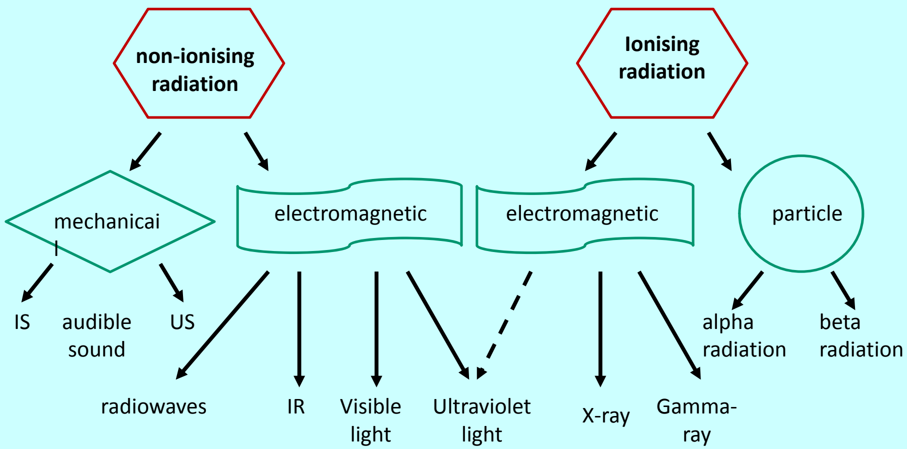
Radiation



Sound

and

ultrasound

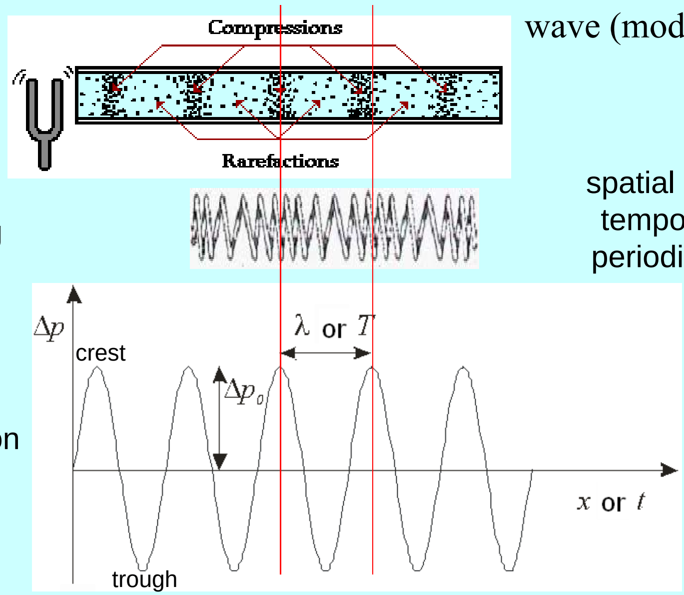
Physics of sound

Sound: mechanical wave (model)

whistle

spring

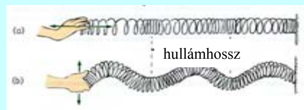
function



spatial and temporal periodicity

Physics of sound

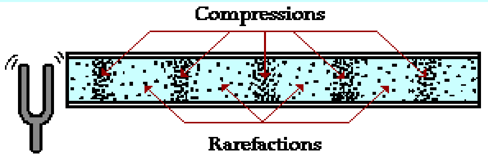
Longitudinal vs. Transverse wave



longitudinal wave
(in the interior of liquids and gases only this type)

transverse wave
can generated in solid materals and at liquid surfaces

whistle



hydrostatic pressure

pressure change, sound pressure

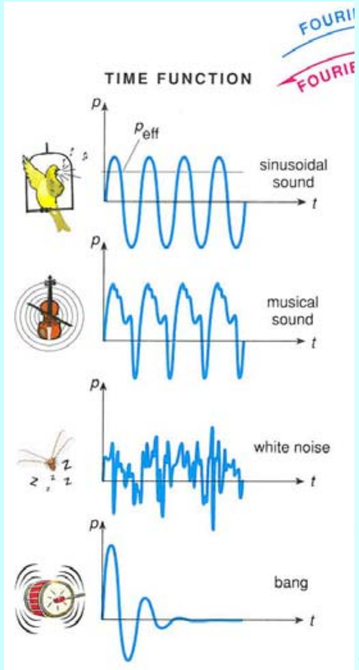
$p_{total} = p_{hydrostat} + \Delta p$

pressure DC + AC

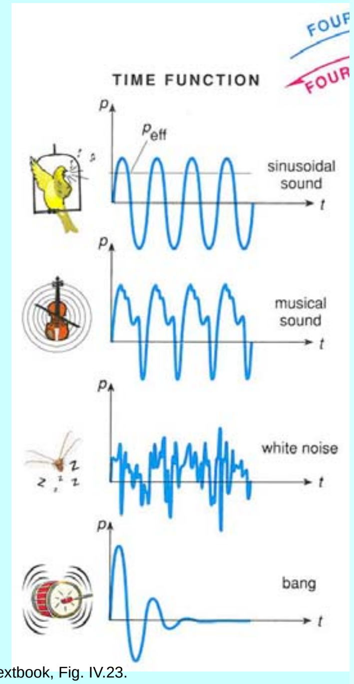
amplitude phase

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

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



$$p(t) = p_1 \sin(\omega t) + p_2 \sin(2\omega t) + p_3 \sin(3\omega t) + .$$



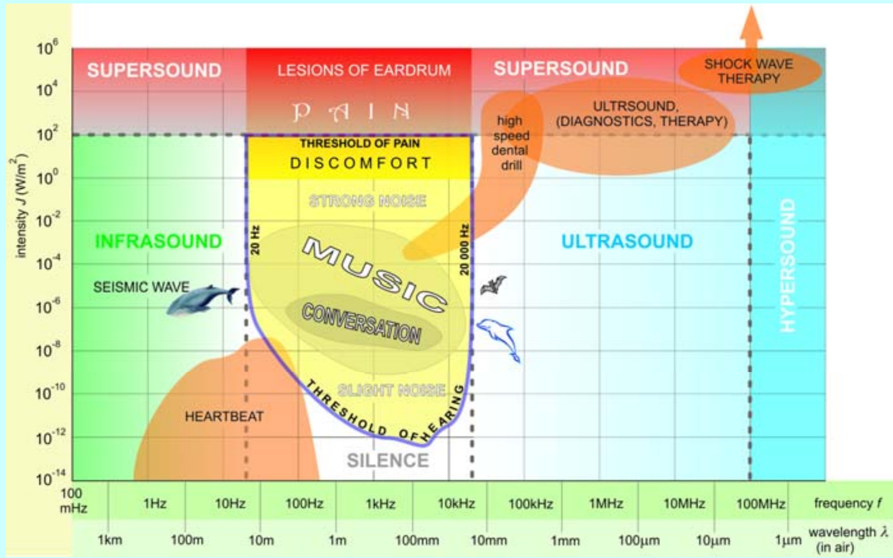
pitch
frequency of the fundamental — hight

timbre
relative strengths of overtones/harmonics (spectrum) — tone colour

intensity
from pressure amplitude — loudness

Textbook, Fig. IV.23.

Frequency and intensity regions of sounds



Lab. manual, Audiometry.

Propagation of sound/ultrasound

The role of elastic medium – *speed* of propagation

$$c = f\lambda$$

$$\kappa = -\frac{1}{V}\left(\frac{\Delta V}{\Delta p}\right)$$

compressibility
relative volume decrease over pressure

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

ρ: density of medium

Speed of propagation is higher in solids than in liquids.

$\rho \uparrow \qquad \kappa \downarrow$

Propagation of sound/ultrasound

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

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

$$Z = \frac{p}{v} = \frac{p_{max}}{v_{max}}$$

acoustic **impedance** (definition)

$$Z_{el} = \frac{U}{I}$$

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

acoustic **impedance** (useful form)

$[kg/m^2 s]$

Propagation of sound/ultrasound

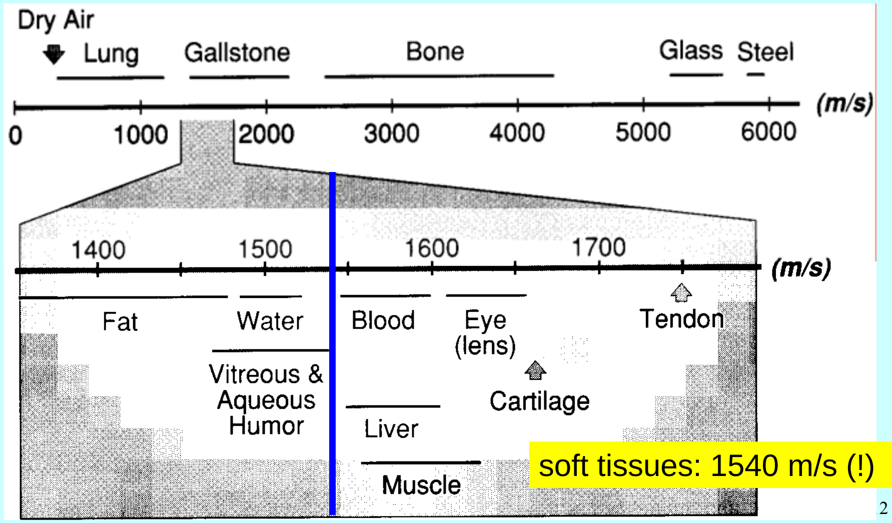
$$c = \frac{1}{\sqrt{\rho\kappa}}$$

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

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

material	ρ [kg/m^3]	κ [1/GPa]	c [m/s]	Z [kg/(m^2·s)]
air	1,3	7650	331	$0{,}00043 \cdot 10^6$
water 20°C	998	0,45	1492	$1{,}49 \cdot 10^6$
aluminum	2700	0,009	6400	$17{,}28 \cdot 10^6$
quertz	2650	0,011	5736	$15{,}2 \cdot 10^6$

Speed of sound/US in various media



Intensity of US

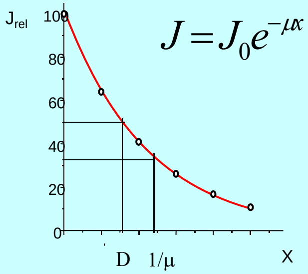
$$J = \frac{1}{Z}\Delta p_{eff}^{\;2}$$

intensity = energy-current density

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

electric analogy

Loss of energy during propagation (absorption)

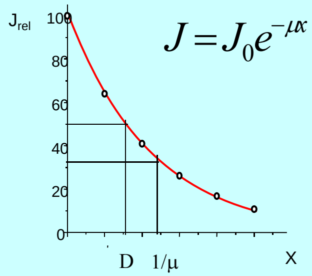


$$J = J_0 e^{-\mu x}$$

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

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

Loss of energy during propagation (absorption)



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

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

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

At f = 1 MHz

D_{air} ~ 1 cm

D_{water} ~ 1 m

μ is proportional to frequency in the diagnostic range

Specific attenuation: $\dfrac{\alpha}{f \cdot x}$

μ is proportional to frequency in the diagnostic range

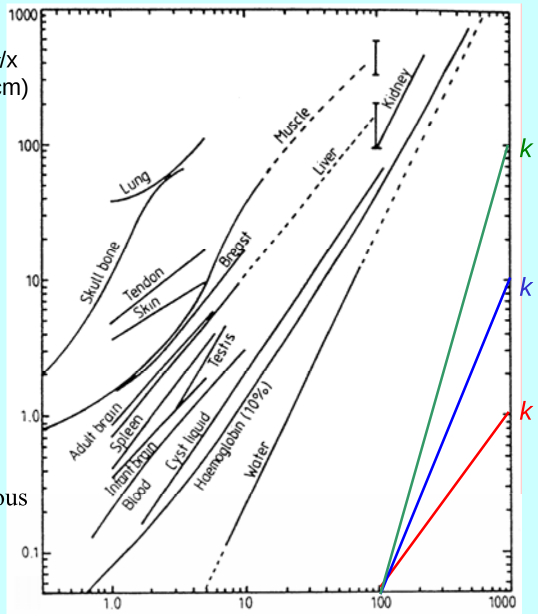
$\mu \sim f^k, \quad k \sim 1 (?)$

$\log \mu \sim k \log f$

if the graph is a linear, the power function approximation is valid

specific attenuation for soft tissues (homogeneous tissue model):

$$\frac{\alpha}{f\,x} \sim 1 \frac{\text{dB}}{\text{cm MHz}}$$

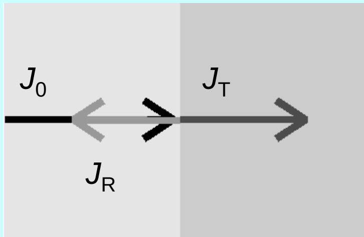


$$\frac{\alpha}{f\,x}$$

tissue	Specific attenuation
liver	0,6 – 0,9
kidney	0,8 – 1,0
fat	1,0 – 2,0
blood	0,17 – 0,24
bones	16 – 23

Phenomena at the boundary of different media

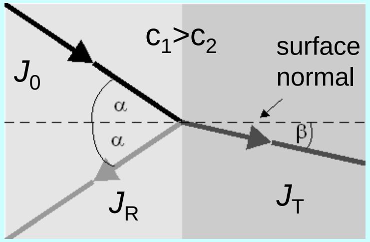
normal/perpendicular incidence



$J_0 = J_R + J_T$

reflection and transmission (penetration)

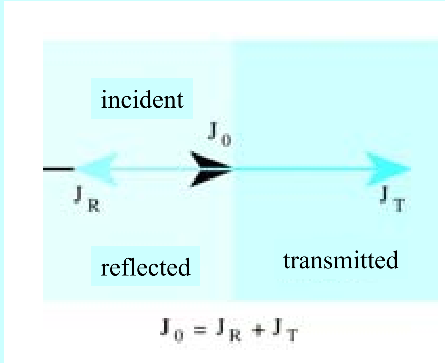
skew incidence



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

Snellius-Descartes

Reflection of ultrasound



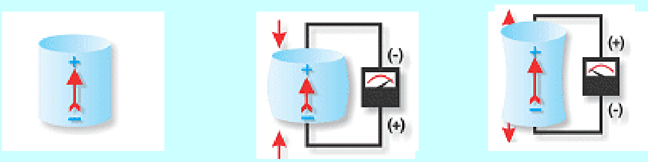
$$R = \frac{J_R}{J_0}$$

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

If $R \approx 1$ ⟶ Total reflection

Detection/Generation of US

Piezoelectric effect



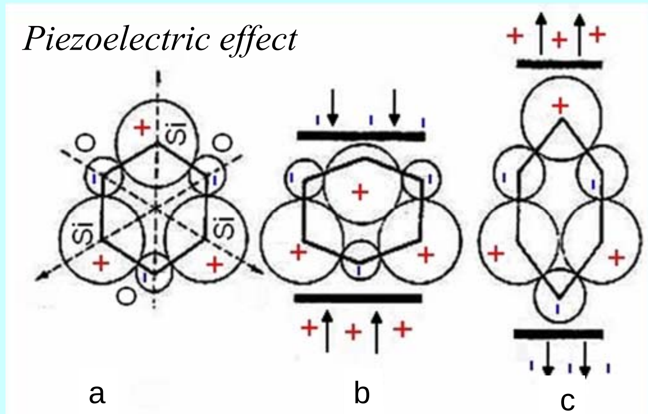
Pressure change

↓

Mechanical deformation of crystal

↓

Electric potential difference

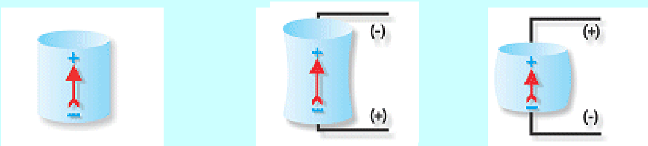


(a) Center of charge of positive and negative charges coincides.

(b) and (c) As a result of pressure , the charge centers are separated, i.e. a potential difference arises

Detection/Generation of US

Inverse piezoelectric effect



Periodic electric potential difference

↓

The crystal is deformed when voltage is applied

↓

Mechanical vibration

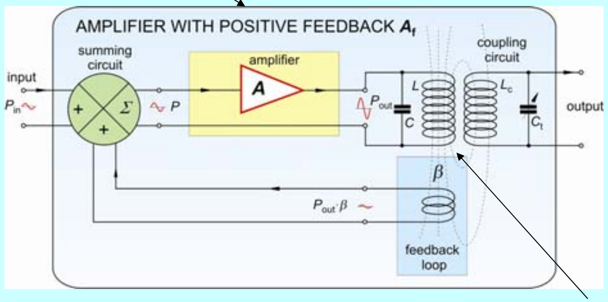
Source of electric signal: **sine wave oscillator**

$$A_f = \frac{P_{out}}{P_{in}} = \frac{A}{1 - A \cdot \beta}$$

$A\beta = 1$

amplification = „infinity" ⇨ sine wave oscillator

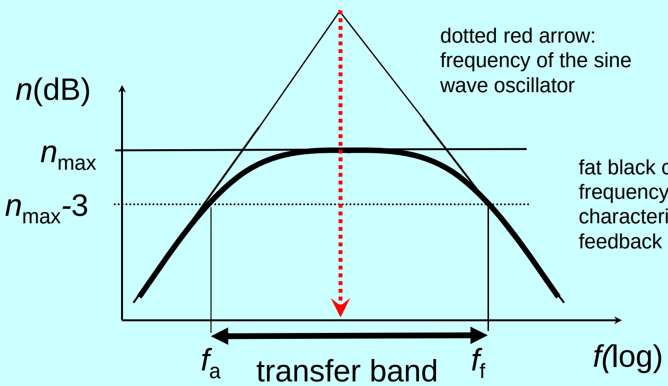
no input signal, output signal: sine voltage



$$f = \frac{1}{2\pi\sqrt{LC}}$$

Source of electric signal: **sine wave oscillator**

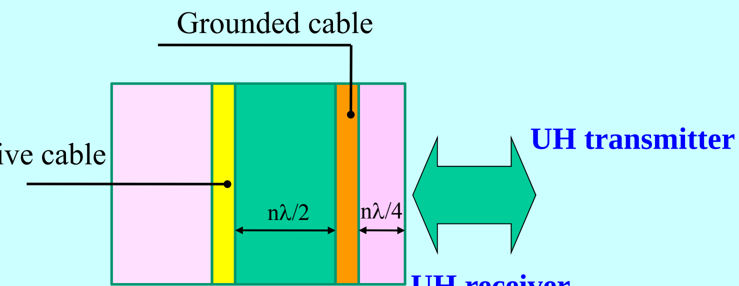
amplifier with positive feedback $$A_{U,\,feedback} = \frac{A_U}{1 - \beta A_U}$$



dotted red arrow: frequency of the sine wave oscillator

fat black curve: frequency response characteristics without feedback

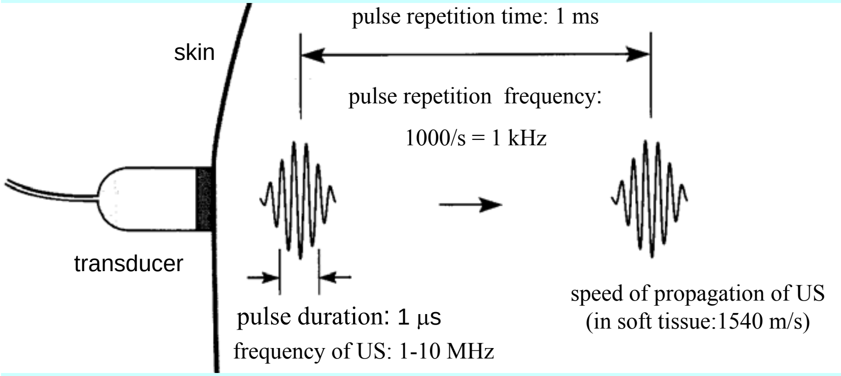
Detection/Generation of US – Ultrasound transducer



Characteristic of US pulses

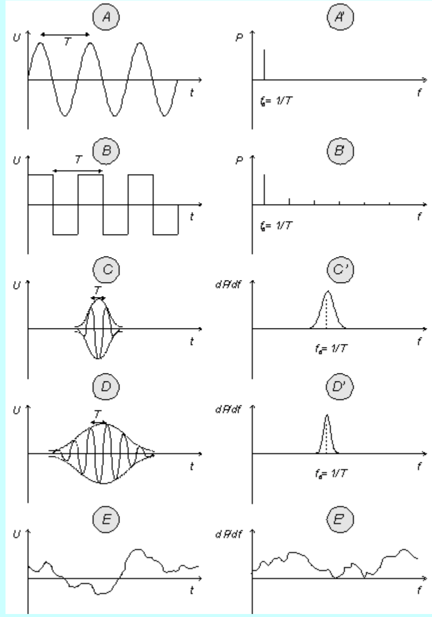
transducer: transmitter and receiver is the same unit

time sharing mode: pulses instead of continuous wave US

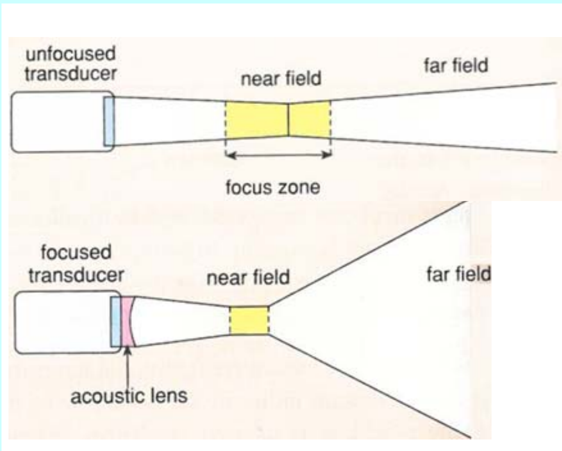


Time function **Spectrum**

sine function		line spectrum (1 line)
square function		line spectrum
sine wave pocket (some „periods")		band spectrum
		US pulse
sine wave pocket (several „periods")		band spectrum
aperiodic function		continuous spectrum



Focusing of the beam



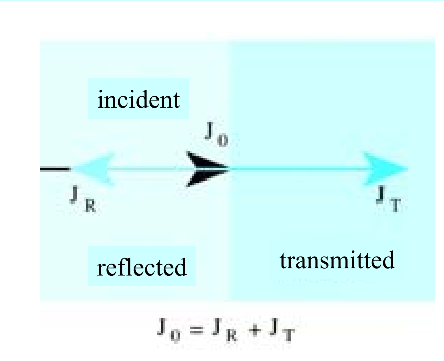
Focusing increases the divergence of the beam in the far field regime and reduces the depth sharpness.

Medical application of ultrasound

Therapy – based on absorption of US

Diagnostics – based on reflection of US

Reflection of ultrasound



$$R = \frac{J_R}{J_0}$$

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

If $R \approx 1$ ⟶ Total reflection

Reflection of US

material	ρ [kg/m^3]	κ [1/GPa]	c [m/s]	Z [kg/(m^2·s)]
air	1,3	7650	331	$0{,}00043 \cdot 10^6$
lung	400	5,92	650	$0{,}26 \cdot 10^6$
fat	925	0,51	1470	$1{,}42 \cdot 10^6$
Soft tissue	1060	0,40	1540	$1{,}63 \cdot 10^6$
Eye lence	1140	0,34	1620	$1{,}84 \cdot 10^6$
Bone marrow	970	0,36	1700	$1{,}65 \cdot 10^6$
Bones (spongy)	1380	0,08	3000	$2{,}2 - 2{,}9 \cdot 10^6$
Bones (solid)	1700	0,05	3600	$6{,}12 \cdot 10^6$

interface	R
muscle/blood	0,0009
fat/liver	0,006
fat/muscle	0,01
bone/muscle	0,41
bone/fat	0,48
soft tissue/air	0,99

$R \approx 1$ ⟶ Total reflection

Reflection of US

material	c (m/s)	ρ (kg/m³)	Z (kg/m²s)
pulp	1570	1000	$1{,}6 \cdot 10^6$
dentin	3800	2000	$7{,}6 \cdot 10^6$
Tooth enamel	6250	3000	$18{,}8 \cdot 10^6$
Al	6300	2700	$17 \cdot 10^6$
borosilicate	5300	3570	$18{,}9 \cdot 10^6$
amalgam	4350	7750	$33{,}7 \cdot 10^6$

interface	R
enamel/dentin	0,18
dentin/pulp	0,43
amalgam/dentin	0,40

Reflection of US

material	ρ [kg/m^3]	κ [1/GPa]	c [m/s]	Z [kg/(m^2·s)]
air	1,3	7650	331	$0{,}00043 \cdot 10^6$
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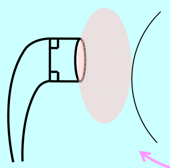
interface	R
muscle/blood	0,0009
fat/liver	0,006
fat/muscle	0,01
bone/muscle	0,41
bone/fat	0,48
soft tissue/air	0,99

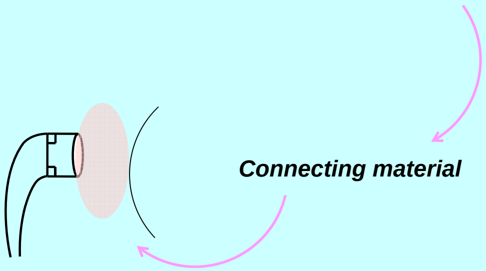


Couplant material

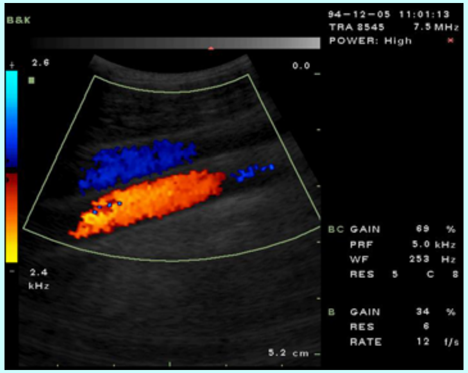
Reflection of US

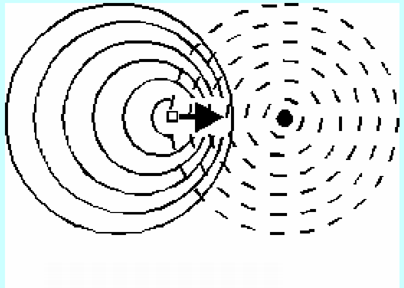
Optimal transmission: $Z_{con} = \sqrt{Z_1 \cdot Z_2}$

$Z_{gel} \sim 6{,}5 \cdot 10^6$ kg/(m²s)



US imaging. Modes of sonography. Doppler-echo.

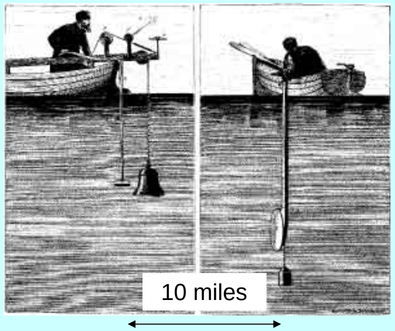


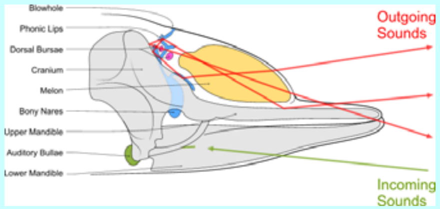


Echo principle

1794 - Spallanzani:
bat's navigation

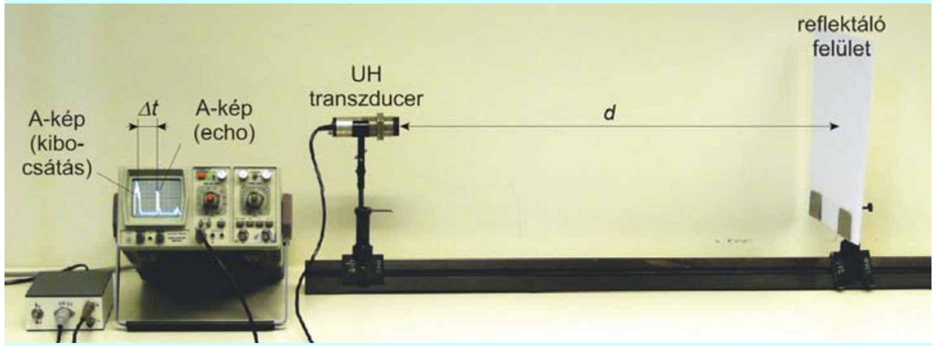
1822 - Colladen measured
the speed of sound in water



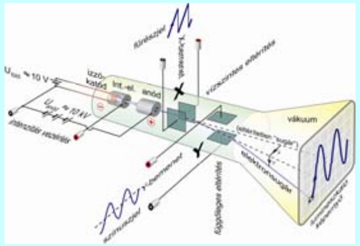


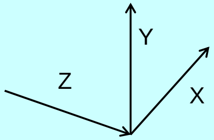
bottlenose dolphin

Echo principle

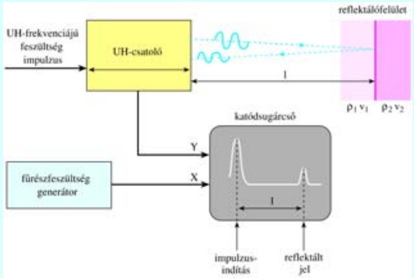


$c\Delta t = d + d = 2d$

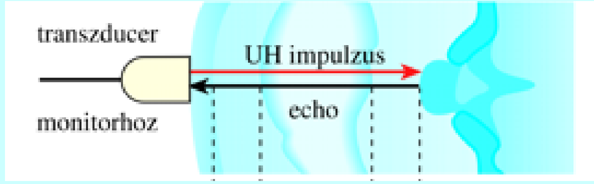


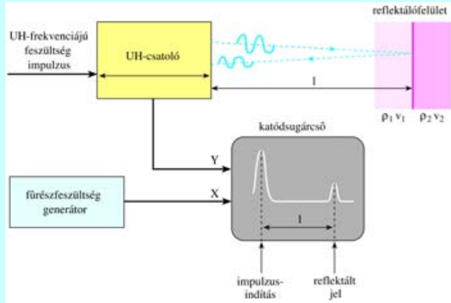


Deflection / controling	A-mode
X	Time (→ axial distance)
Y	Amplitude (→ I_{refl})
Z	(Brightness)



A-image - *A*mplitúdó

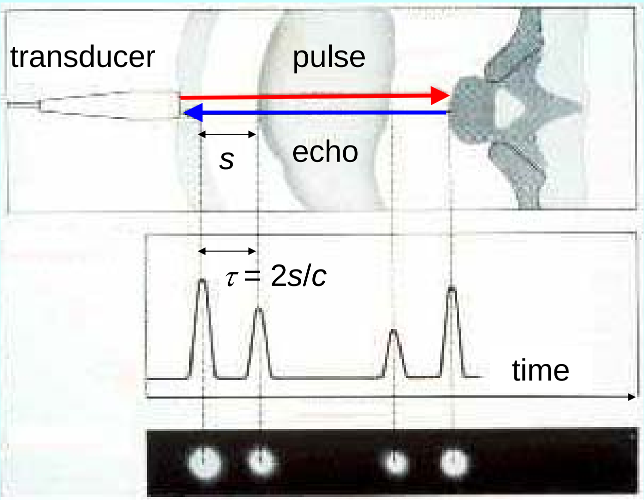




One-dimensional only

$c\Delta t = d + d = 2d$

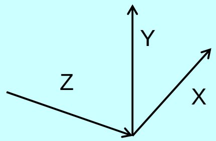
B-image - *Brightness*

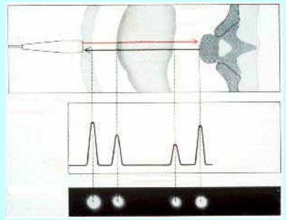


A-mode (***A***mplitude) only 1-dimensional

B-mode (***B***rightness) only 1-dimensional

cf. Textbook Fig. VIII.33





Deflection / controling	A-mode	1-dimensional B-mode
X	Time (→ axial distance)	Time (→ axial distance)
Y	Amplitude (→ I_{refl})	-
Z	(Brightness)	Brightness (→ I_{refl})

Question of the week

What is the function of couplant materials in US diagnostics?

Kapcsolódó fejezetek:
Damjanovich, Fidy, Szöllősi: Orvosi Biofizika

II. 2.4.
VIII. 4.2.