ULTRASOUND

Miklós Kellermayer

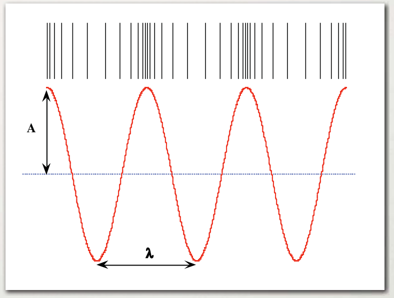
Ultrasound

Ultrasound

- Generation and physical properties of ultrasound
  - What is ultrasound?
  - Generation and detection of ultrasound
  - Physical properties of ultrasound
- Effects of ultrasound
  - Primary
  - Secondary
- Medical applications of ultrasound
  - Therapy
  - Diagnostics

What is ultrasound?

Longitudinal mechanical wave (pressure wave)

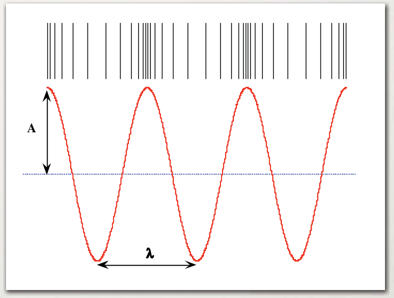


Longitudinal wave

Transverse wave

What is ultrasound?

Longitudinal mechanical wave (pressure wave)



1. Harmonic oscillation:

$$y(t) = A\sin(ft + \varphi)$$

y=actual pressure
t=time
f=frequency
A=amplitude
ϕ=phase shift

What is ultrasound?

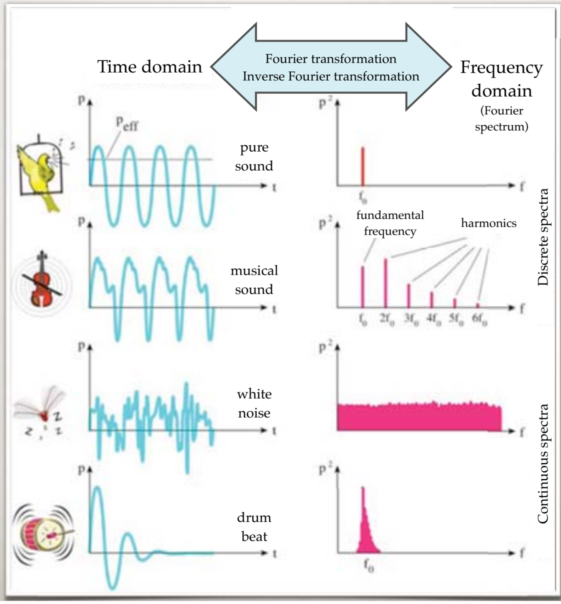
2. Frequency (Hz):

$$f = \frac{1}{T}$$

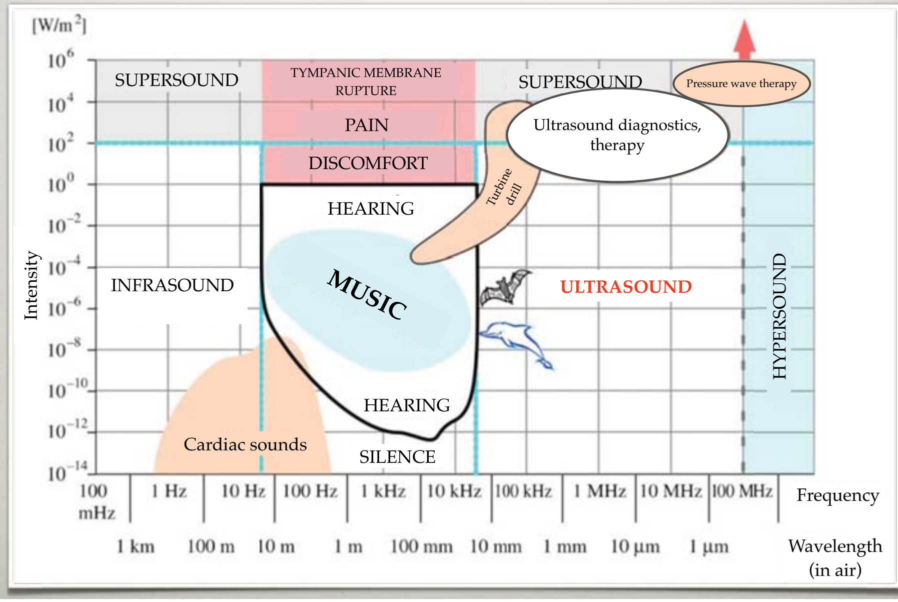
T=period (s)

Sound type	Infrasound	Audible sound	**Ultrasound**	Hypersound (praetersound or microsound)
Frequency	<16 Hz	16-20.000 Hz	**>20.000 Hz**	>10^{13} Hz

What is ultrasound?



What is ultrasound?

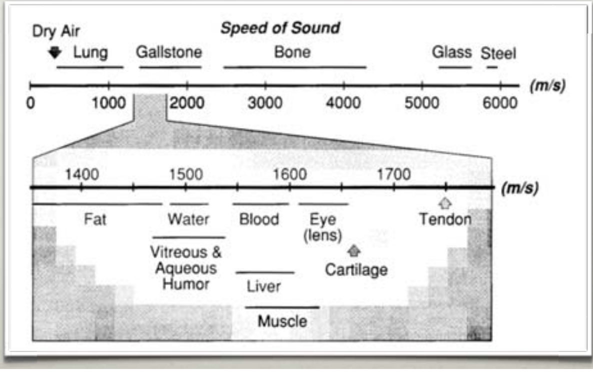


What is ultrasound?

3. Propagation velocity: $S = f\lambda = \frac{\lambda}{T}$

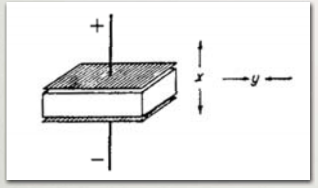
Depends on properties of medium: $S = \sqrt{\frac{Y}{\rho}} = \sqrt{\frac{1}{\kappa\rho}}$

Y=elastic modulus of medium
ϱ=density of medium
k=compressibility of medium

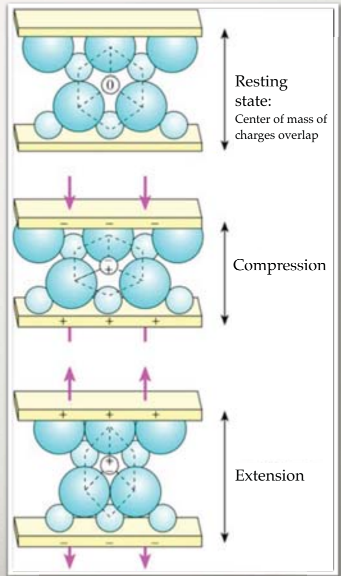


Generation of ultrasound

A. Inverse piezoelectric effect
Piezoelectricity (Pierre and Jacques Curie, 1880): "pressure electricity"



Electric polarization occurs in some crystals upon mechanical deformation



Generation of ultrasound

Direct piezoelectric effect:
electric polarization (P) occurring in certain crystals upon mechanical deformation:

$$P = d \times \frac{F}{A}$$

d=piezoelectric coefficient (m/V)
F/A=stress

Inverse piezoelectric effect:
deformation in certain crystals induced by potential difference:

$$\frac{\Delta l}{l} = E \times d$$

Δl/l= strain
E= electric field
d=piezoelectric coefficient

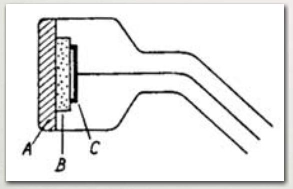
Resonance occurs if the frequency of the applied alternating voltage matches the resonant frequency of the crystal.
Typical ultrasound frequency >1 MHz.
Often used piezoelectric crystals: quartz (d=3x10^{-12} m/V), ammonium-dihydrogen phosphate, etc.

B. Magnetostriction
Deformation of ferromagnetic materials (rods) in magnetic field. Resonance occurs in periodically changing magnetic field at the resonant frequency.

Detection of ultrasound

Using ***direct piezoelectric effect***.

Ultrasound-generating and detecting head: transducer

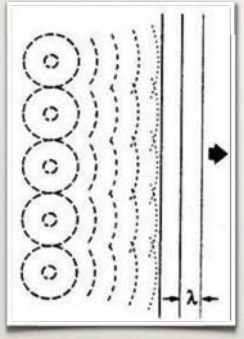


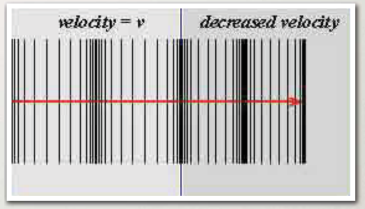
A, cover pate, B, crystal, C, electrode.

Properties of Ultrasound

A. Propagation

Diffraction; Huygens' principle (points along the wave are sources of further waves).
Frequency remains constant during propagation.
Wavelength changes in proportion to the change in velocity





Frequency is unchanged, therefore the wavelength decreases with the decrease in velocity.

Intensity is attenuated in proportion to the distance travelled.
Ultrasound is reflected and refracted on the boundary of media with different propagation velocities.

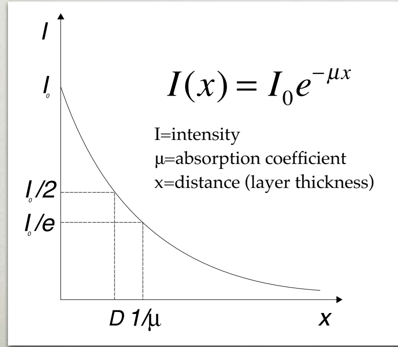
Properties of Ultrasound

B. Attenuation

Decrease in intensity

1. *$1/r^2$ law ("inverse square law")*: intensity decreases as the inverse square of distance (propagation on the spherical surface).

2. *Absorption:*
Mechanisms: a. incoherent molecular motion (heat), b. viscosity of the medium



Absorption increases with frequency and distance travelled.

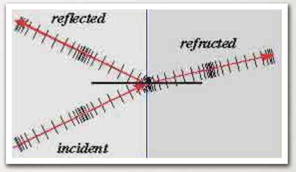
Half-value layer thicknesses (D, at 1 MHz):

Air	1 cm
Water	few meters

Properties of Ultrasound

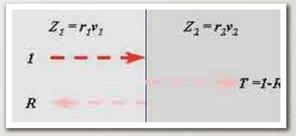
C. Refraction

Bending at the boundary between media of different velocities. Refraction increases with the angle of incidence.



D. Reflection

Acoustic energy is partially reflected from the boundary between media of different acoustic impedances. The reflected energy increases with the difference in acoustic impedances. On certain boundaries (e.g., soft tissue/bone), total reflection may occur.



Reflectivity:

$$R = \left(\frac{z_1 - z_2}{z_1 + z_2}\right)^2$$

z=specific acoustic impedance

Specific acoustic impedance:

$$z = \rho S$$

ϱ=density
S=propagation velocity
Unit of z: rayl (in honor of Lord Rayleigh)

Properties of Ultrasound

E. Doppler effect

In case of moving sound source the observed frequency is changed:
- Approaching sound source: frequency increases.
- Departing sound source: frequency decreases.

Christian Andreas Doppler (1803 - 1853)

Frequency shift: Doppler shift

Magnitude of Doppler shift:

$$f_o = f_s \frac{S + v_o}{S - v_s}$$

f_o: observed frequency
f_s: source frequency
S: sound propagation velocity
v_o: velocity of observer
v_s: velocity of source

Effects of ultrasound

A. Primary effects

1. Cavitation
Formation of short-lived cavities (small bubbles) upon the breakage of intermolecular cohesion forces.
Sonoluminescence: light emission following the collapse of cavities.
Mechanism:
a. in the rarified phase of the ultrasound wave, 5-70-μm bubbles form
b. the bubbles shrink in the compressive phase of the wave.
c. the internal temperature of the bubble may reach temperatures of 20.000-30.000 °K!
d. the noble gases remaining in the bubble (Ar, Xe) emit photons.

2. Sound pressure
The ultrasound wave exerts pressure on an objects in its direction of propagation.
The pressure is directly proportional to ultrasound intensity.

3. Absorption
Energy absorption by the medium that leads to an increase in its temperature.

Absorption increases with frequency and distance travelled:

$$I(x) = I_0 e^{-\mu x}$$

I=intensity
μ=absorption coefficient
x=distance (layer thickness)

Effects of ultrasound

B. Secondary effects

1. Mechanical
Based on the resonance of particles in the exposed medium (dispersion, cleansing, etc.)

2. Chemical
Absorption -> chemical reactions may be induced (oxidation, pl. precipitation of iodine from KI solution, etc.).

3. Biological
Complex bactericidal, fungicidal, anti-viral, etc. effects.

Therapeutic applications of ultrasound

Therapeutic application of ultrasound are based primarily on its physical effects.

1. Local heating

2. Micromassage

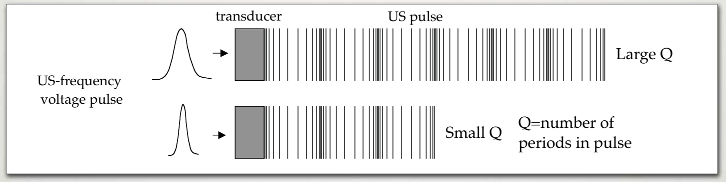
3. High Intensity Focused Ultrasound (HIFU): Kidney stones, prostate cancer

4. Physical therapy

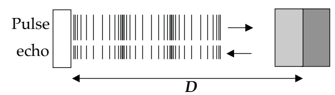
Diagnostic applications of ultrasound

Imaging method based on differential ultrasound absorption and reflection by tissues (different acoustic impedance of tissues).

1. Pulse-echo principle



2. Distance measurement with ultrasound



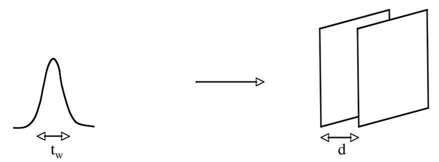
Distance: $D = \frac{vT}{2}$

D= distance between transducer and reflecting surface
v=US speed in medium
T= time elapsed between pulse emission and echo return

US frequency:few MHz; Pulse frequency: 1 kHz; Pulse width: 1 μs; Q= few periods

Diagnostic applications of ultrasound

3. Axial resolution



In order to resolve the ***d*** axial distance: $vt_w < 2d$

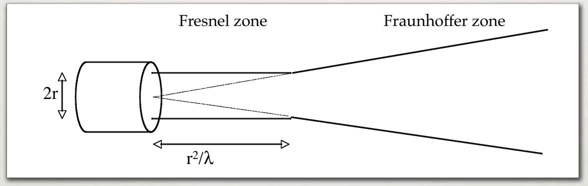
For a given frequency, axial resolution improves by reducing Q.
For a given Q, axial resolution improves by reducing frequency.

Diagnostic applications of ultrasound

4. Time-gain compensation

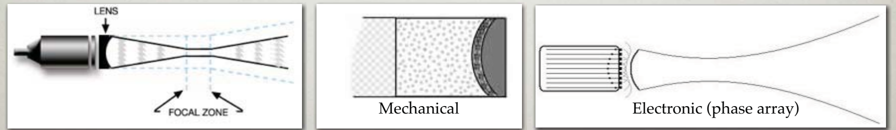
Intensity decreases with distance (attenuation).
Acoustic attenuation can be partially compensated by amplifying the detected signal.
Accordingly, signal gain is gradually increased as a function of time following ultrasound pulse emission.

5. Transducer and ultrasound beam (important in lateral resolution)



Upon increasing frequency, the Fresnel zone lengthens and divergence is reduced: the beam can be focused better.

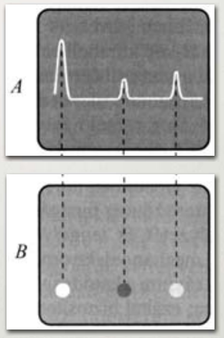
Beam focusing



Diagnostic applications of ultrasound

6. Ultrasound imaging modes:

A-mode (Amplitude modulated):
Single transducer, single beam in one direction.
Echos are detected as voltage pulses on the oscilloscope.
Pulse amplitude corresponds to echo intensity.



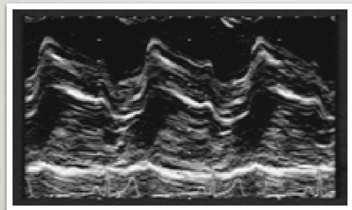
B-mode (Brightness):
Voltage pulses are shown as grayscale spots.
Grayscale depth corresponds to amplitude.
Greater the amplitude, brighter the spot.

Diagnostic applications of ultrasound

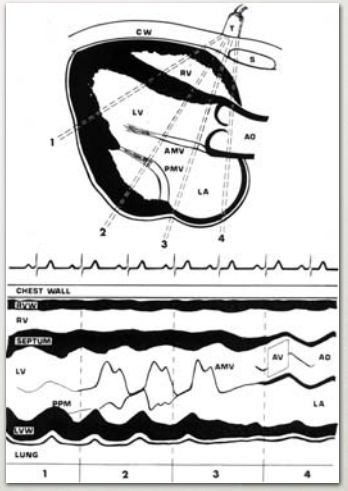
M-mode (time Motion)

Display of periodically moving objects as a function of time.
(e.g., echocardiography)

X-axis: time
Y-axis: 1D B-mode image (line)

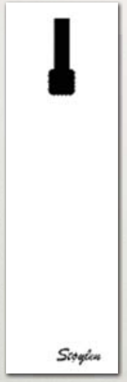


Mitral stenosis

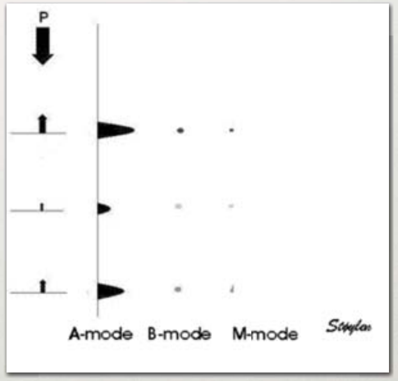


Diagnostic applications of ultrasound

One-dimensional imaging modes - Comparison



Pulse-echo

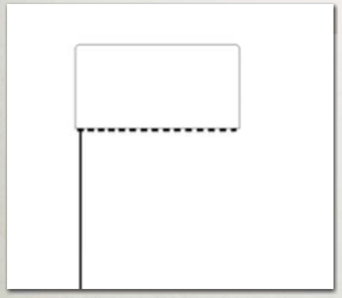


Imaging modes

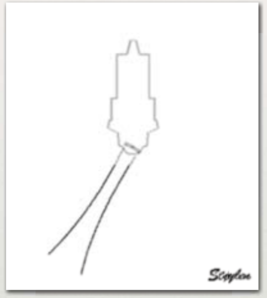
Diagnostic applications of ultrasound

2-dimensional B-mode (Brightness)

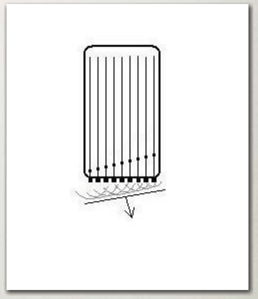
A two-dimensional plane is scanned.



Linear array
(hundreds of piezo crystals arranged along a line)



Mechanical scanning
(single piezo crystal rapidly scanned along a line)



Electronic scanning
(phase array)

Diagnostic applications of ultrasound

2-dimensional B-mode (Brightness)

Real-time recordings are possible with rapid scanning.

Diagnostic applications of ultrasound

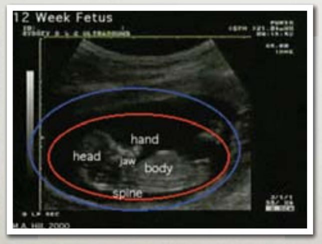
OB-GYN applications of 2D B Mode ultrasound imaging

Gestation age, developmental malformations, placenta position, fetus orientation

Biparietal distance

Femur length

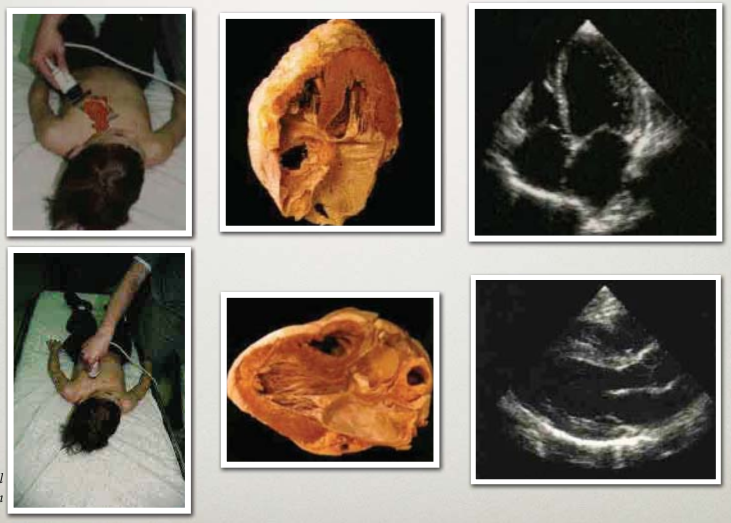
12-week-old fetus



7-week twins

Diagnostic applications of ultrasound

Cardiology applications of 2D B Mode ultrasound imaging



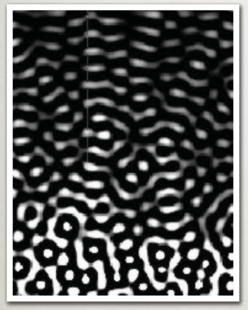
Apical position

Left parasternal longitudinal position

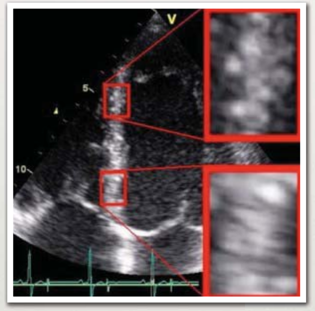
Diagnostic applications of ultrasound

Cardiology applications of 2D B Mode ultrasound imaging

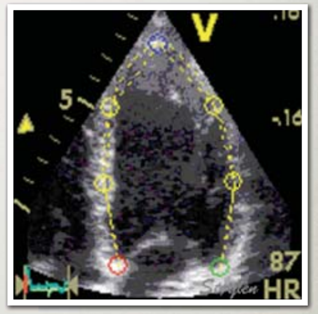
Speckle tracking



Ultrasound interference pattern



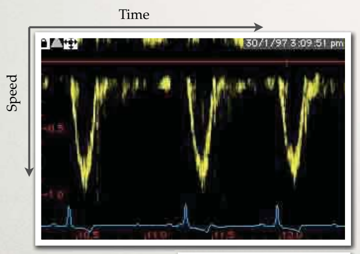
Interference pattern is stable and identifiable (speckle)



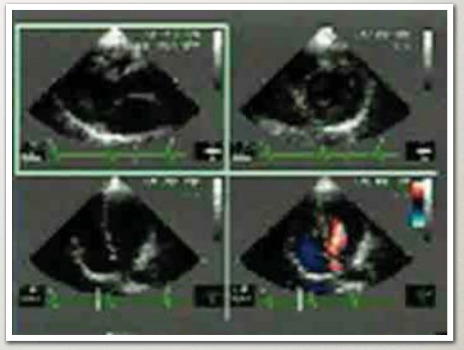
Speckle tracking with image processing algorithms

Diagnostic applications of ultrasound

Cardiology applications: Doppler cardiography



„Flow mapping":
Superposition of 2D B-mode and M-mode
Red: approaching blood flow,
Blue: reproaching blood flow



Diagnostic applications of ultrasound

3-dimensional ultrasound

Rotating, fan shaped scanner.
Image reconstruction using sophisticated computer processing methods.

Diagnostic applications of ultrasound

3-dimensional ultrasound

Spatial information can be arbitrarily manipulated and presented.

Boy or Girl?

Diagnostic applications of ultrasound

4-dimensional ultrasound: time-dependent 3D ultrasound

Yawning fetus

Smiling fetus

Summary

- Ultrasound is a high-frequency mechanical wave
- Generation by inverse piezoelectric effect
- Detection by direct piezoelectric effect
- During propagation in media: reflection, refraction
- Direct and indirect effects related to local pressure changes
- Image formation based on pulse-echo principle