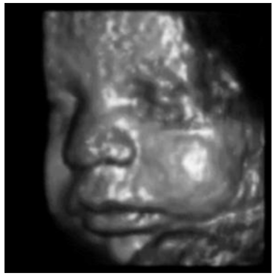
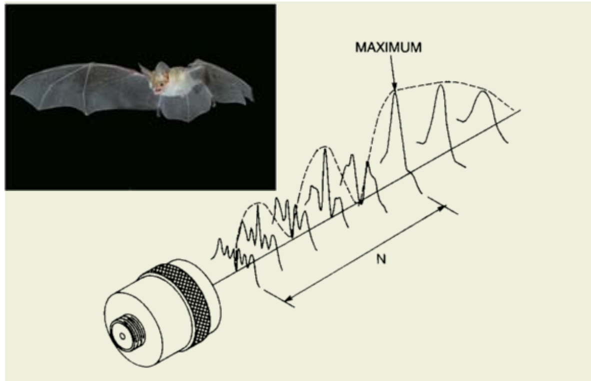
ULTRASOUND

Ultrasound
physical phenomenon
properties
basics of medical applications,





History

LEOPOLDI AUENBRUGGER

INVENTUM NOVUM
EX
PERCUSSIONE THORACIS HUMANI
UT SIGNO
ABSTRUSOS INTERNI
PECTORIS MORBOS
DETEGENDI

VINDOBONÆ,

MDCCLXI.

Dr. Leopold Auenbrugger 1761 - medical doctor
first suggests the method of **percussion** in diagnostics

History

Dr. Leopold Auenbrugger 1761 - son of an innkeeper in Graz, Austria

Percussion -------- from barrels to human body

Ultrasound – a physical phenomenon

Sound is a **Radiation, a „Wave”**

- Harmonic change of a physical parameter propagates in space
- Described by a „wave function”
- Radiation: energy propagation

Reference to remember

Electromagnetic wave:

* Harmonic change of E and B field vectors propagates

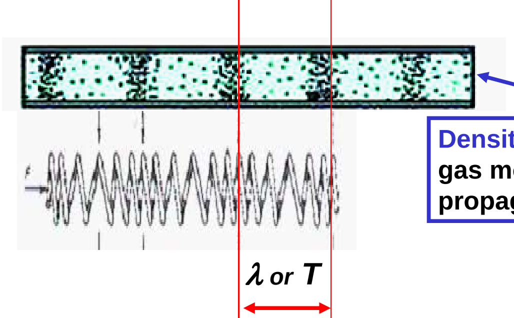
* Propagation does not require a medium

***** Energy propagating : electric and magnetic

Sound is a *mechanical* wave

whistle

spring



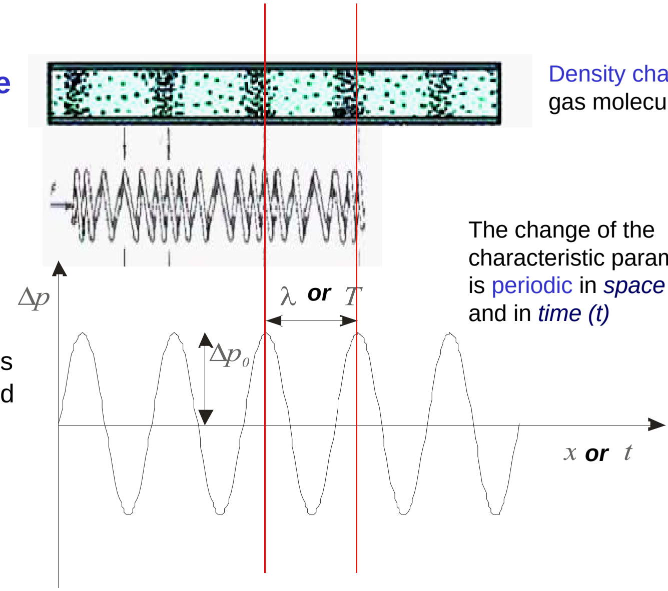
Density change of gas molecules propagates

The change of the characteristic parameter is periodic in *space (x)* and in *time (t)*

Sound is a *mechanical* wave……

whistle

spring



Density change of gas molecules

The change of the characteristic parameter is periodic in *space (x)* and in *time (t)*

Sound waves are described as

pressure-waves

Sound is a mechanical wave…..

* The energy that is propagating: ***mechanical energy***

$$Energy : \tfrac{1}{2} m v^2$$

* Propagation requires a ***medium***

Reminder…

Waves can be

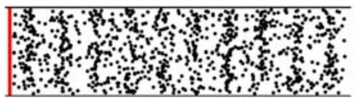
longitudinal : direction of harmonic change in the physical parameter is ***parallel*** with the direction of propagation

or

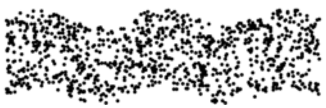
transverse: direction of harmonic change in the physical parameter is ***perpendicular*** to the direction of propagation

e.g. ***electromagnetic wave*** is a transverse wave

$$\vec{E} \perp \vec{c}$$



sound in liquids (tissues) and gases:
longitudinal wave

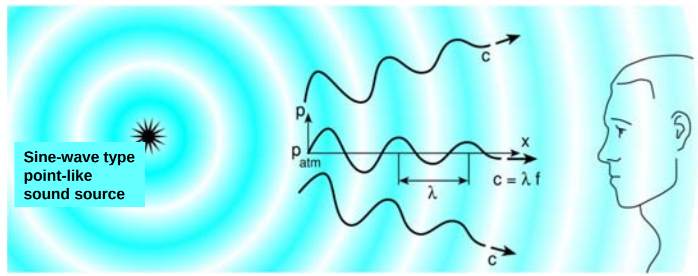


sound in solid materials (bones):
transverse or longitudinal wave

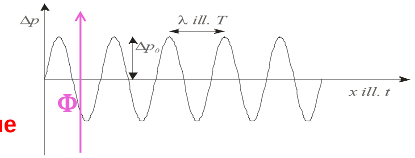
Robe or string: transverse wave

(not sound)

Density change in air – wave motion



Description of a sound wave in a medium



$p_t = p_{hydrostat} + \Delta p$

pressure change due to sound wave

amplitude   +phase

$$\Delta p(t,x) = \Delta p_{max} \sin\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda} + \frac{\Phi}{2\pi}\right)\right]$$

$$c \cdot T = \lambda, \quad c = f \cdot \lambda$$

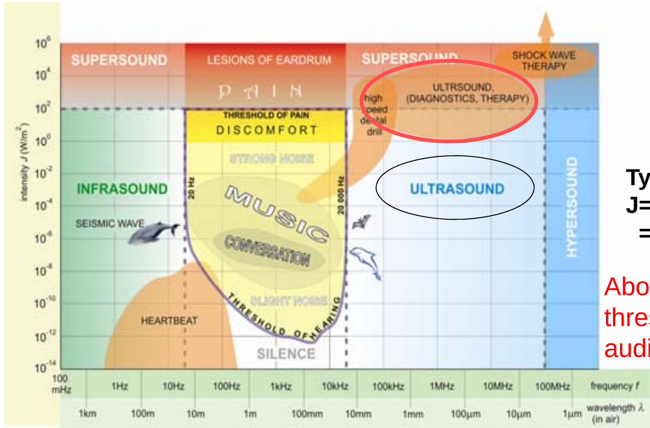
f=1/T : frequency

speed of sound wave propagation, not the speed of light!!!!

Sound - Ultrasound

f>20 kHz, ***c*** does not depend on ***f*** c_{air}= 343 m/s

therapy diagnostics



Typical value:
J= 1W/cm²
= 10^4 W/m²

Above the pain threshold in the audible range!

Ultrasound – physical parameters

$$\Delta p(t,x) = \Delta p_{max} \sin\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right)\right]$$

Intensity of US (is an important parameter in practical applications)

I or

$$J = \frac{\Delta E}{\Delta t * A}\left[\frac{W}{m^2}\right]$$

flux or energy-density denoted now by ***J***

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Power - application for sound?

Ultrasound – physical parameters

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Power - application for sound?

Analogy with electric power

$$P_{el}(AC) = \frac{1}{R_{el}} U_{eff}^2$$

Impedance **Z**

$$U_{max} = U_{eff} * \sqrt{2}$$

Ultrasound – physical parameters

$$\Delta p(t,x) = \Delta p_{max} \sin\left[2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right)\right]$$

Intensity

$$J_{el} \approx P_{el} = \frac{1}{Z_{el}} U_{eff}^2$$

analogy

$$J = \frac{1}{Z} \Delta p_{eff}^2$$

$$J = \frac{\Delta E}{\Delta t * A}\left[\frac{W}{m^2}\right]$$

acoustic impedance

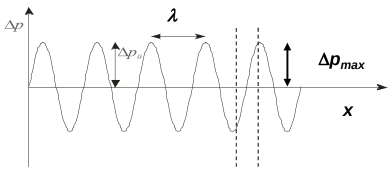
($\Delta p_{eff}^2 = \Delta p_{max}^2/2$)

$$J = \frac{1}{Z} \Delta p_{eff}^2 = \frac{1}{2Z} \Delta p_{max}^2$$

High intensity means large Δp_{max}!

Ultrasound – physical parameters

The Intensity of Ultrasound must be limited



$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

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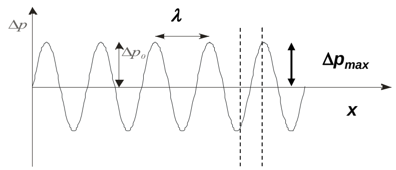
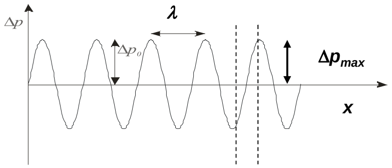


$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

Therapy: f= 0.5 – 1 MHz → **?**

The Intensity of Ultrasound must be limited



$\frac{\lambda}{2}$ = distance of p_{max} and p_{min}

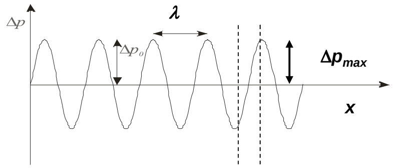
Therapy: f= 0.5 – 1 MHz

c_{muscle}=1600m/s

λ=c/f ⟶ λ= 3.2 – 1.6 mm

⟶ λ/2= 1.6 – 0.8 mm

The Intensity of Ultrasound must be limited



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Therapy: f= 0.5 – 1 MHz c_{muscle}=1600m/s

λ=c/f ⟶ λ= 3.2 – 1.6 mm ⟶ λ/2= 1.6 – 0.8 mm

- very small distance between max and min of p!
- pressure change $=2\Delta p_{max}$ within a distance of **λ/2**

Therapy: f= 0.5 – 1 MHz

suggested limiting value of $J_{average}$= 1W/cm²
(in practice it may go up to 3 W/cm²)

$$J = \frac{1}{Z}\Delta p_{eff}^{\;2} = \frac{1}{2Z}\Delta p_{max}^{\;2}$$

Z_{muscle}

$2\Delta p_{max}$~ 3.2 x atmospheric !!!
within a cell size

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$$J = \frac{1}{Z}\Delta p_{eff}^{\;2} = \frac{1}{2Z}\Delta p_{max}^{\;2}$$

Z_{muscle}

$2\Delta p_{max}$~ 3.2 x atmospheric !!!
within about 1 mm

danger for cavitation and chemical reactions

The Intensity of Ultrasound must be limited

Diagnostics: f= (1) 2 – 10 MHz

→ λ/2= 800 – 160 μm in soft tissue

cellular and subcellular size!

J in practice may be high : 10 W/cm²

???

The Intensity of Ultrasound must be limited

Diagnostics: f= (1) 2 – 10 MHz

→ λ/2= 800 – 160 μm in soft tissue

cellular and subcellular size!

J in practice may be high : 10 W/cm²

BUT: in most cases, ***pulse-mode*** is used

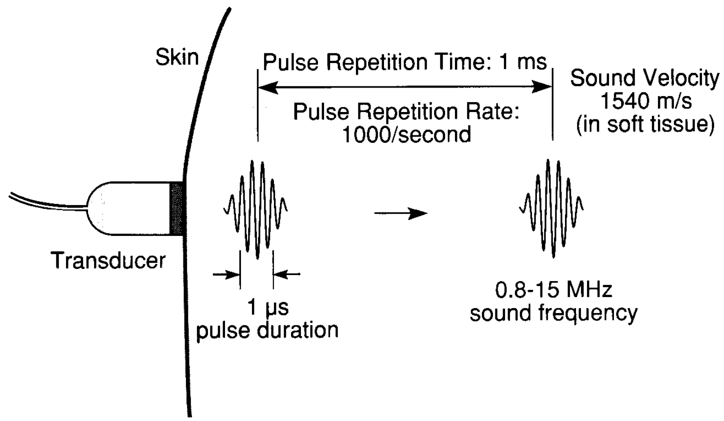
Why pulses?

Diagnostic applications are based on registering the time span between the emission and return of ultrasound pulses from a reflecting surface

↓

Pulse Echo - techniques

Features of pulsed ultrasound



J understood in the pulse with Δt~1 μs and 1ms pause

average *J* ~ 10mW/cm² Low value!

Ultrasound – physical parameters - role of the medium

$$c = \frac{1}{\sqrt{\rho\kappa}}$$

Speed of propagation depends on the ***ρ density*** and ***κ compressibility*** of the medium

$$\kappa = -\frac{\frac{\Delta V}{V}}{\Delta p}$$

κ expresses the negative relative volume change (=decrease) induced by pressure change ***Δp*** (=increase)

compressibility

Role of the *medium* in the propagation….

$$J = \frac{1}{2Z}\Delta p_{max}^{\ 2}$$

Z* acoustic impedance** determines how large pressure fluctuations will be generated by US flux ***J

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Relation to the tissue – properties ?

Role of the *medium* in the propagation….

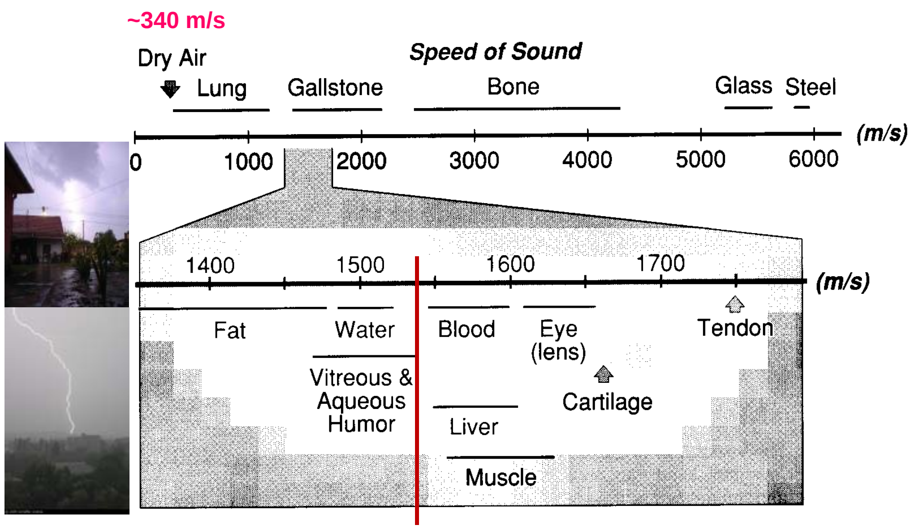
$$J = \frac{1}{2Z}\Delta p_{max}^{\ 2}$$

Z* acoustic impedance** determines how large pressure fluctuations will be generated by US flux ***J

$$Z = c\rho = \sqrt{\frac{\rho}{\kappa}}$$

Z is determined by the properties of the medium

Speed of propagation in various media



Speed in average soft tissue=1540 m/s

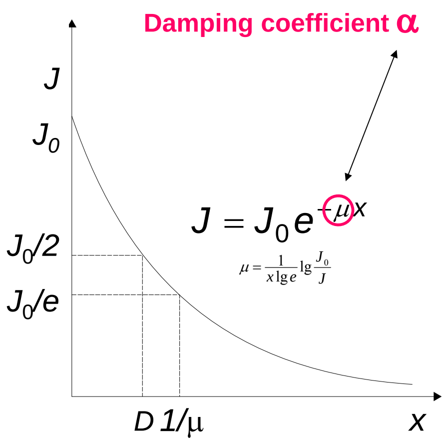
	c(m/s)	ρ(kg/m³)	Z ρ*c
air	343	1.29	$4.43 \cdot 10^2$
water	1500	1000	$1.5 \cdot 10^6$
muscle	1600	1040	$1.7 \cdot 10^6$
bone	3600	1700	$6.1 \cdot 10^6$
brain	1530	1025	$1.6 \cdot 10^6$

Z can be

significantly different

Another feature of tissues - Absorption of sound waves

Described by the exponential law of radiation attenuation



$$\alpha = 10 \cdot \lg \frac{J_0}{J} \text{ dB}$$

$$\alpha = 10 \cdot \mu \cdot x \cdot \lg e \text{ dB}$$

$$\frac{\alpha}{x} = const * \mu$$

Absorption is a disadvantage in US diagnostics!

The attenuation of sound waves depends on the frequency

$$\alpha = 10 \cdot \mu \cdot x \cdot \lg e \text{ dB}$$

$$\frac{\alpha}{x} = const_1 * \mu$$

$$\mu = const_2 * f$$

~ linear dependence on the frequency in the high f range

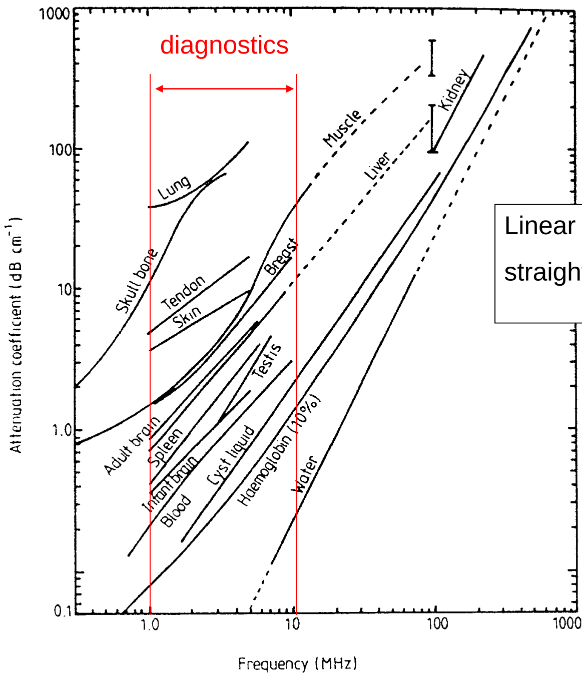
Introducing α_{spec}

$$\alpha_{spec} = \frac{\alpha}{f \cdot x}$$

Specific damping coefficient → **characterizes solely the tissue**

α_{spec} will not depend on the frequency of radiation and on the thickness of tissue

e.g. soft tissues ~1dB/(cm·MHz)



Linear dependence:

straight line at 45°

$$D = \frac{0.693}{\mu}$$

	c(m/s)	ρ(kg/m³)	Z ρ*c	D(m) 10kHz	D(m) 1 MHz
air	343	1.29	$4.43*10^2$	100	10^{-2}
water	1500	1000	$1.5*10^6$	10^5	few
muscle	1600	1040	$1.7*10^6$	--	$2*10^{-2}$
bone	3600	1700	$6.1*10^6$	--	$\sim 10^{-3}$
brain	1530	1025	$1.6*10^6$	--	10^{-2}

too high absorption

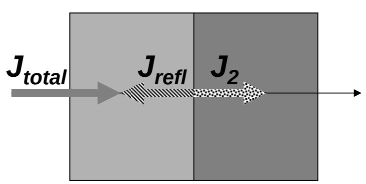
Half value thickness in function of frequency:
Radiation with higher f is absorbed more

	anyag	ρ sűrűség [kg/m³]	κ kompresszi-bilitás [1/GPa]	c terjedési sebesség [m/s]	Z akusztikus impedancia [kg/(m²·s)]	$\alpha(f_X)$ Specific damping [dB/(cm·MHz)]
Air	levegő	1,3	7650	331	430 = 0,00043·10⁶	1,2
Lung	tüdő	400	5,92	650	0,26·10⁶	
Fat	zsír	925	0,51	1470	1,42·10⁶	0,63
Water	víz, 20°C	998		1492	1,49·10⁶	0,0022
Water	víz, 36°C	994		1530	1,53·10⁶	
Brain	agy	1025		1530	1,56·10⁶	0,85
Soft tissue	*lágy szövet*	1060		1540	1,63·10⁶	0,3 – 1,7
Liver	máj	1060	0,38	1549–1570	1,65·10⁶	0,94
Kidney	vese	1040	0,40	1560	1,62·10⁶	1,0
Spleen	lép	1060		1566	1,64·10⁶	
Muscle	izom	1040–1080		1568	1,63·10⁶	1,3 – 3,3
Blood	vér	1060	0,38	1570	1,61 – 1,66·10⁶	0,18
Eye lens	szemlencse			1620	1,84·10⁶	2,0
Bone marrow	csontvelő	970		1700	1,65·10⁶	
Bone-porous	csont, porózus	1380	0,08	3000	2,2 – 2,9·10⁶	
Bone-solid	csont, tömör	1700	0,05	3600	6,12·10⁶	20,0
Al	aluminium	2700	0,009	6400	17,28·10⁶	
Contact gel	csatoló gél				6,5·10⁶	
Lead-Zirconate-Titanate	ólom-cirkonát-titanát	7650		3791	29·10⁶	
Quartz	kvarc	2650		5736	15,2·10⁶	

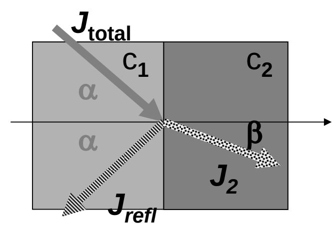
Basics of Pulse-Echo techniques

US is reflected and refracted at the boundary of media with different ρ and κ.

Incident beam is ⊥ to the boundary



*Incident beam hits the boundary at **α** angle*



$$J_{total} = J_{refl} + J_2$$

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$$

Incidence at right angle to the boundary
reflection and transmission

Incidence at α angle
Snell's law is valid
US „optics" with mirrors, lenses

Pulse-echo: **US diagnostics is based on the *reflection* of radiation at internal media-boundaries**

Reflectivity R

Total reflection: R=1

$$R = \frac{J_{\text{reflected}}}{J_{\text{incident}}} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

$Z_1 << Z_2, \quad R \approx 1$

US is ***totally*** reflected at boundaries of media of very different impedances

reflection of radiation at internal media-boundaries….

$$R = \frac{J_{\text{reflected}}}{J_{\text{incident}}} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

Total reflection: R=1 $\quad Z_1 << Z_2, \quad R \approx 1$

Source ↔ Body

AIR

Ceramics
Crystal
Solid state material

Skin

Total reflection!

Coupling medium to avoid total reflection

$$Z_{\text{coupling}} \approx \sqrt{Z_{\text{source}} * Z_{\text{skin}}}$$

(e.g. Pb-Zr-Ti source – see Table)

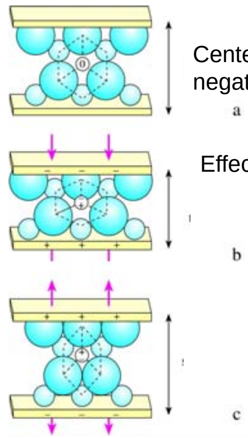
	c(m/s)	ρ(kg/m³)	Z ρ*c	D(m) 10kHz	D(m) 1 MHz	R
air	343	1.29	$4.43*10^2$	100	10^{-2}	~1
water	1500	1000	$1.5*10^6$	10^5	few	~1
muscle	1600	1040	$1.7*10^6$	--	$2*10^{-2}$	~0.3
bone	3600	1700	$6.1*10^6$	--	$\sim 10^{-3}$	~0.3
brain	1530	1025	$1.6*10^6$	--	10^{-2}	

Partial reflection is good condition for diagnostics

Sources of Ultrasound radiation:

Piezoelectric crystal - *transducer*

ELECTRIC ↔ MECHANICAL



Center of weight of positive and negative charges overlaps.

Effect of alternating compression (b) and dilatation (c)

→ Alternating charge separation

Direct piezoelectric effect
receiver

MECH → EL
Case b and c

Inverse piezoelectric effect
source

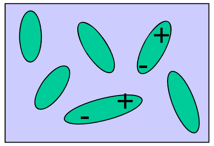
EL → MECH

The same unit can be used both as receiver and source

Examples for piezoelectric crystals:

quartz (SiO_2)
Rochelle salt ($KNaC_4H_4O_6*4H_2O$)

Ceramics based on electro/magneto-striction



Materials built up from magnetic or electric dipole elements

External field induces orientation → deformation

Comparison with piezoelectric ***transducers***:

- lower frequencies are possible
- mechanically more endurable materials

Dental applications: 20-40 kHz US transducer in direct contact with dental deposits-> disintegration ->cleaning

End of the first part