CARDIOVASCULAR SYSTEM:
BIOPHYSICS OF CIRCULATION
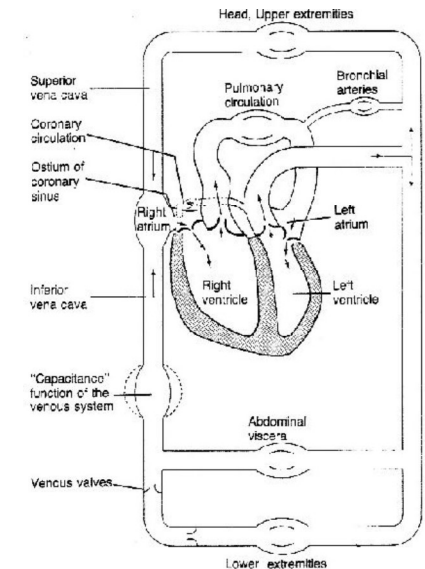## CARDIAC BIOPHYSICS

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The vascular system is a closed vessel system returning into itself

A. Function:
Maintenance of environmental parameters of cells ("steady state")
Transport:
Gases
Metabolites
Hormones, signal transmitters
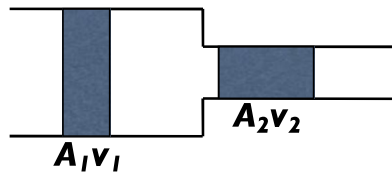Immunoglobulins
Heat

B. Hemodynamic requirements:
Slow (matches diffusion-driven processes)
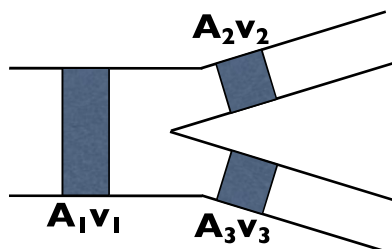Steady (no fluctuations)
Unidirectional

Fluid flow in bifurcating vessel system

Continuity equation

$$A_1 v_1 = A_2 v_2 = const$$

A = cross-sectional area
v = flow rate

$$A_1 v_1 = A_\Sigma (v)_{average} = const$$

A_Σ = total cross-sectional area

THERMODYNAMIC CURRENTS

- Natural processes are rarely reversible.
- If there are inequalities in the intensive variables at different locations within the system, thermodynamic currents arise.
- Thermodynamic currents aim at the restoration of equilibrium.
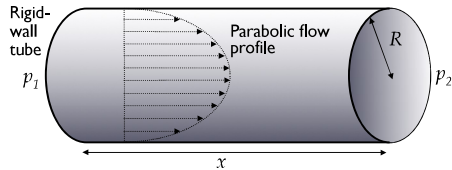- Extensive variables flow.

Thermodynamic current	Relevant intensive variable (its difference maintains current)	Current density	Physical law
Heat flow	Temperature (T)	$J_E = -l \dfrac{\Delta T}{\Delta x}$	Fourier
Volumetric flow	Pressure (p)	$J_V = -\dfrac{R^2}{8h} \dfrac{\Delta p}{\Delta x}$	Hagen-Poiseuille
Electric current	Electric potential (φ)	$J_Q = -\dfrac{1}{r} \dfrac{\Delta j}{\Delta x}$	Ohm
Material transport (diffusion)	Chemical potential (μ)	$J_n = -D \dfrac{\Delta c}{\Delta x}$	Fick

Laws of flow in viscous fluids II.

Hagen-Poiseuille's law

G.H.L. Hagen (1797-1884) J.-L.-M. Poiseuille (1799-1869)

Thermodynamic current	Relevant intensive variable (its difference maintains current)	Current density	Physical law
Volumetric flow	Pressure (p)	$J_v = -\dfrac{R^2}{8\eta}\dfrac{\Delta p}{\Delta x}$	Hagen-Poiseuille

Rigid-wall tube
p_1
Parabolic flow profile
R
p_2
x

$$J_V = \frac{V}{tA} = \frac{R^2}{8\eta}\frac{\Delta p}{\Delta x}$$

N.B. 1: $\quad A = R^2\pi \quad\Rightarrow\quad I_V = \frac{V}{t} = -\frac{R^4\pi}{8\eta}\frac{\Delta p}{\Delta x}$

N.B. 2: $\quad I_V = -\frac{R^4\pi}{8\eta\Delta x}\Delta p \quad\Rightarrow\quad -\Delta p = R_{tube}\cdot I_V \Rightarrow \boxed{U=R\cdot I}$

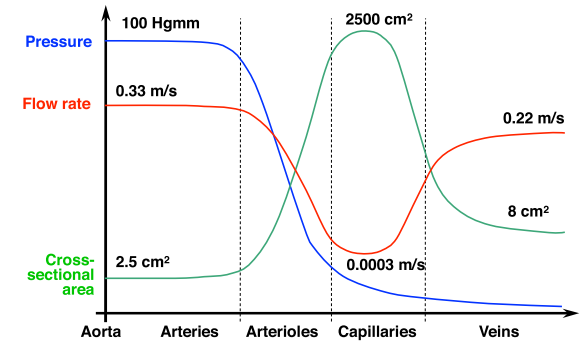$1/R_{tube}$ Ohm's law!

N.B. 3: $\quad \dfrac{\Delta v}{\Delta r} \sim r \quad\Rightarrow\quad \left(\dfrac{\Delta v}{\Delta r}\right)_{max} = R \quad\Rightarrow\quad \tau_{max} = R$

Shear stress is maximal at the tube wall because of the parabolic flow profile.

V = volume	$V/t = I_V$ = volumetric vlow rate
t = time	$\Delta p/\Delta x$ = pressure gradient, maintained by p_2-p_1 (negative!)
R = tube radius	
η = viscosity	
p = pressure	A = cross-sectional area of tube
x = tube length	I_V = volumetric flow rate

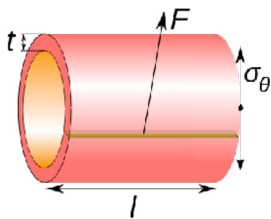# Structure and physical properties of the vascular system

- **Pressure** on blood vessel wall: **"blood pressure"**. Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance - most of energy is converted to heat.
- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity, Av = constant).
- Flow rate typically does not exceed the **critical** (see Reynolds number), and flow remains laminar. (Exceptions: behind aortic valve, constricted vessels, low-viscosity conditions, Korotkoff sound).
- **Arterioles** (vessels containing smooth muscle, under vegetative innervation) are pressure-regulators: **"resistance vessels."**
- Most of blood volume in veins: **"capacitance vessels."**

Wall tension and bood pressure

Circumferential stress (σ_θ) depends on blood pressure:
(Young-Laplace - equation)

$$\sigma_\theta = \frac{P\cdot r}{t}$$

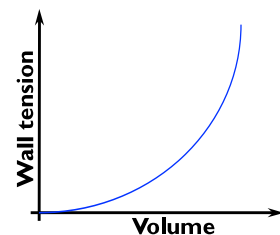P = blood pressure
r = radius of tube
t = wall thickness

$$\sigma_\theta = \frac{F}{t\cdot l}$$

F = force
l = tube length

Wall tension or circumferential stress is the average force exerted circumferentially (perpendicular to both the axis and the radius) in the cylinder wall.

Vessel wall displays non-linear elastic properties
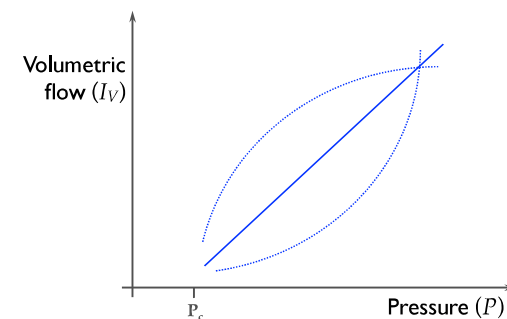

Determinants of vascular elasticity:
Elastin
Collagen
Smooth muscle

Implications of vascular easticity:
Storage of potential (elastic) energy
Dampening of pressure pulses
Constant flow rate
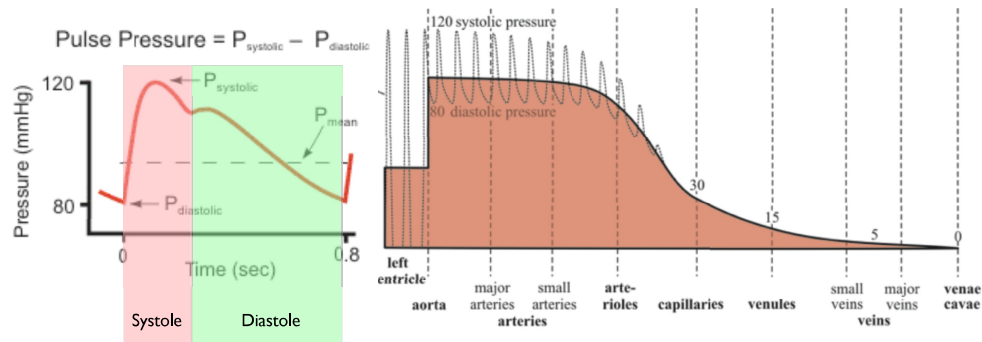
Relationship between flow intesity and pressure

Below certain pressure vessels collapse and flow ceases

N.B.:
-The curves intersect the pressure axis at values greater than 0 (critical closing pressure, P_c).
-P_c in arteries, at resting conditions, is ~20 Hgmm.
During blood pressure measurement we compress the limb by raising the cuff pressure above the local P_c.

Dynamic pressure-changes in the arterial system

Pulse Pressure = $P_{systolic} - P_{diastolic}$

Because of vessel wall elasticity, pressure fluctuations are dampened.

Capillary circulation, fluid exchange

1. Capillaries:
Length: 400-700 μm
Diameter: 0.5 μm

2. Open state depends on function
Number of open caillaries in muscle:
Rest - 5/mm^2
Activity - 200/mm^2

3. Capillary fluid exchange
fluid movement between bloof plasma and interstitium
driven by: difference in blood pressure and colloid osmotic pressure
Colloid osmotic (oncotic) pressure:
osmotic pressure caused by the presence of colloidal proteins (2.6 kPa)

	Arterioles	Capillaries	Venules
Bood pressure	4.0 kPa	2.6 kPa	1.3 kPa
Colloid osmotic pressure	2.6 kPa	2.6 kPa	2.6 kPa

Auxiliary factors of circulation

1. Arterial elasticity
elastic fibers ➝ storage of potential energy

2. Venous valves (Harvey's experiment)
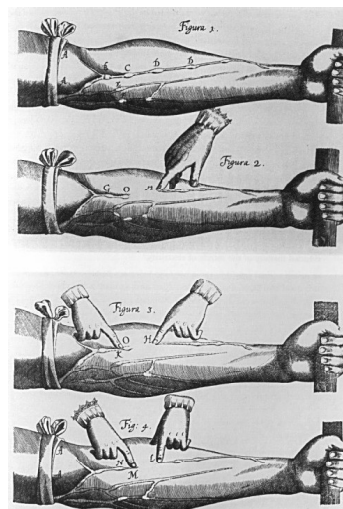*"Exercitatio anatomica de motu cordis et sanguinis in animalibus" (1628)*

3. Muscle action

4. Negative intrathoracic pressure

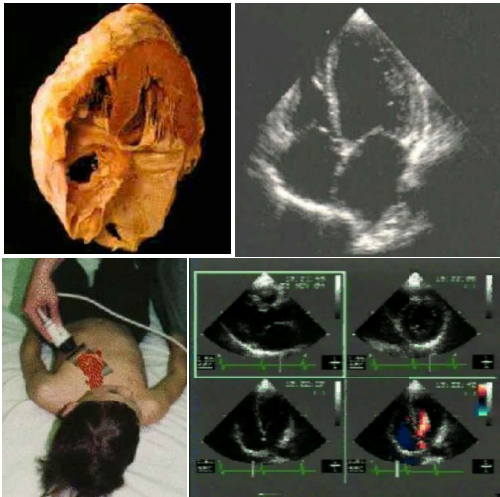**5.** "Up-and-down" movement
of **atrioventricular plane**
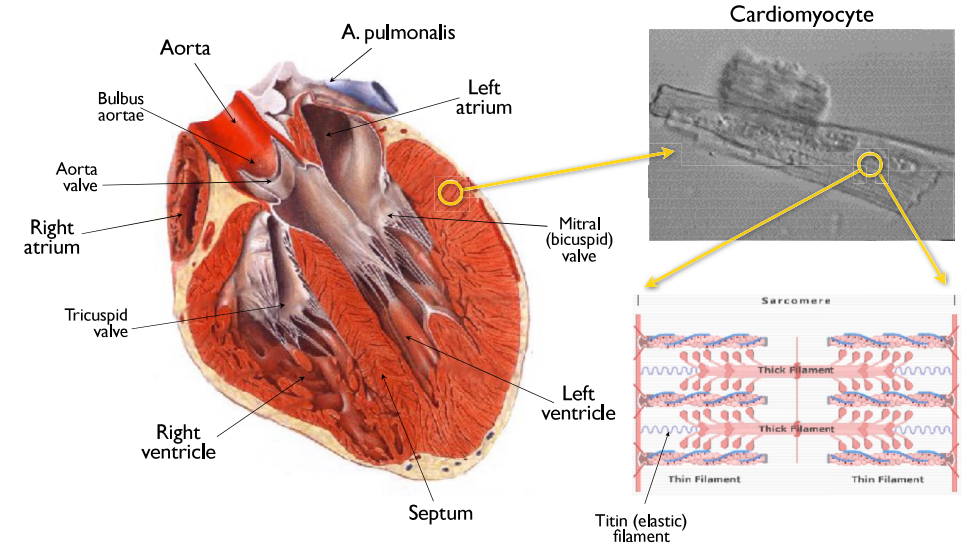
Harvey's experiment (1628)

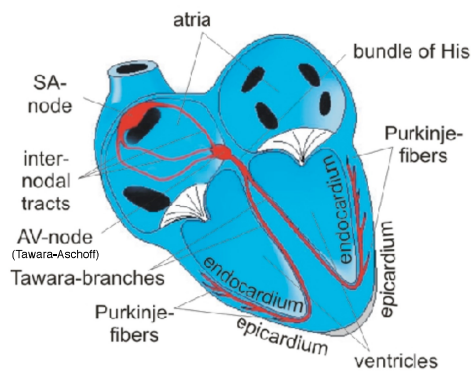# CARDIAC BIOPHYSICS

Heart:

Pump of the circulatory system

	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	~2.5 x 10^9	~220 x 10^6 l

Schematic structure of the human heart

Cardiomyocyte

Aorta
A. pulmonalis
Bulbus aortae
Left atrium
Aorta valve
Right atrium
Mitral (bicuspid) valve
Tricuspid valve
Sarcomere
Left ventricle
Thick Filament
Right ventricle
Septum
Thin Filament
Titin (elastic) filament

Activation of coordinated cardiac contractions

Electrocardiogram (ECG)

atria
bundle of His
SA-node
Purkinje-fibers
inter-nodal tracts
AV-node (Tawara-Aschoff)
Tawara-branches
Purkinje-fibers
endocardium
epicardium
ventricles

QRS complex
R
PQ segment
ST segment
P
T
1 mV
Q
S
PQ interval
QT interval
atrial depolarization
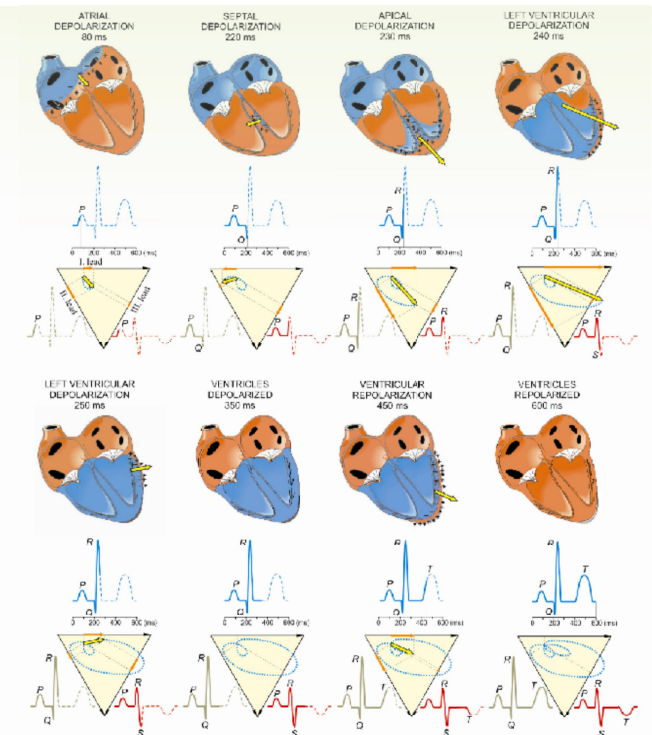ventricular depolarization + atrial repolarization
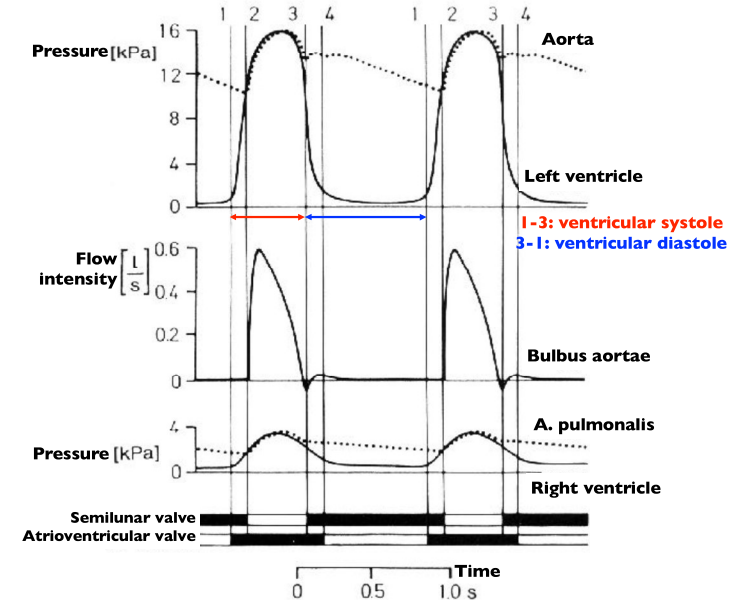ventricular repolarization
800 ms

EKG:

Vectorial projections (according to leads) of the resultant dipole (integral vector) that changes in time and space during myocardial depolarization and repolarization.
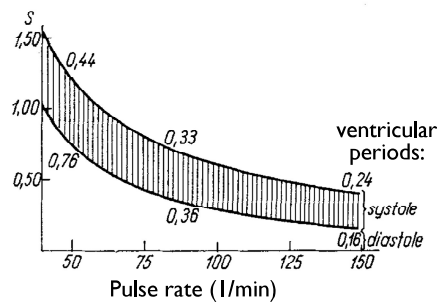
The cardiac cycle

Contraction (systole) - relaxation (diastole) cycle of the heart

	systole	diastole
atrium	0,1 s	0,7 s
ventricle	0,3 s	0,5 s

Events of the cardiac cycle 1.

Events of the cardiac cycle 2.

Electrokardiogram (ECG)

Pressure-volume diagram of left ventricle

Work of the heart

(work of the left ventricle)

Indicator diagram:
Simplified pressure-
volume relationship

$$L = p\Delta V + \frac{1}{2}mv^2$$

pΔV=static (volumetric) component
1/2mv²=dynamic component
p=pressure
ΔV=**stroke volume**

$$13,3 \cdot 10^3 \, N/m^2 \times 0,08 \cdot 10^{-3} \, m^3 + \frac{1}{2} 0,08 kg \times (1m/s)^2 = 1,06 Nm + 0,04 Nm = 1,1 J$$