RESPIRATORY BIOPHYSICS

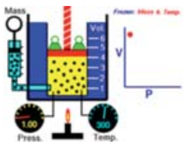
MIKLÓS KELLERMAYER

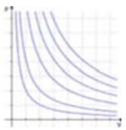
History of respiratory biophysics

- Aristotle (300 BC): respiration cools the heart and blood
- Galenus (170 BC): breathing adds something to the blood (“*spiritus vitalis*”)
- Leonardo da Vinci (1452-1519): animals die in a closed room where air refreshment is blocked.
- Vesalius (1543): the animal dies of its chest is opened, but survives if its lung is rythmically ventilated.
- Gas laws (17-18. century, Clausius, Clapeyron, Boyle, Mariotte, Gay-Lussac, Charles)
- Black (1754): discovery of carbon dioxide. Priestley (1771): discovery of oxygen.
- “Blood gases”: Magnus (1837), Haldane (1900)
- Surfactant: Neergaard (1920s), Pattle and Clements (1950s)

Relevant physical and physico-chemical laws

1. Ideal gas law (derives from Clausius-Clapeyron’s, Boyle-Mariotte’s, Charles’s laws): Relationship between the pressure, volume, temperature and amount of gas.





Pressure-volume isotherms

$$PV = nRT$$

P = pressure (Pa)
V = volume (m^3)
n = amount (moles)
R = gas constant (8.314 $JK^{-1}mol^{-1}$)
T = absolute temperature (K)

2. Dalton’s law (John Dalton, 1801): The total pressure exerted by the mixture of non-reactive gases is equal to the sum of the partial pressures of individual gases.

$$P_{total} = \sum_{i=1}^{n} p_i$$

p_i = partial pressure of the ith gas
n = number of gases in the mixture
[$p_i = P_{total} \times r$; r = ratio of the gas in the mixture]

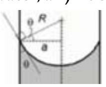
3. Henry’s law (William Henry, 1803): At a constant temperature, the amount of a given gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid.

$$p = k_H c$$

p = partial pressure (Pa; atm)
k_H = Henry’s constant (l · atm/mol)
c = concentration of dissolved gas (mol/l)

4. Young–Laplace equation: Describes the capillary pressure difference sustained across the interface between two static fluids (e.g., water, air) due to surface tension.

In a sufficiently narrow tube:

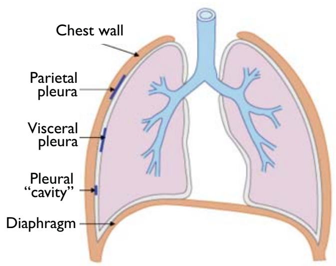


$$\Delta p = \frac{2\gamma}{R}$$

p = pressure (Nm^{-2})
γ = surface tension (Nm^{-1}; Jm^{-2})
R = radius of curvature

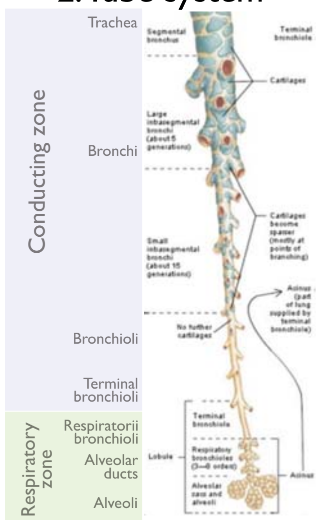
Simplified respiratory system

1. Box



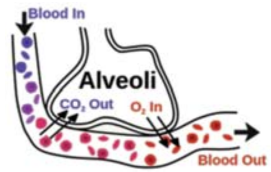
- Intrapulmonary pressure (P_{pulm}): fluctuates around external (atmospheric) pressure
- Intrathoracic or intrapleural pressure (P_{pl}): “negative” (balance between atmospheric pressure, adhesional and contractile forces)
- Transmural (transpulmonary) pressure (P_{tm}): pressure difference across chest wall
- *Pneumothorax!*

2. Tube system



- 23-25 dichotomic divisions
- Laws of fluid flow (Hagen-Poiseuille!)

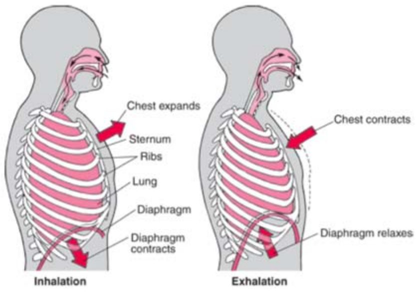
3. Gas exchange surface

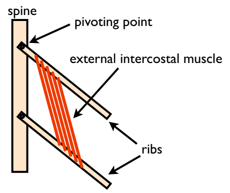


- Alveole: open thermodynamic system
- Surface for gas exchange.
- Number: ~300 million (*N.B.*: 2^{25}=33,554,432)
- Size (d~200 μm), area (5×10^{-7} m^2/alveolus)
- Total alveolar area: ~100 m^2
- Alveolar wall (~0.5 μm): alveolar epithelium (~0.2 μm) basal membrane (~0.1 μm) capillary endothelium (~0.2 μm)
- Driving force of gas exchange: diffusion (Fick’s laws!)
- The partial pressures of gas phases tend to equilibrate with blood plasma gas tensions.

Respiratory cycle

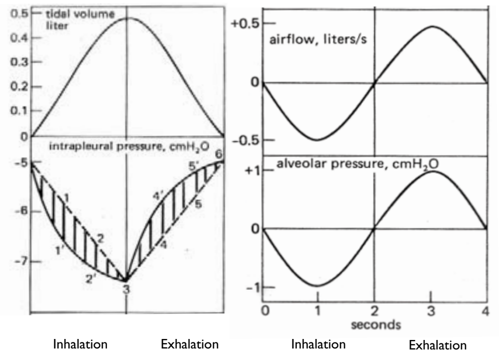
1. Mechanical control





- Eupnoe: normal breathing (14-16/min)
- Polypnoe, tachypnoe: number of breaths >16/min
- Dyspnoe: shortness of breath

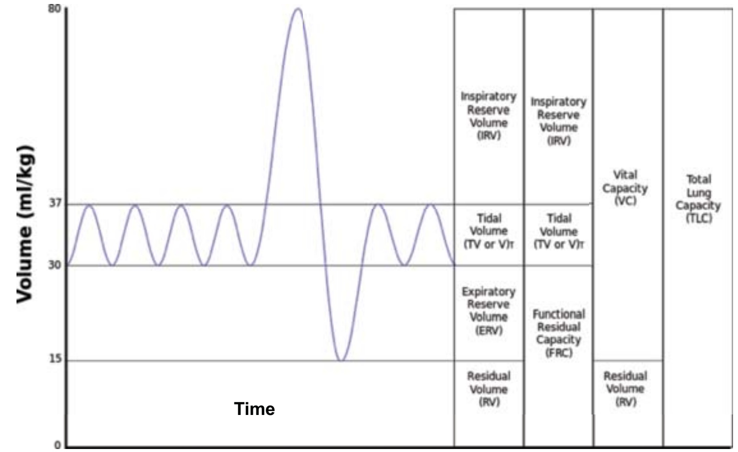
2. Changes in physical parameters



1 cmH_2O = 0.1 kPa = 0.7 mmHg

Pulmonary volumes and capacities

Capacity: sum of volumes

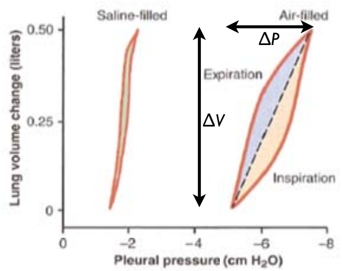


Volume	Value (litres) In men	Value (litres) In women
Inspiratory reserve volume	3.3	1.9
Tidal volume	0.5	0.5
Expiratory reserve volume	1.0	0.7
Residual volume	1.2	1.1

Volume	Average value (litres) In men	Average value (litres) In women	Derivation
Vital capacity	4.8	3.1	IRV plus TV plus ERV
Inspiratory capacity	3.8	2.4	IRV plus TV
Functional residual capacity	2.2	1.8	ERV plus RV
Total lung capacity	6.0	4.2	IRV plus TV plus ERV plus RV

Processes of the respiratory cycle

1. Lung cyclically expands and contracts



Compliance ("deformability", "stretchability", "distensibility"):

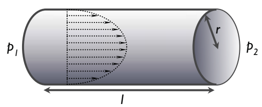
$$C = \frac{\Delta V}{\Delta P}$$

C = compliance (mN^{-1}; *N.B.*: inverse of stiffness)
ΔP = change in pressure (Pa, Nm^{-2})
ΔV = change in volume (m^3)

Surfactant

- Pulmonary surfactant: surface-active lipoprotein complex (phospholipoprotein) formed by (type II) alveolar cells.
- Composition: 90 % lipids, 10 % proteins ("surfactant protein" SP-A, SP-B, SP-C, SP-D)
- Function: reduces surface tension
- Effect: the smaller the surface tension, the less pressure needed to keep alveoli open (for a given pressure, smaller alveoli can be opened) (Young-Laplace equation!).
- *Restrictive diseases:* pulmonary compliance is reduced (fibrosis, lack of surfactant, etc.).

2. Gas flows in airways



Hagen-Poiseuille's law

$$\frac{V}{t} = \frac{\pi r^4}{8\eta}\frac{dp}{dl}$$

V = volume
t = time
($V/t = Q$ = flow intensity)
r = tube radius
η = viscosity
p = pressure
l = length of tube
(dp/dl = pressure gradient, maintained by p_1-p_2)

- Normally (eupnoe): flow is laminar.
- Tachypnoe or disease: turbulent airflow
- *Obstructive diseases*: pulmonary airflow is compromised (COPD - "chronic obstructive pulmonary disease").

Respiratory work

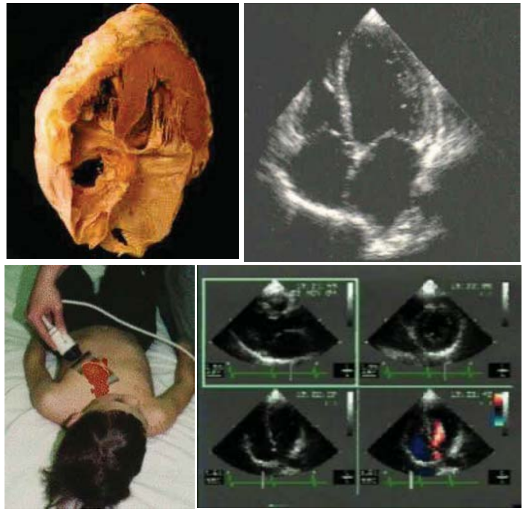
- Volume change against average transmural pressure
- Minute volume (MV) = 7 l
- Breathing rate (BR) = 14/min
- Pressure (P_{tm}) = 0.7 kPa
- Respiratory volume (V) = 0.5 l (5×10^{-4} m^3)
- Work (W) = $P_{tm} \times V$ = 0.35 J/inspiration (294 J/h)

- At great loads it may reach 8400 J/h

Cardiac biophysics

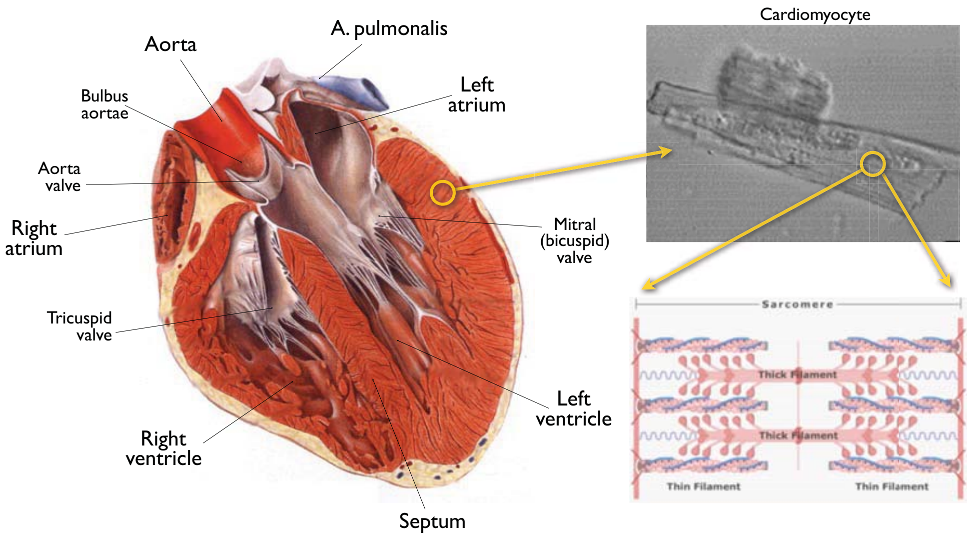
Heart:

Pump of the circulatory system

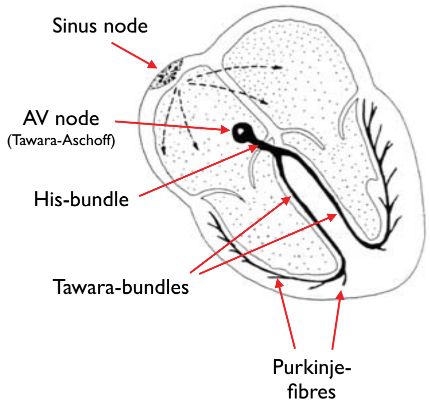


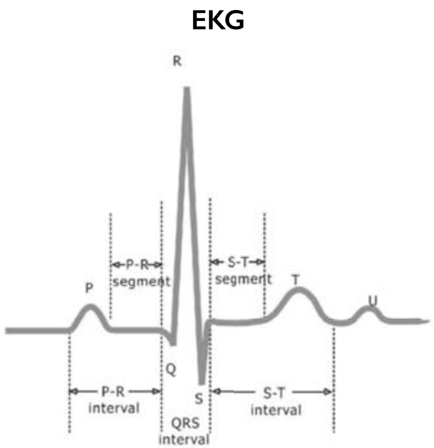
	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100.000	~8600 l
Life (70 yrs)	~2.5 x 10^9	~220 x 10^6 l

Structure of the human heart



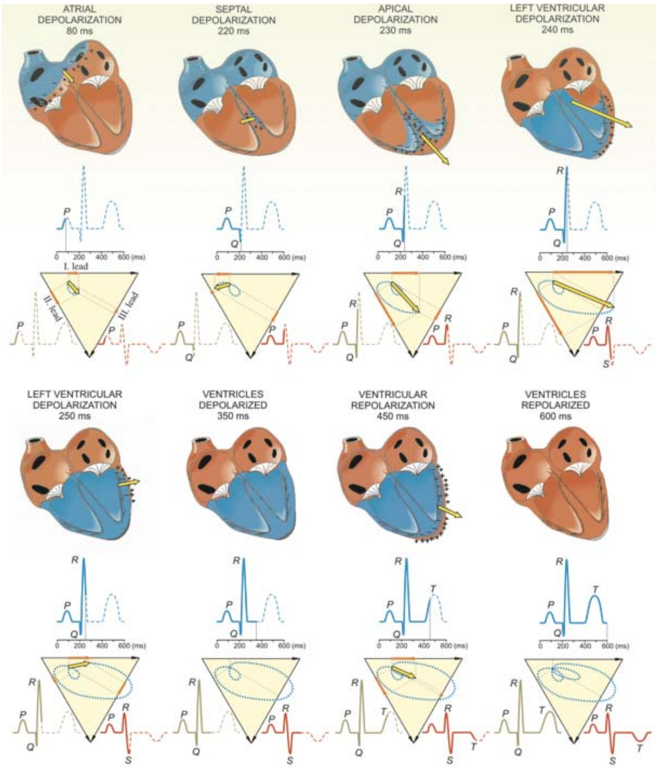
Activation of coordinated contractions





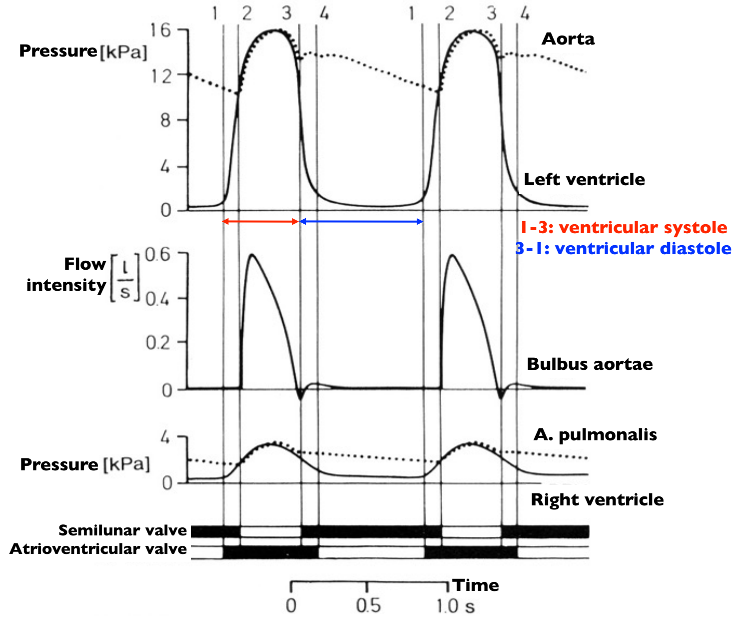
EKG:

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

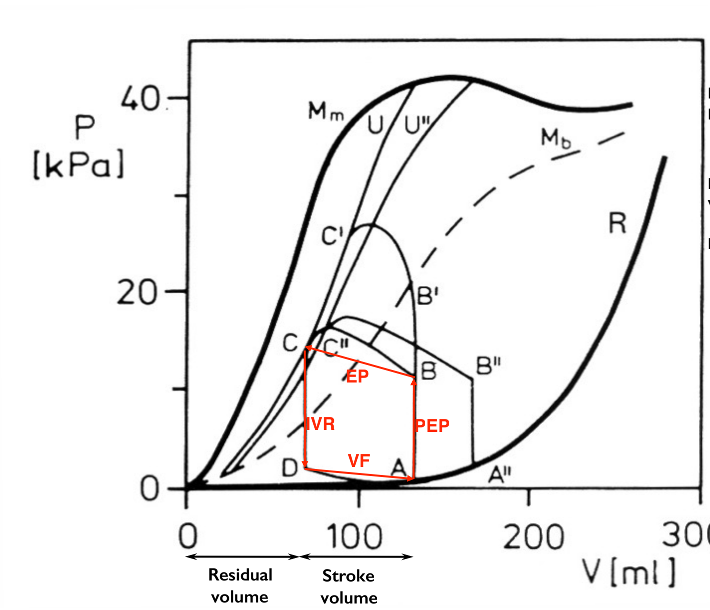


Events of the cardiac cycle

1-2: pre-ejection period (PEP) **2-3:** ejection period (EP) **3-4:** isovolumetric relaxation (IVR) **4-1:** ventricular filling (VF)



Pressure-volume diagram of left ventricle



M_m=Isovolumetric Pressure maximum

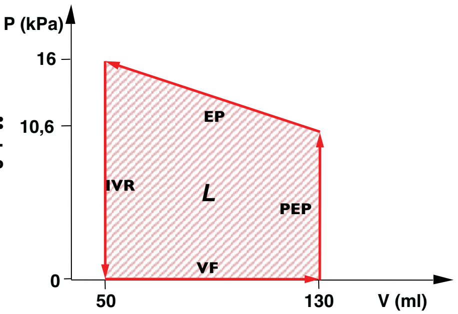
M_b=Isobaric Volume minimum

R=Relaxed 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

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

Physical basis of physical examination

Physical examination

- Inspection
- Palpation
- Percussion
- Auscultation

Inspection

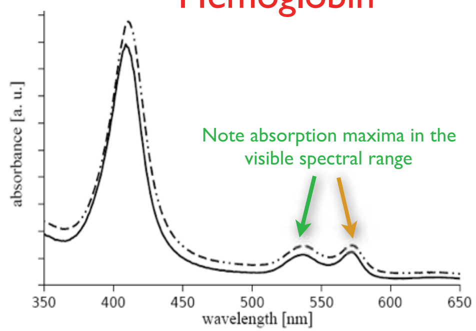
What is it?
Visual examination of the patient

What do we visualize?
Behavior, morphology, structure, ***color***

Relationship to biophysics:
Absorption spectroscopy

Light absorption

Hemoglobin



From the general law of radiation attenuation:

$$J = J_0 e^{-\mu x}$$

$$\lg \frac{J_0}{J} = \mu x \lg e$$

$$\lg \frac{J_0}{J} \approx \mu$$

absorbance, optical density

$$\lg \frac{J_0}{J} = \varepsilon_\lambda c x$$

Lambert-Beer's Law

ε_λ = molar extinction coefficient

c = concentration

Examples

Cyanosis (rise in deoxygenated hemoglobin)

Icterus (jaundice, hyperbilirubinaemia)

Erythema (redness of the skin)

Palpation

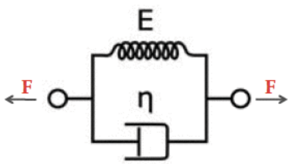
What is it?
Examining the patient by touching

What do we palpate?
Size, shape, location, ***firmness***

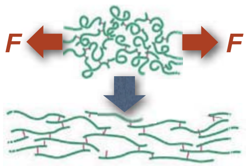
Relationship to biophysics:
Biomechanics

Viscoelasticity

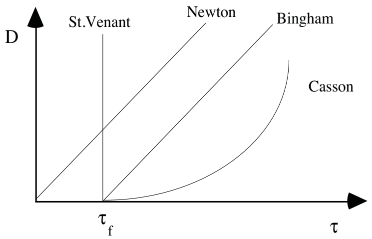
Spring-dashpot model



Schematic mechanism



Velocity gradient versus shear stress function of newtonian and non-newtonian fluids



Example: edema (pitting)

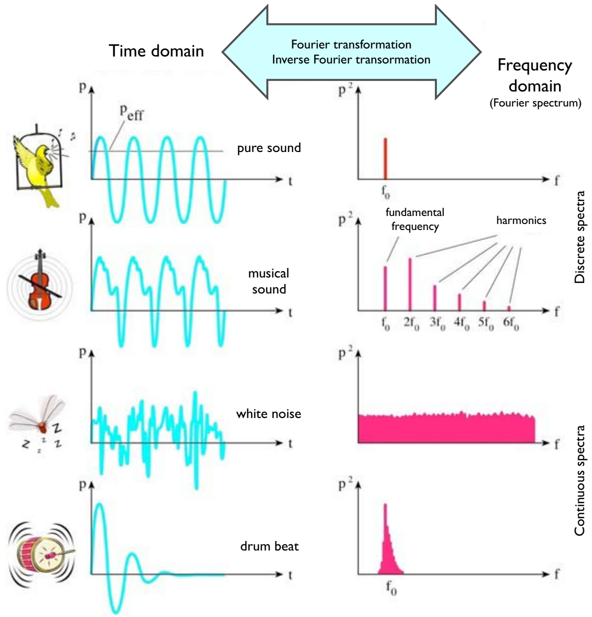
Percussion

What is it?
Examining the patient by locally striking (tapping) with short, sharp blows

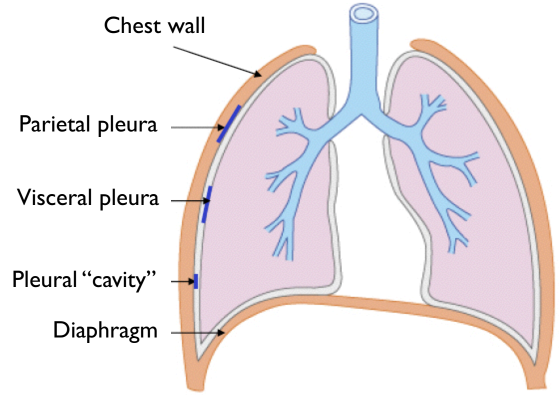
What do we examine by percussion?
Material content, shape, boundaries

Relationship to biophysics:
Sound generation, propagation and detection

Sounds and their spectra



Respiratory system as a box



Percussion sounds may be flat (muscle), dull (liver), or resonating (normal lung)

Boundaries of the diaphragm, heart, liver (and other, parenchymal organs) may be detected by percussion.

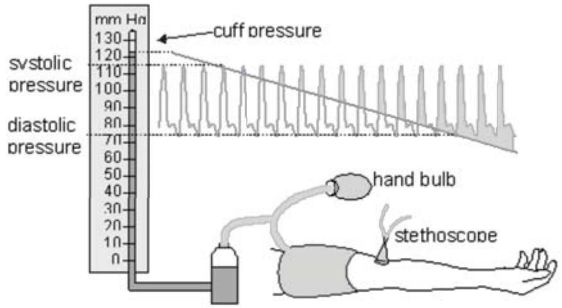
Auscultation

What is it?
Examining the patient by listening (with a stethoscope) for sounds (murmurs) within the body

What do we examine by auscultation?
Loudness, pitch, tone, duration, temporal variation (rythm)

Relationship to biophysics:
Sound generation, propagation, fluid flow, turbulence

Korotkow's sound



1. tapping
2. swishing
3. knocking
4. muffling

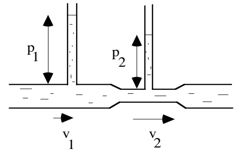
Reynolds number:

$$R = \frac{vr\rho}{\eta}$$

v=flow rate (m/s)
r=tube radius (m)
ρ=density of fluid (kg/m³)
η=viscosity (Ns/m²)

Turbulent flow (R> ~1000) causing sound effects

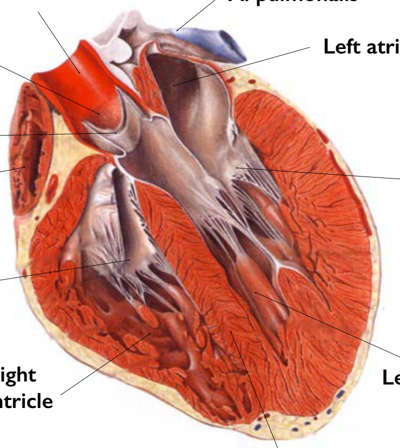
Bernoulli's law



Fluctuation of static and dynamic pressures resulting in rapid opening and closing of brachial artery

Heart sounds and murmurs

Sources: mechanical vibrations (e.g., valve closing), turbulent flow
Conductance: towards blood-filled compartments



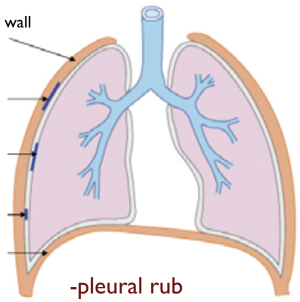
2. Aorta stenosis: systolic murmur

3. Mitral stenosis: diastolic murmur

1. Normal heart sound: systolic - diastolic (boo - tupp)

Respiratory sounds

Sources: mechanical resonance (organ-pipe action), mechanical vibrations (rubbing), bubbling through fluid



-pleural rub
(friction between pleural walls)

Tracheobronchial sounds

Conducting zone
Trachea
Bronchi
Bronchioli
Terminal bronchioli

-wheeze
(airway obstruction)

Vesicular sounds

Respiratory zone
Respiratory bronchioli
Alveolar ducts
Alveoli

-crackles
(bubbling through ducts)
-crepitation
(alveolar opening-closing)