have 24 times the compliance of arteries
  - carry 65% of the blood
  - have even higher blood storage capacity
- Autonomic control
  - alters resistance but not compliance (slopes of curves)
  - acts to shift blood volume



Viscosity

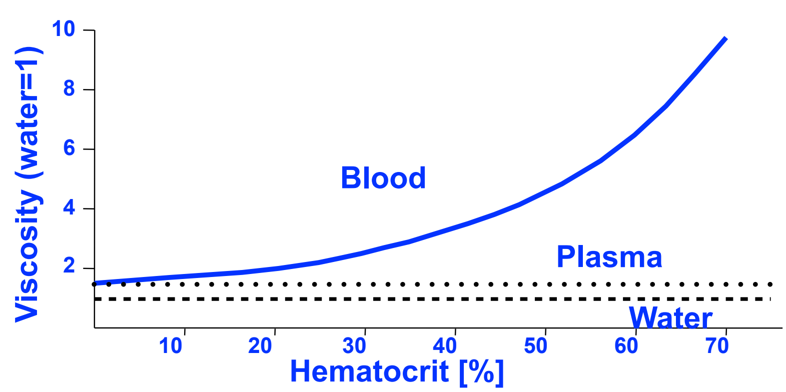


$$\eta = \frac{\tau}{du/dy} = \frac{F/A}{U/Y} = \frac{\text{Shear stress}}{\text{Shear rate}}$$

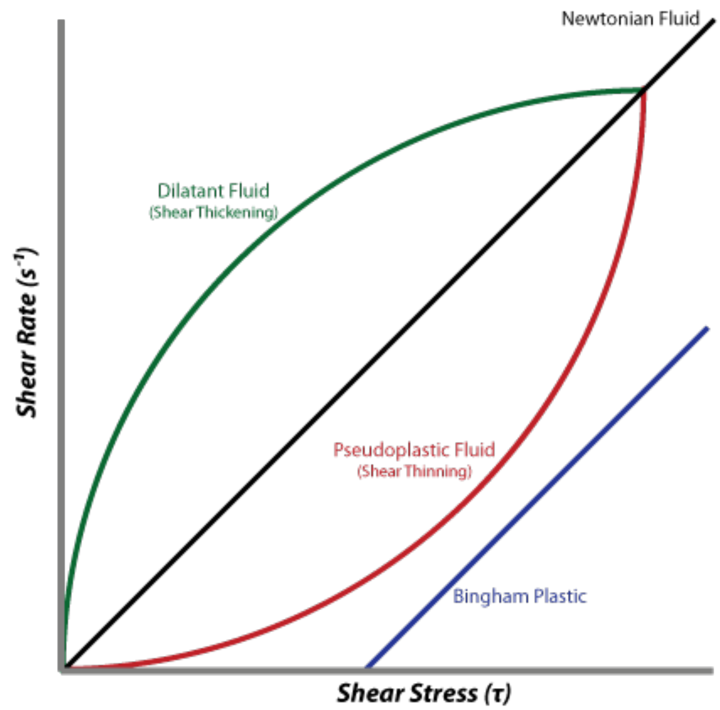
Definition for homogenous Newtonian fluid

Poor formula for viscosity in small vessels

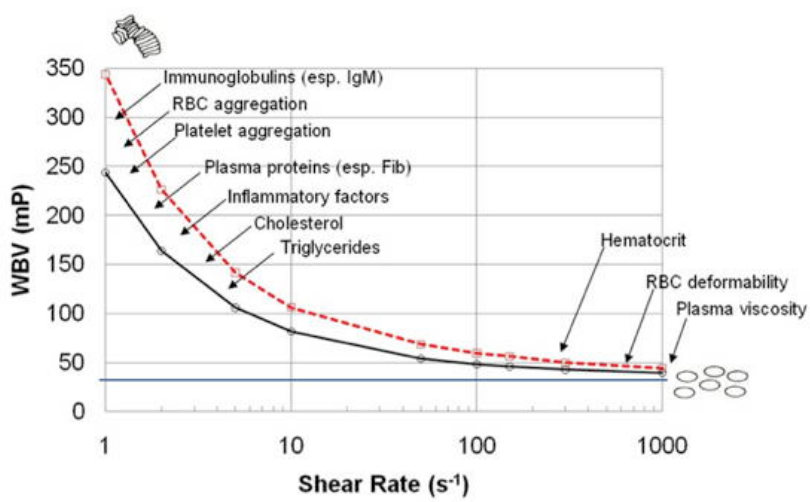
- Viscosity increases with
  - increased hematocrit
  - constrictions in vessels
- Viscosity decreases with
  - increased flow velocity
  - vessel diameter below 300 μm



Viscosity



Viscosity



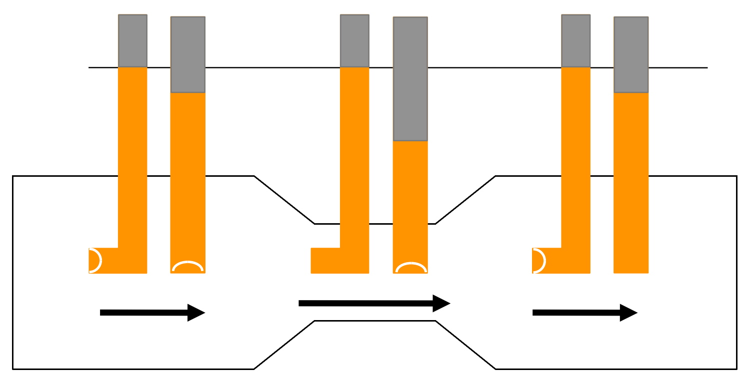
Shear Thinning or Thickening?

Factors that Affect Viscosity

- Flow rate: as flow decreases, viscosity increases up to 10-fold. Mechanism: RBCs adhering to each other, and the vessel walls.
- RBCs stick at constrictions, increase viscosity.
- Concentration, distribution, shape, and rigidity of the suspended particles (e.g., RBCs drift to the center so velocity profile flattens from ideal parabolic)
- Fahraeus-Lindqvist effect: reduced η when RBCs line up in small vessels (< 300 μm).
- In very small vessels (< 20 μm), η increases as RBCs fill the capillaries, “tractor tread” motion
- Temperature, blood pressure, presence of anticoagulants,
- Measurement conditions: higher in vitro than in vivo.
- History (pulsatile flow)

Velocity and Pressure

- Example: Aortic stenosis
  - increased velocity
  - decreased lateral pressure
  - reduced coronary flow
  - coronary ischemia



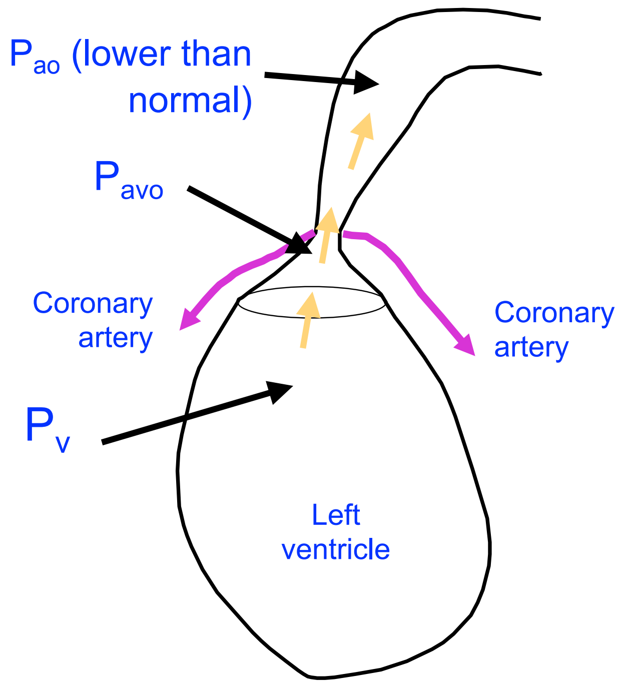
$$\begin{aligned} \dot{Q} &= \dot{Q}_o \\ v &= v_o \\ P_{tot} &= P_o \\ &= P_{do} + P_{lo} \\ P_d &= \frac{1}{2}\rho v_o^2 \\ &= P_{do} \\ P_l &= P_{lo} \end{aligned}$$

$$\begin{aligned} \dot{Q} &= \dot{Q}_o \\ v &= k v_o \\ P_{tot} &= P_o \\ &= P_d + P_l \\ P_d &= \frac{1}{2}\rho (k v_o)^2 \\ &= k^2 P_{do} \\ P_l &= P_{tot} - P_d \\ &< P_{lo} \end{aligned}$$

$$\begin{aligned} \dot{Q} &= \dot{Q}_o \\ v &= v_o \\ P_{tot} &= P_o \\ P_d &= P_{do} \\ P_l &= P_{lo} \end{aligned}$$

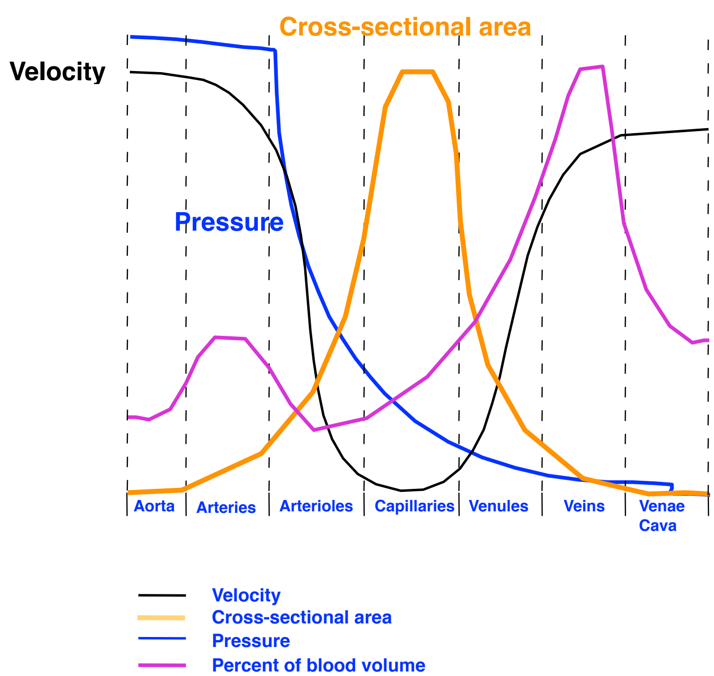
Aortic Stenosis

- Pressure losses
  - kinetic energy conversion
  - energy loss (friction)

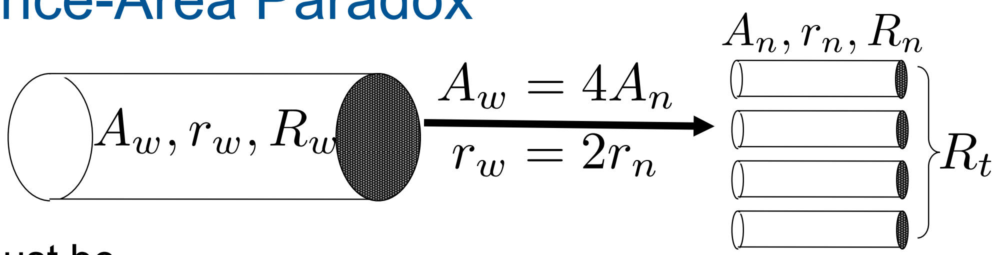


Resistance of the Circulatory System

- Resistance high where pressure drops
- Arterioles have highest resistance
- Paradox?
  - arterioles have more total area than arteries
  - vessels with larger area have smaller resistance
  - but arterioles have larger resistance than arteries?



Resistance-Area Paradox



- Net flow must be constant
- One vessel splitting to four increases total resistance!

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

$$\frac{1}{R_t} = \sum_{1=1}^{4} \frac{1}{R_n} = \frac{4}{R_n}$$

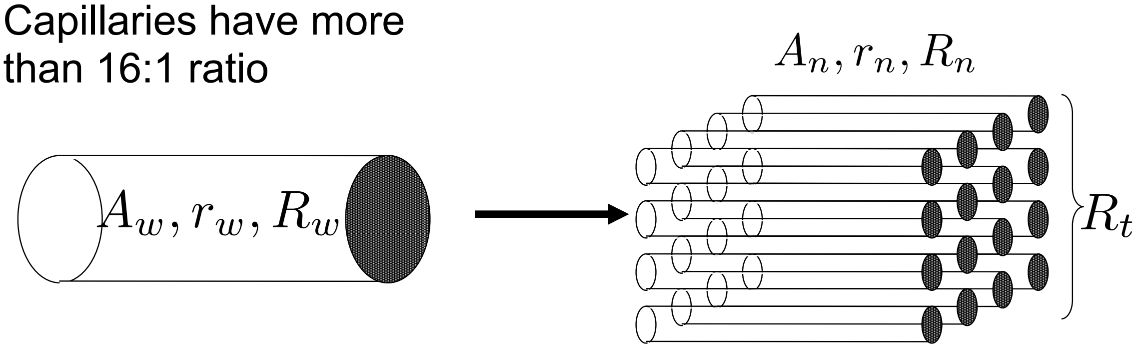
$$R_t = \frac{R_n}{4} = \frac{k}{4r_n^4}$$

$$R_w = \frac{k}{r_w^4} = \frac{k}{(2r_n)^4} = \frac{k}{16r_n^4} = \frac{1}{4} * \frac{k}{4r_n^4} = \frac{R_t}{4}$$

$$R_t = 4R_w!$$

Resistance Break Even Point

- Break-even point at 16 to 1 (for R_w=R_t).
- Capillaries have more than 16:1 ratio



$$A_t = 16A_n = 4A_w$$

$$R_w = R_t$$