Cardiovascular system:

Biophysics of circulation

Cardiac biophysics

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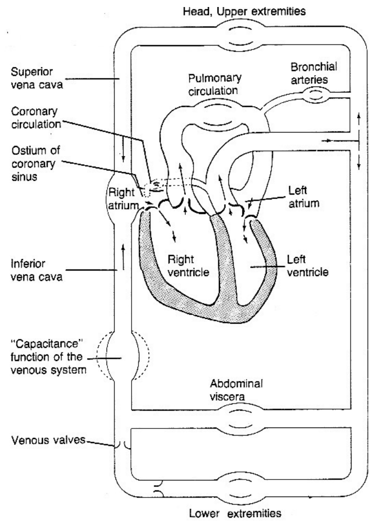
The vascular system is a closed vessel system returning into itself

A. Function:

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

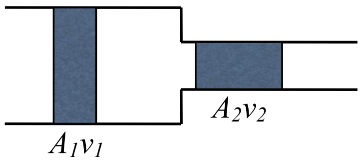
B. Hemodynamic requirements:

Slow (matches diffusion-driven processes)
Steady (no fluctuations)
Unidirectional (but not open-ended)



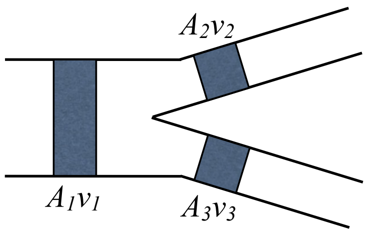
Fluid flow in bifurcating vessel system

Continuity equation



$$A_1v_1 = A_2v_2 = const$$

A = cross-sectional area
v = flow rate



$$A_1v_1 = A_\Sigma(v)_{average} = const$$

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.

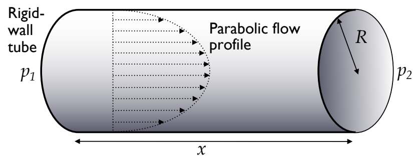
Thermodynamic current	Relevant intensive variable (its difference maintains current)	Current density	Physical law
Heat flow	Temperature (T)	$J_E = -\lambda \frac{\Delta T}{\Delta x}$	Fourier
Volumetric flow	Pressure (p)	$J_V = -\frac{R^2}{8\eta}\frac{\Delta p}{\Delta x}$	Hagen-Poiseuille
Electric current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



V = volume
t = time
R = tube radius
η = viscosity
p = pressure
x = tube length

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

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

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

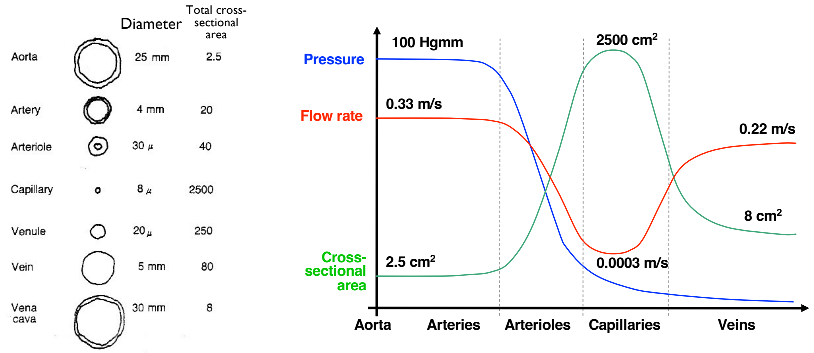
N.B. 2: $I_V = -\frac{R^4\pi}{8\eta\Delta x}\Delta p \Rightarrow -\Delta p = R_{tube}\cdot I_V \Rightarrow U = R\cdot I$

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

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

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

Structure and physical properties of the vascular system



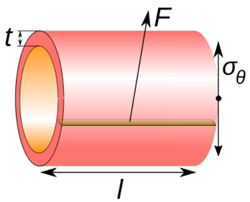
- **Pressure** on blood vessel wall: ***"blood pressure"***. Pressure drop along vessel maintains blood flow.
- Reason of **pressure drop**: flow resistance - most of energy is converted to heat.
- **Flow rate** and total **cross-sectional area** change inversely (based on equation of continuity, *Av* = 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

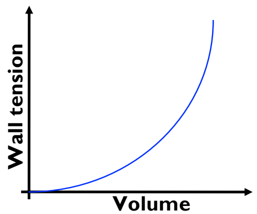


$$\sigma_\theta = \frac{F}{t\cdot l}$$

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

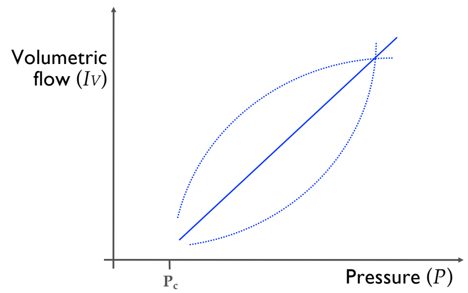


Determinants of vascular elasticity:
Elastin
Collagen
Smooth muscle

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

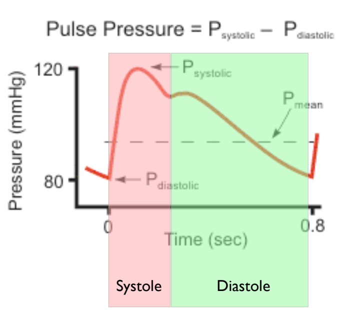
Relationship between flow intensity and pressure

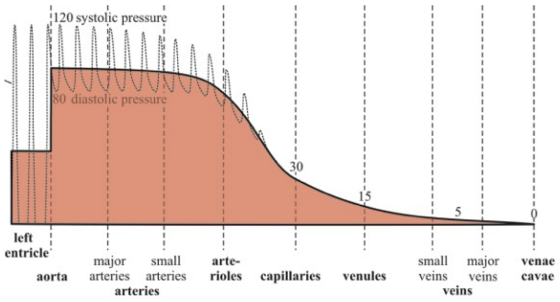
Below certain pressure vessels collapse and flow ceases



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.

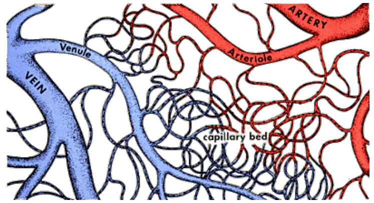
Dynamic pressure-changes in the arterial system





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 - $200/mm^2$

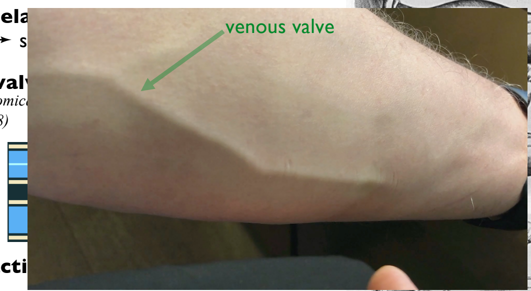
3. Capillary fluid exchange
fluid movement between blood plasma and interstitium
driven by: difference in blood pressure and colloid osmotic pressure
Colloid osmotic (oncotic) pressure:
osmotic pressure caused by the presence of colloidal proteins (2.6 kPa)

	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 ela
elastic fibers → s

2. Venous val
"Exercitatio anatomic
animalibus" (1628)

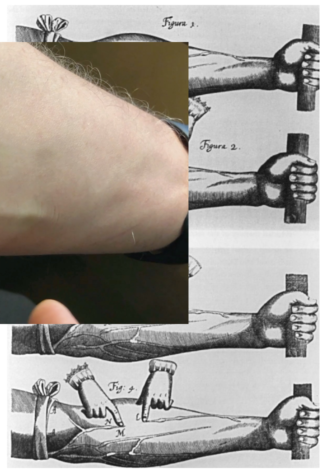


3. Muscle acti

4. "Negative" intrathoracic pressure

5. "Up-and-down" movement
of **atrioventricular plane**

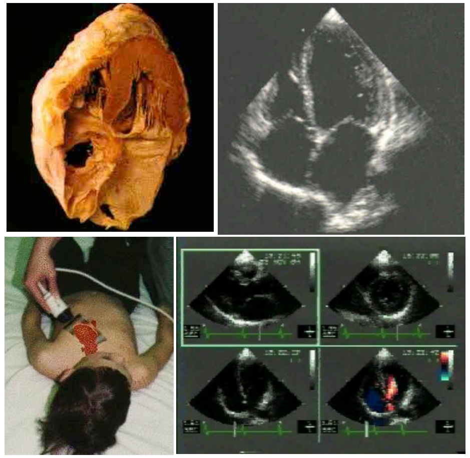
Harvey's experiment (1628)



Cardiac biophysics

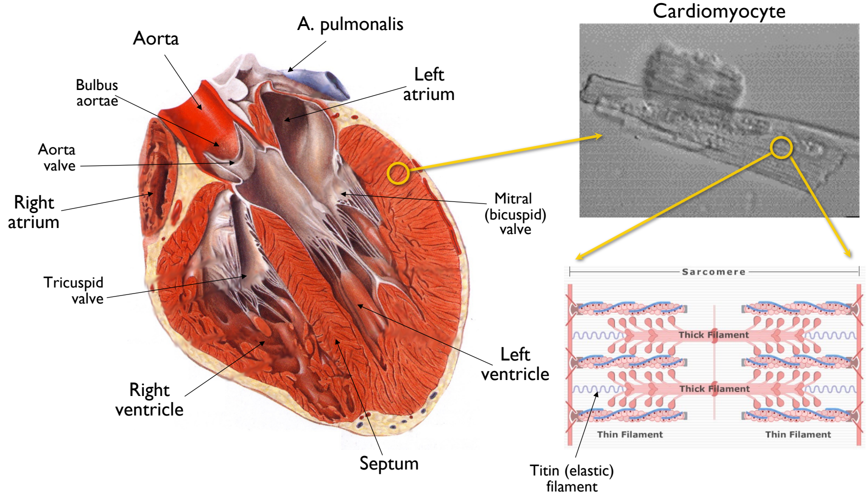
Heart:

Pump of the circulatory system

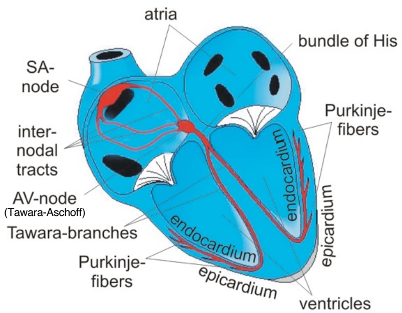


	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	~2.5 x 10^9	~220 x 10^6 l

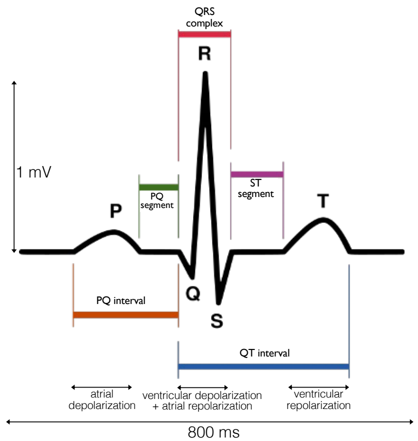
Schematic structure of the human heart



Activation of coordinated cardiac contractions

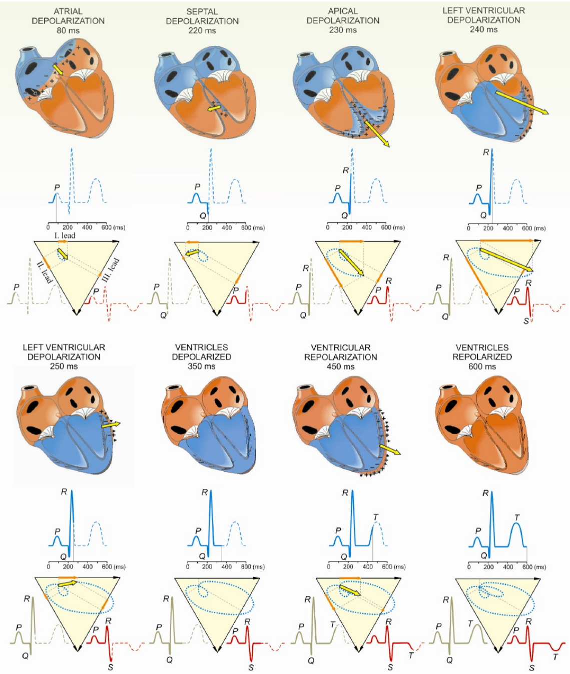


Electrocardiogram (ECG)



EKG:

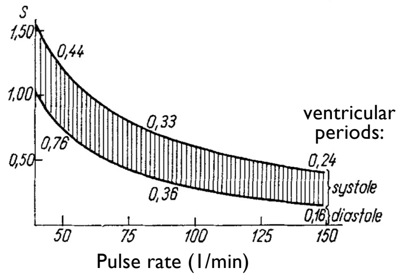
Vectorial projections (according to leads) of the resultant dipole (integral vector) that changes in time and space during myocardial depolarization and repolarization.



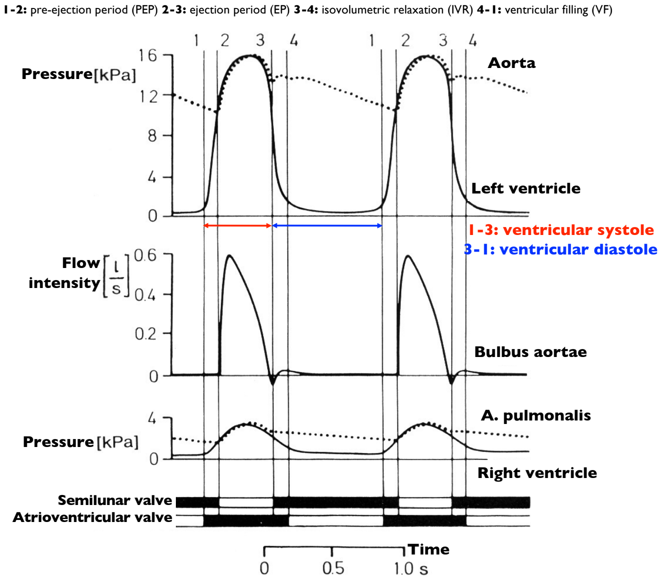
The cardiac cycle

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

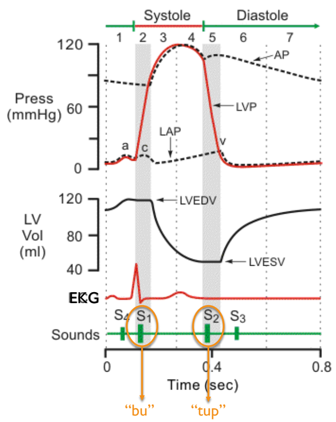
	systole	diastole
atrium	0,1 s	0,7 s
ventricle	0,3 s	0,5 s

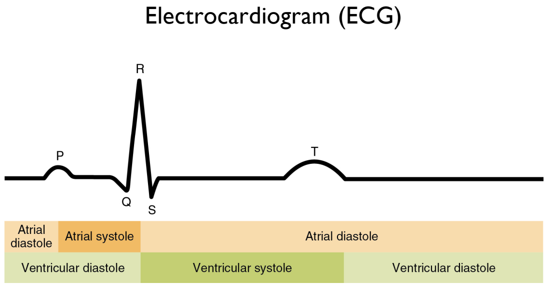


Events of the cardiac cycle 1.

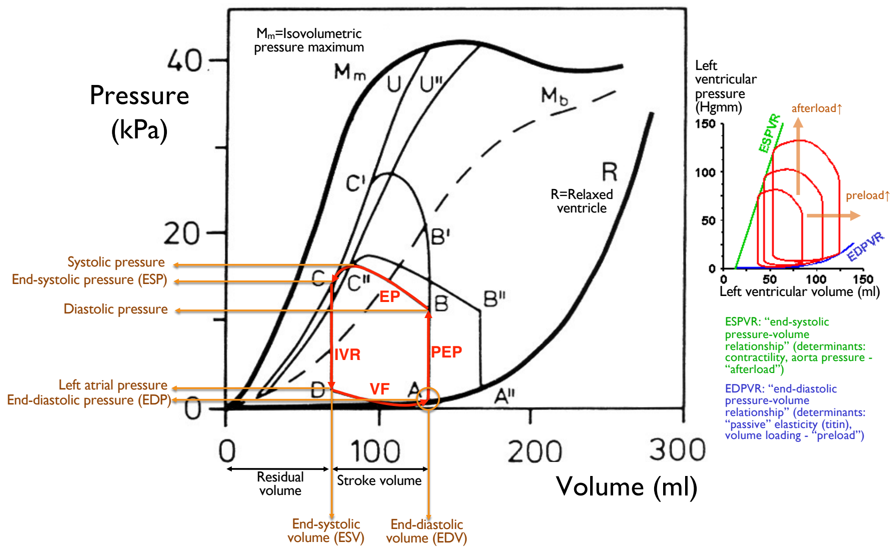


Events of the cardiac cycle 2.





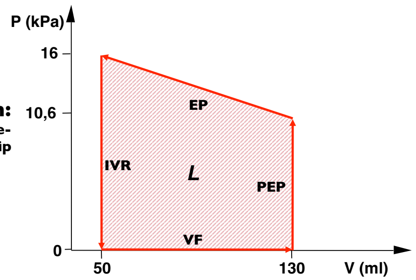
Pressure-volume diagram of left ventricle



Work of the heart

(work of the left ventricle)

Indicator diagram:
Simplified pressure-volume relationship



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

$p\Delta V$=static (volumetric) component
$1/2mv^2$=dynamic component
p=pressure
ΔV=**stroke volume**

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

Feedback

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