

RESPIRATORY BIOPHYSICS

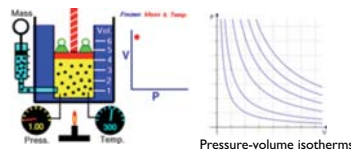
MIKLÓS KELLERMAYER

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 if its chest is opened, but survives if its lung is rhythmically 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.



$$PV = nRT$$

P = pressure (Pa)
 V = volume (m^3)
 n = amount (moles)
 R = gas constant ($8.314 \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$)
 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.

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

p_i = partial pressure of the i th gas
 n = number of gases in the mixture
 $[p_i = P_{\text{total}} \cdot r_i; r_i = \text{ratio of the gas in the mixture}]$

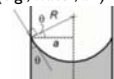
3. Henry's law (William Henry, 1803): At a constant temperature, the amount of a given gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid.

$$p = k_H c$$

p = partial pressure (Pa; atm)
 k_H = Henry's constant ($\text{l} \cdot \text{atm}/\text{mol}$)
 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.

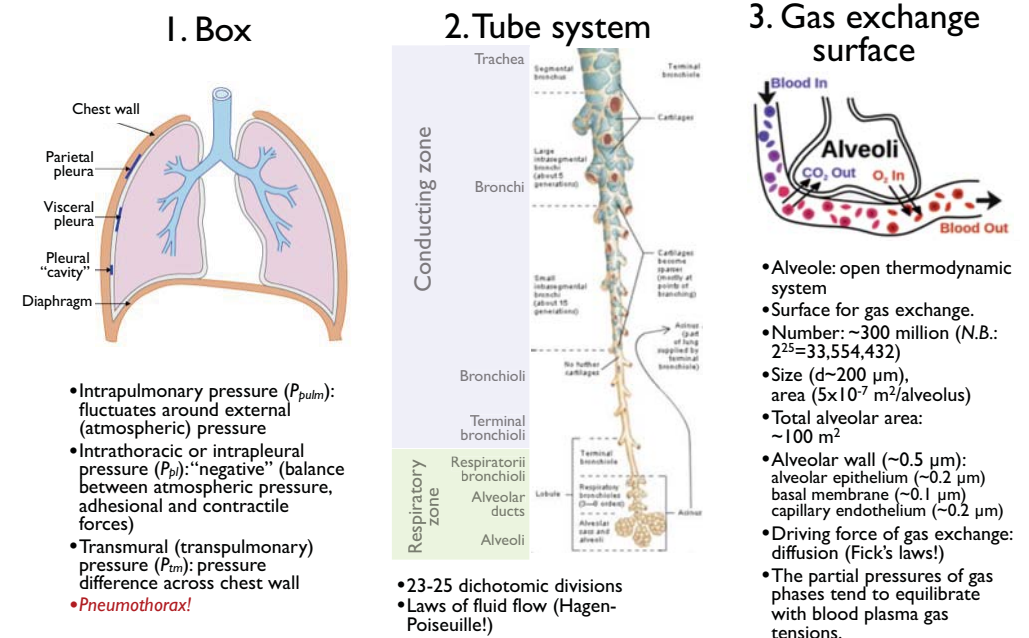
In a sufficiently narrow tube:



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

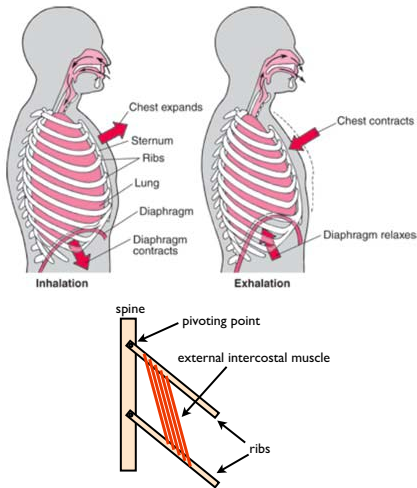
p = pressure (Nm^{-2})
 γ = surface tension ($\text{Nm}^{-1}; \text{Jm}^{-2}$)
 R = radius of curvature

Simplified respiratory system



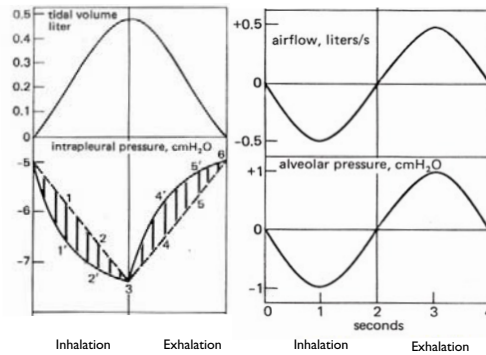
Respiratory cycle

1. Mechanical control



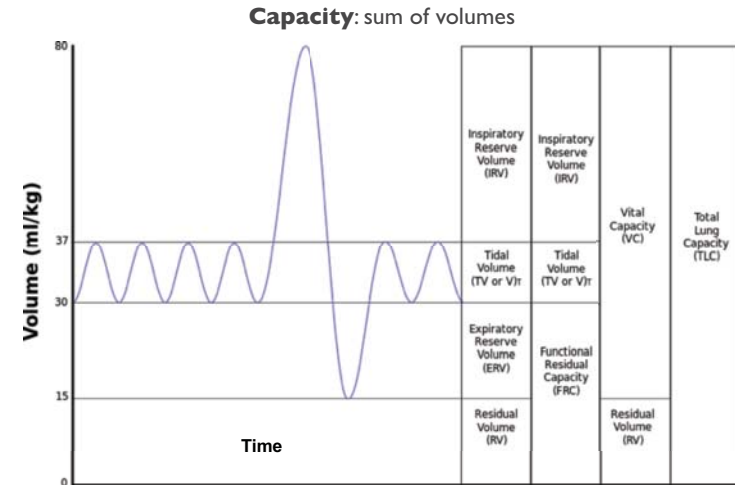
- Eupnoe: normal breathing (14-16/min)
- Polypnoe, tachypnoe: number of breaths >16/min
- Dyspnoe: shortness of breath

2. Changes in physical parameters



$$1 \text{ cmH}_2\text{O} = 0.1 \text{ kPa} = 0.7 \text{ mmHg}$$

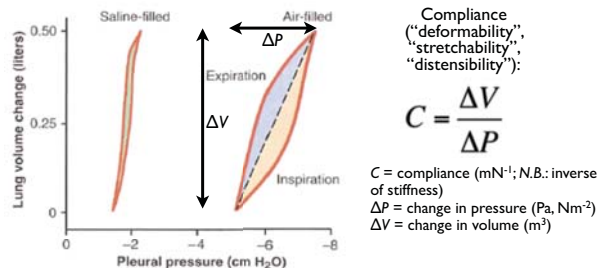
Pulmonary volumes and capacities



Volume	Value (litres)		Volume	Average value (litres)		Derivation
	In men	In women		In men	In women	
Inspiratory reserve volume	3.3	1.9	Vital capacity	4.8	3.1	IRV plus TV plus ERV
Tidal volume	0.5	0.5	Inspiratory capacity	3.8	2.4	IRV plus TV
Expiratory reserve volume	1.0	0.7	Functional residual capacity	2.2	1.8	ERV plus RV
Residual volume	1.2	1.1	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"):

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

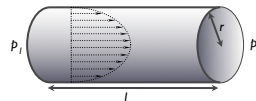
C = compliance (mN^{-1} ; N.B.: inverse of stiffness)
 ΔP = change in pressure (Pa , Nm^{-2})
 ΔV = change in volume (m^3)

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

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

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").

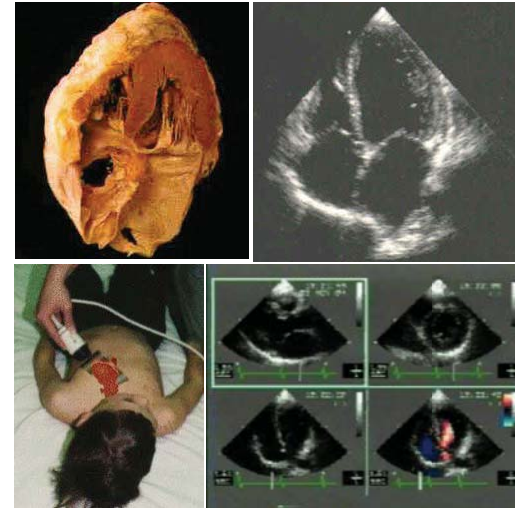
Respiratory work

- 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 ($5 \times 10^{-4} \text{ m}^3$)
- Work (W) = $P_{tm} \times V = 0.35 \text{ J/inspiration}$ (294 J/h)
- At great loads it may reach 8400 J/h

CARDIAC BIOPHYSICS

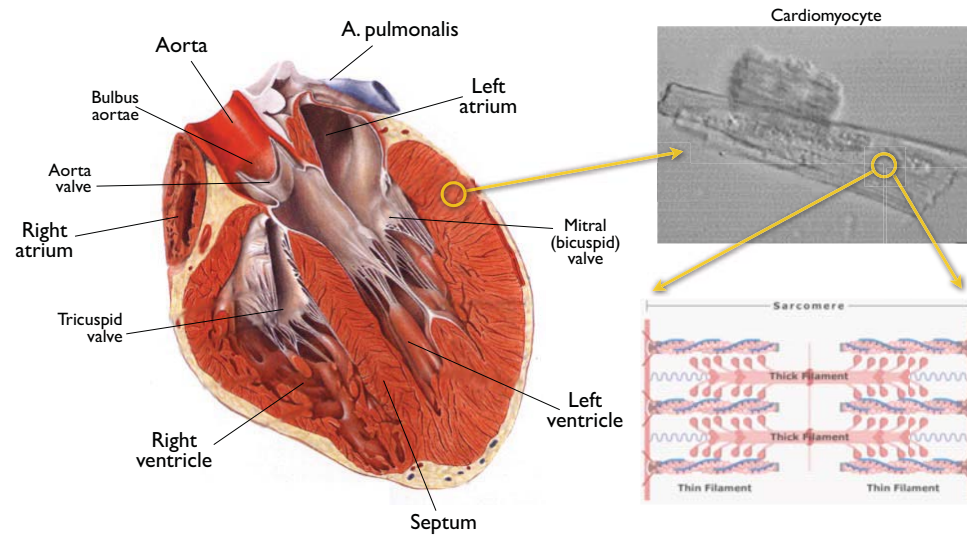
Heart:

Pump of the circulatory system

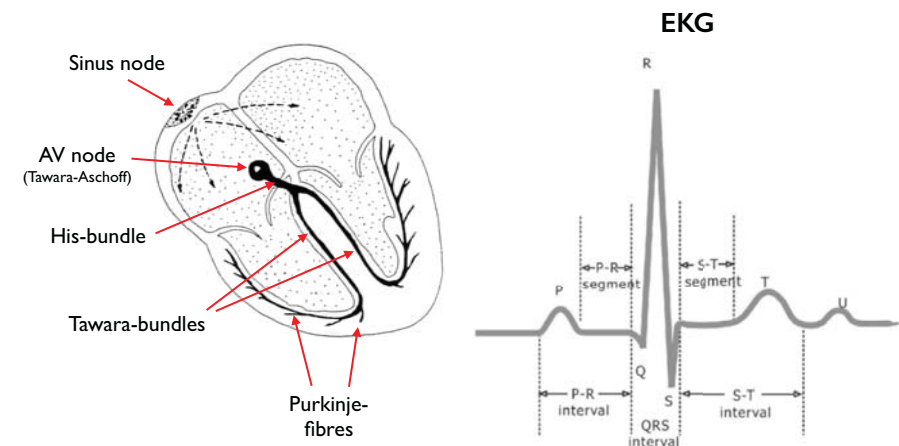


	Number of contractions	Expelled blood volume
1 min	~70	~6 l
1 day	~100,000	~8600 l
Life (70 yrs)	$\sim 2.5 \times 10^9$	$\sim 220 \times 10^6$ l

Structure of the human heart

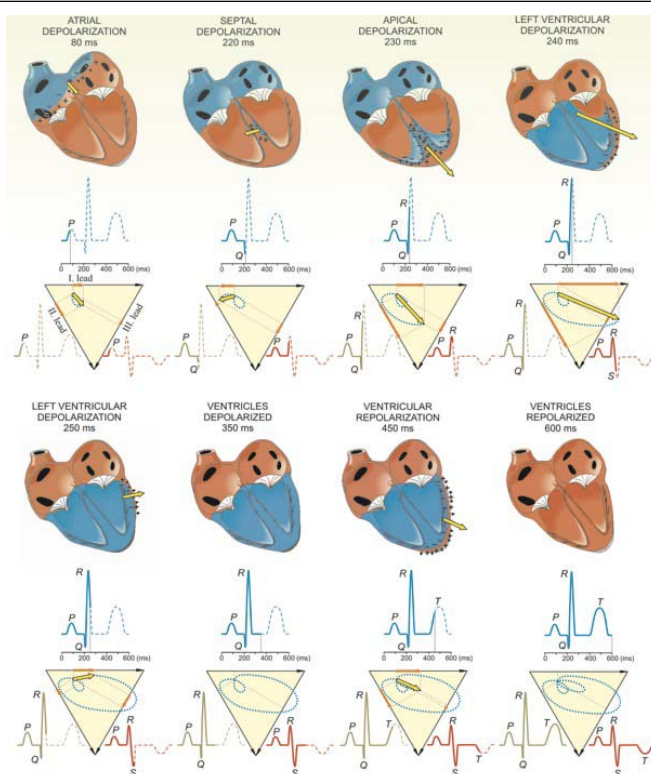


Activation of coordinated contractions



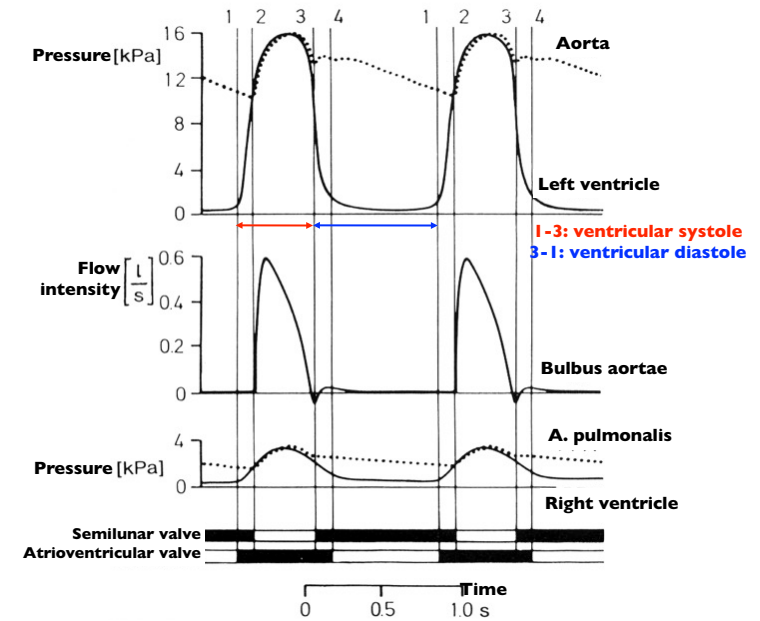
EKG:

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

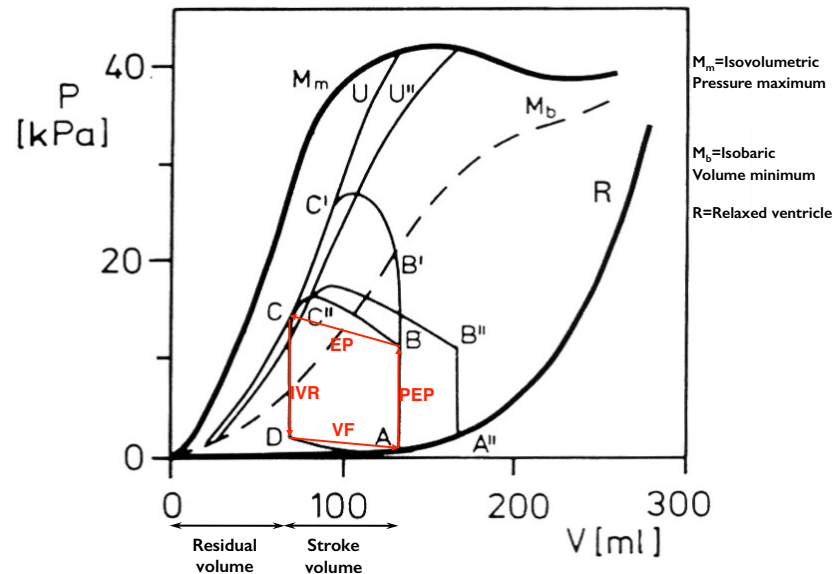


Events of the cardiac cycle

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



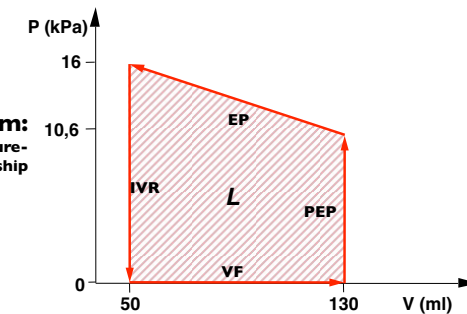
Pressure-volume diagram of left ventricle



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
 $\frac{1}{2}mv^2$ =dynamic component
 p =pressure
 ΔV =stroke volume

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

PHYSICAL BASIS OF PHYSICAL EXAMINATION

Physical examination

- Inspection
- Palpation
- Percussion
- Auscultation

Inspection

What is it?

Visual examination of the patient

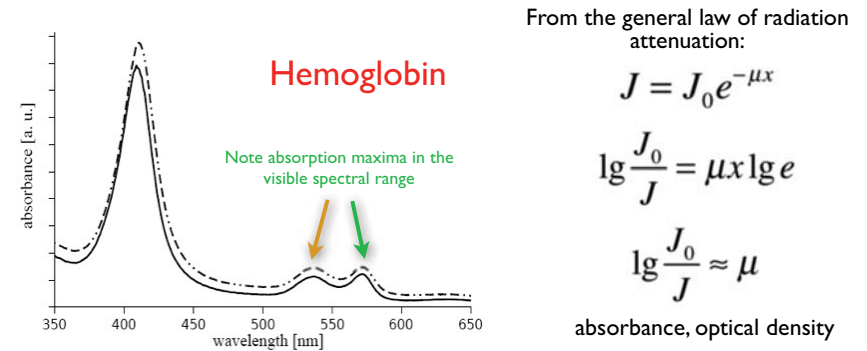
What do we visualize?

Behavior, morphology, structure, **color**

Relationship to biophysics:

Absorption spectroscopy

Light absorption



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

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?

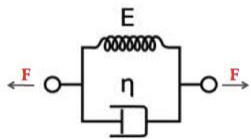
Size, shape, location, ***firmness***

Relationship to biophysics:

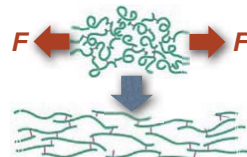
Biomechanics

Viscoelasticity

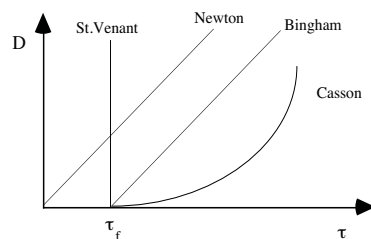
Spring-dashpot model



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

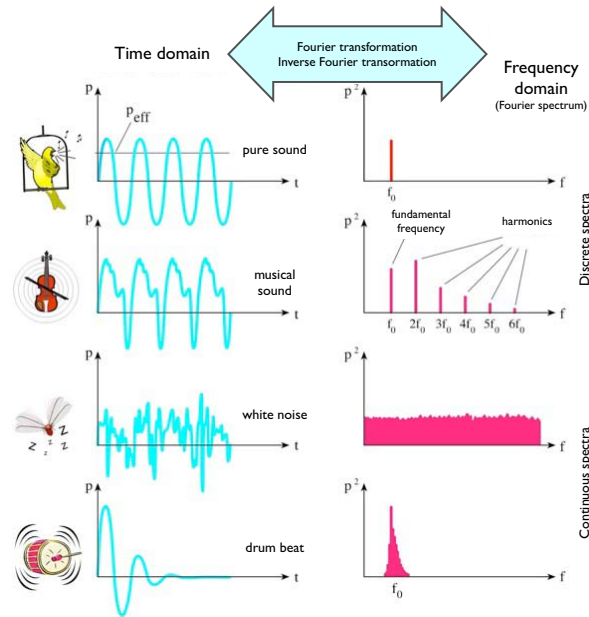
What do we examine by percussion?

Material content, shape, boundaries

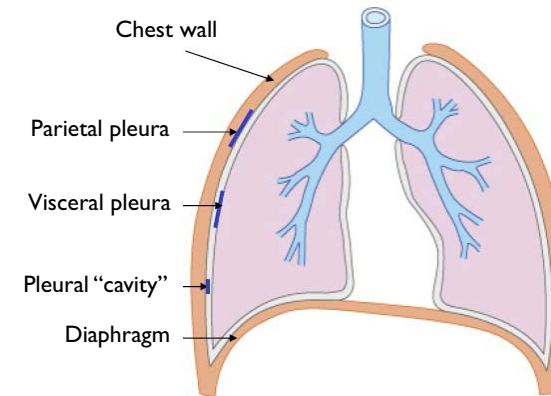
Relationship to biophysics:

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

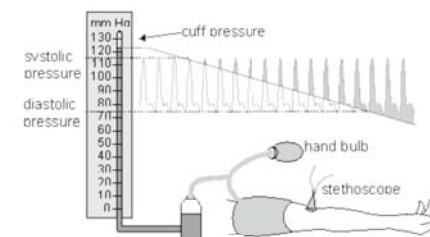
What do we examine by auscultation?

Loudness, pitch, tone, duration, temporal variation (rhythm)

Relationship to biophysics:

Sound generation, propagation, fluid flow, turbulence

Korotkow's sound

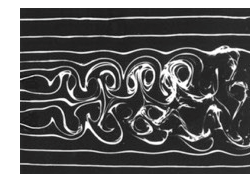


1. tapping
2. swishing
3. knocking
4. muffling

Reynolds number:

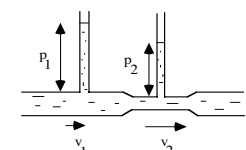
$$R = \frac{vr\rho}{\eta}$$

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



Turbulent flow ($R > \sim 1000$) causing sound effects

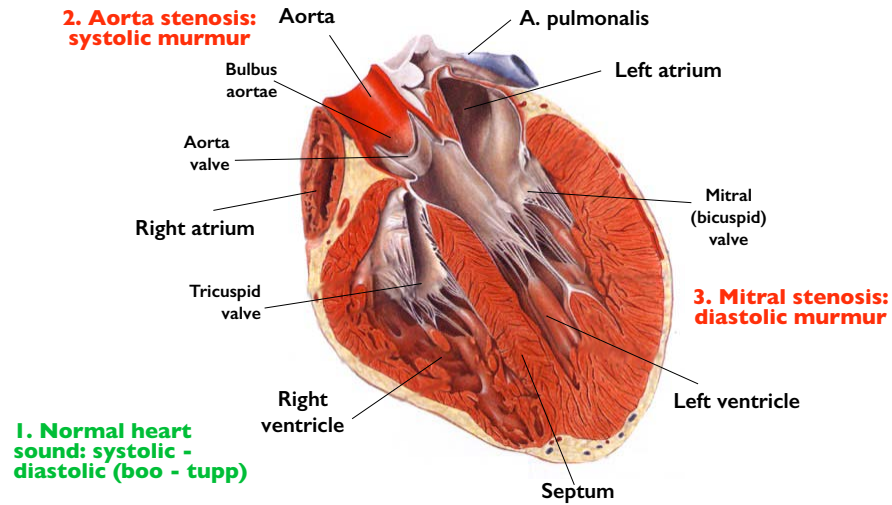
Bernoulli's law



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

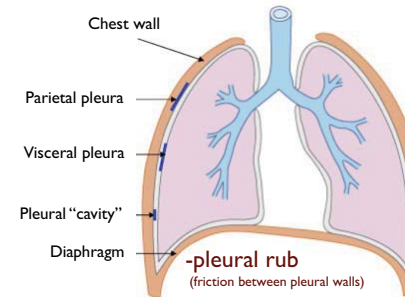
Heart sounds and murmurs

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



Respiratory sounds

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



Tracheobronchial sounds

-wheeze
(airway obstruction)

Vesicular sounds

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

Conducting zone

Trachea
 Bronchi
 Bronchioli
 Terminal bronchioli

Respiratory zone

Respiratory bronchioli
 Alveolar ducts
 Alveoli

