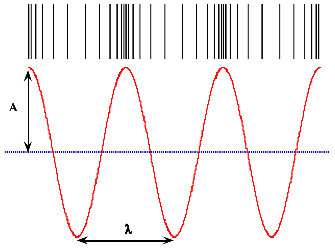
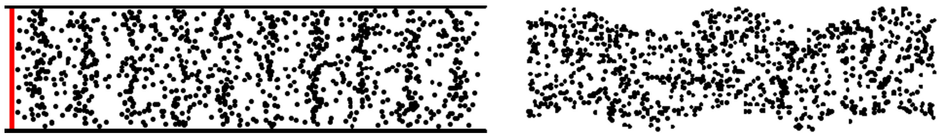
Sound, Ultrasound

Miklós Kellermayer

Sound

Longitudinal mechanical wave (pressure wave)





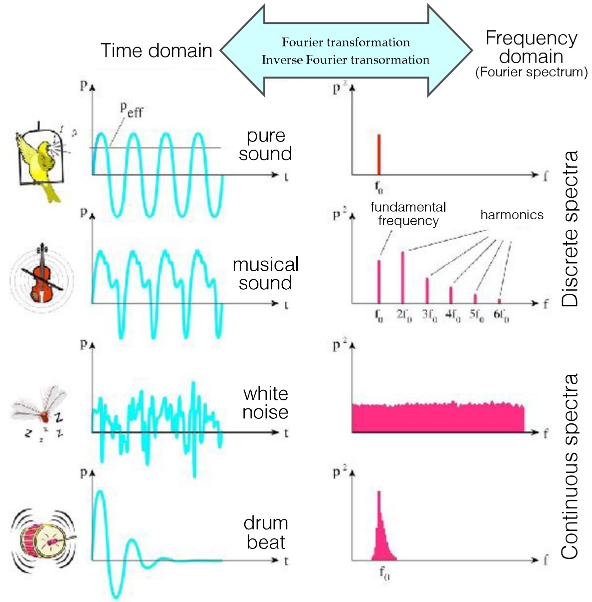
Longitudinal wave

Transverse wave

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

y=actual pressure; t=time
f=frequency (Hz); A=amplitude
φ=phase shift

Sounds and their spectra



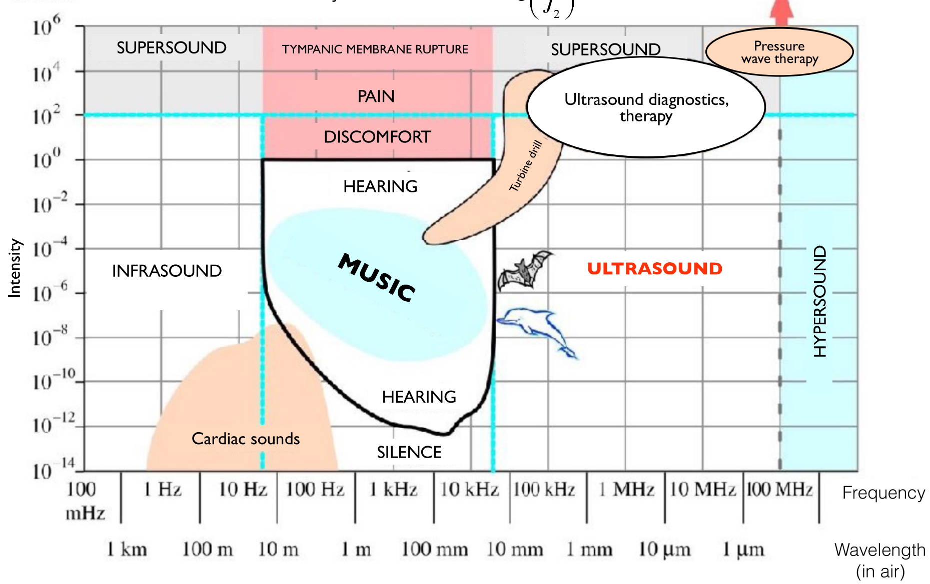
Fourier theorem:
any function can be expressed as the sum of a fundamental sine wave and its harmonics

Steps of Fourier transformation:

Octave - frequency difference with a 2:1 ratio

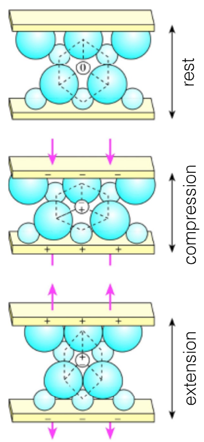
Frequency and intensity of sounds

Intensity level: $n(dB) = 10\lg\left(\frac{J_1}{J_2}\right)$



Generation and detection of ultrasound: piezoelectric effect

Piezoelectricity (Pierre and Jacques Curie, 1880): "pressure electricity"



Electrical polarization upon mechanical deformation. Centers of + negative - charges are spatially separated.

1. Direct piezoelectric effect: electrical polarization (P) that occurs in certain crystals upon mechanical deformation:

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

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

Application: detection of ultrasound, piezoelectric lighter

Up to kV voltage!

2. Inverse piezoelectric effect: deformation in a crystal placed in electric field:

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

$\Delta l/l$=strain
E=electric field
d=piezoelectric coefficient (m/V)

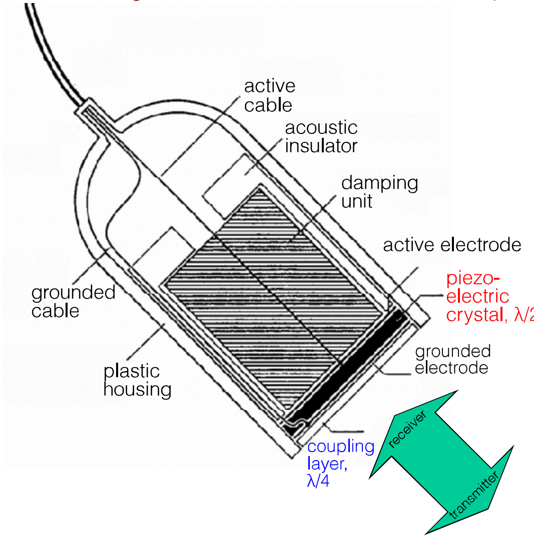
Application: generation of ultrasound

Resonance: frequency of alternating voltage coincides with the Eigen (resonance) frequency of the crystal. Typical ultrasound frequencies >1 MHz.

Frequently used piezoelectric crystals: quartz (d=3x10^{-12} m/V), ammonium-dihydrogen phosphate, lead-zirconium-titanate (PZT), etc.

The ultrasound transducer

"Head" that generates and detects ultrasound (*transducere* ~ to lead across, to convert)



Shape and size of the ultrasound transducers vary with applications.

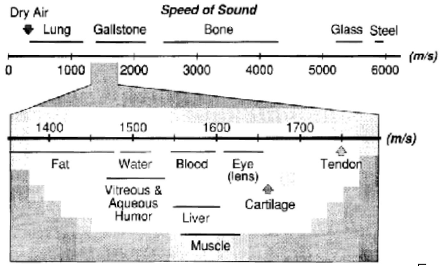
Properties of ultrasound: propagation

Speed of propagation (S, v, c): $$S = f\lambda = \frac{\lambda}{T}$$

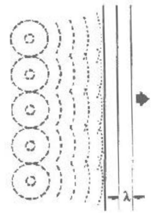
US propagates solely as a longitudinal wave in gases and liquids; in solids it may also propagate as a transverse wave.

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

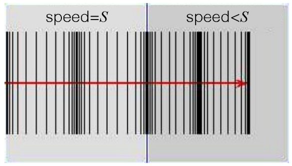
Y = Young's modulus
ρ = density of the medium
k = compressibility of the medium



Speed of ultrasound in different media



Formation of wavefront: based on Huygens-principle



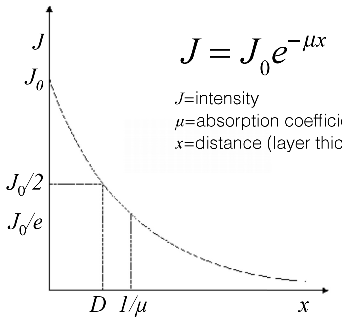
During propagation frequency is unchanged. Wavelength varies with speed.

Properties of ultrasound: Attenuation

Attenuation: decrease of intensity, "weakening"

1. $1/r^2$ law ("inverse square law"): intensity decreases with the inverse of the square of propagation distance (sound power is distributed across a spherical surface).

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



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

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

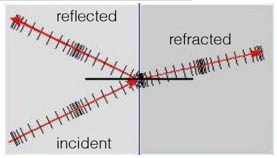
Material	D (f=1 MHz)
Air	~1 cm
Water	few m

Properties of ultrasound: Refraction and Reflection

Refraction

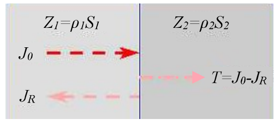
Change in the direction of propagation at surfaces bounded by media in which the speed of US propagation is different. Refraction increases with increasing angle of incidence.
Snell's Law applies:

$$\frac{\sin\alpha}{\sin\beta} = \frac{S_1}{S_2}$$



Reflection

Part of the acoustic intensity is reflected from surfaces bounded by media with different acoustic impedances. Reflected intensity increases with increasing difference in the acoustic impedance of the media. At certain surfaces (e.g., soft tissue/bone), total reflection may occur.



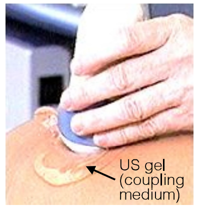
Reflectivity (reflection coefficient): $$R = \frac{J_R}{J_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \qquad Z = \rho S$$

Z= acoustic impedance (rayl)
ρ=density
S=speed of propagation

boundary surface	R
muscle/blood	0.001
fat/liver	0.006
fat/muscle	0.01
bone/muscle	0.41
bone/fat	0.48
soft tissue/air	0.99

"Total" reflection:
$$Z_1 \ll Z_2, R \approx 1$$

Optimal coupling:
$$Z_{coupling} \approx \sqrt{Z_{source} Z_{skin}}$$



Properties of ultrasound: Doppler effect

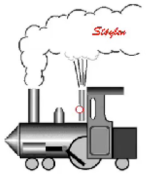
In case of a moving US source, the detected frequency is changed:
- If the source is approaching, then the detected frequency increases.
- If the source is departing, then the detected frequency decreases.

Christian Andreas Doppler (1803 - 1853)

Frequency shift: Doppler shift

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

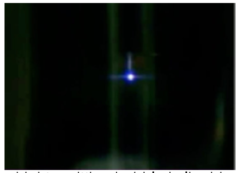
f_o: detected frequency
f_s: frequency of source
S: speed of propagation of US
v_o: speed of the observer
v_s: speed of the US source



Effects of ultrsound

Primary effects

1. Cavitation: (formation of cavities; cavum = cavity): short-lived cavities generated upon the breakdown of cohesion forces between participating molecules.
Sonoluminescence: photon emission upon the collapse of the cavity. Mechanism:
- In the expansive phase of the pressure wave, bubbles are formed (5-70 µm).
- In the compressive phase, the bubbles contract.
- The temperature inside the bubble may reach levels up to 20.000-30.000 ˚K.
- The excited noble gas (Ar, Xe) atoms remaining in the bubbles emit photons.



Light-emitting bubble in liquid irradiated with US (several MHz)

2. Sound pressure: Pressure exerted on the object standing in the path of US wave. Directly proportional to US intensity.

3. Absorption: Absorption of radiation energy by the medium, leading to increased temperatures (increases with frequency and layer thickness).

Secondary effects

1. Mechanical: resonance of particles suspended in the medium (dispersion, cleaning, dentistry, etc.)
2. Chemical: energy absorption may initiate chemical reactions (oxidation, e.g.,. condensation of iodine from KI solution).
3. Biological: Complex mechanisms - bactericidal, fungicidal, virucidal, etc., effects.

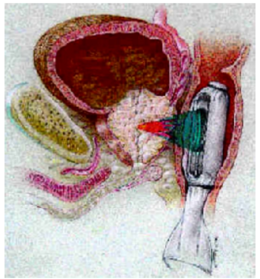
Therapeutic applications of ultrasound

The therapeutic applications of US deped on its physical effects

1. Local heating

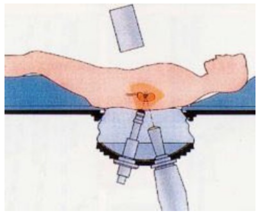
2. Micromassage

3. High Intensity Focused Ultrasound (HIFU): Crushing of prostate tumors



HIFU

Shock wave therapy (not really US!)
ESWL (Extracorporeal Schockwave Lithotripsy)
Crushing of kidney stones



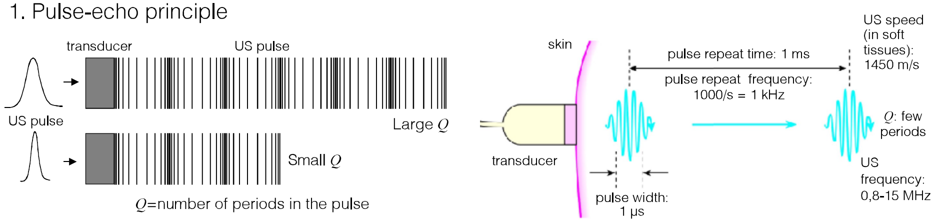
ESWL

4. Physical therapy

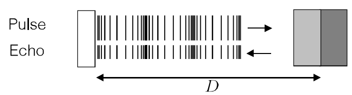
Diagnostic applications of ultrasound

Imaging method. Its basis is differential absorption and reflection by the bounding media. The acoustic impedance of the bounding media are different.

1. Pulse-echo principle



2. Distance measurement with ultrasound

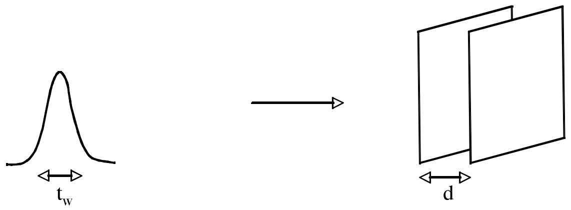


Distance: $$D = \frac{ST}{2}$$

D=transzducer és visszaverő felület közötti távolság
S=UH terjedési sebessége a közegben
T=impulzus emissziója és visszaérkezése között eltelt idő

Diagnostic applications of ultrasound

3. Axial resolving power



Condition of resolving smallest axial distance (d): $St_w<2d$

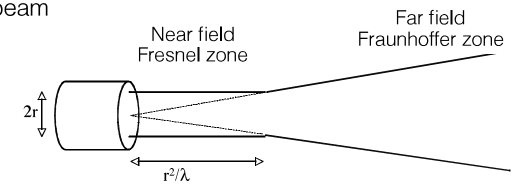
At a given frequency, axial resolution increases with decreasing Q value.
At a given Q value the axial resolution increases with increasing frequency.

Diagnostic applications of ultrasound

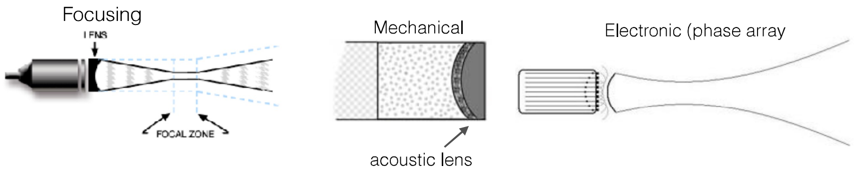
4. Time-gain compensation

Intensity decreases with increasing distance (attenuation).
Acoustic attenuation can be partially compensated for by amplificaton of the detected signal.
After pulse emission, gain is constantly increased as a function of time.

5. Ultrasound beam



Upon increasing frequency, the length of the Frenel zone increases, divergence decreases: the beam may be better focused.

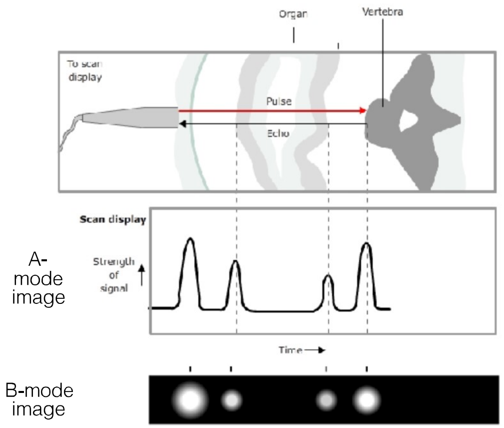


Diagnostic applications of ultrasound

6. Ultrasound imaging modes:

A-mode (Amplitude-modulated):
Single transducer; beam propagates along a single line.
The echo is detected as a voltage pulse on an oscilloscope.

B-mode (Brightness):
Voltage pulses are displayed as points of varying gray level.
Grayscale density is proportional to voltage amplitude: the greater the voltage the brighter the point and vice versa.

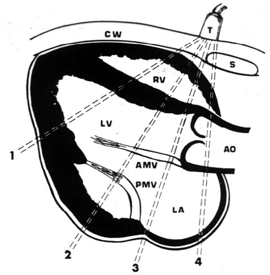


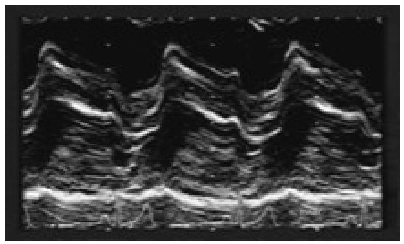
Diagnostic applications of ultrasound

M-mode (time Motion)

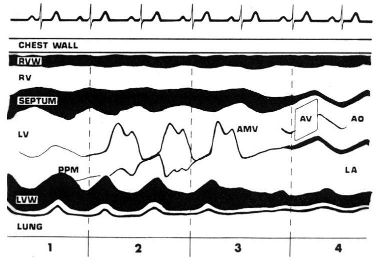
Displays periodic motions as a function of time (e.g., echocardiography)

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





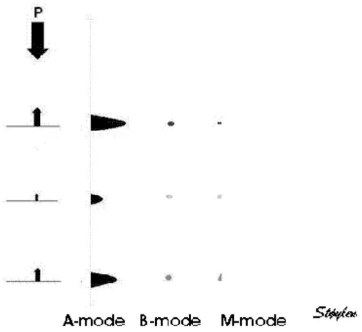
Mitral stenosis



Diagnostic applications of ultrasound

One-dimensional imaging modes - comparison

Pulse-echo principle

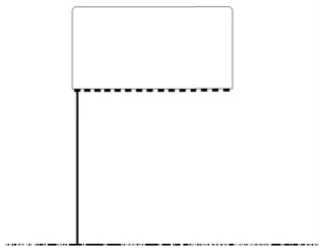


Basic imaging modes

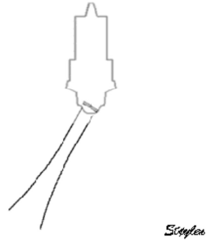
Diagnostic applications of ultrasound

2-dimensional B-mode (Brightness)

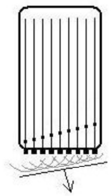
Scanning is carried out in two dimensions



“Linear array“ (hundreds of small piezo crystals arranged linearly)



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

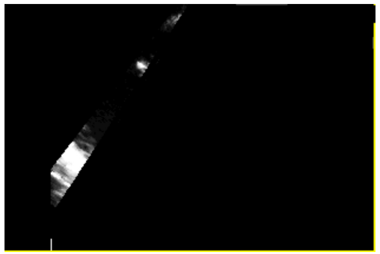


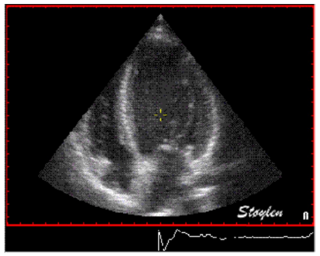
Electronic scanning (phase array)

Diagnostic applications of ultrasound

2-dimensional B-mode (Brightness)

With fast scanning, real-time images may be recorded.





Diagnostic applications of ultrasound

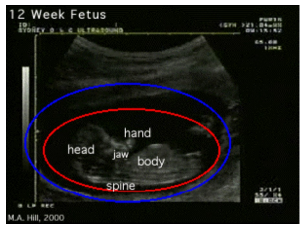
A 2D B-mode in obstetrics and gynecology

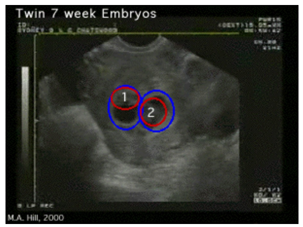
Gestational age, developmental pathology, placenta position, fetus position.

Biparietal diameter

Femur length

12-week fetus





7-week twin pregnancy

Diagnostic applications of ultrasound

A 2D B-mode in cardiology

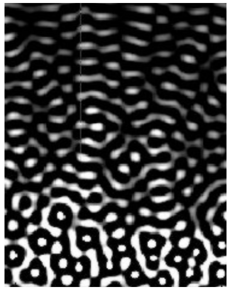
Apical position

Left parasternal longitudinal position

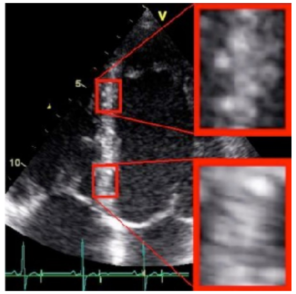
Diagnostic applications of ultrasound

A 2D B-mode in cardiology

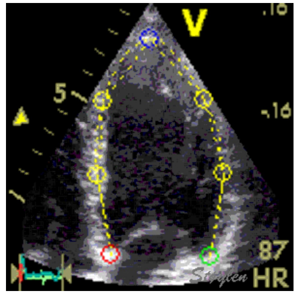
Speckle tracking



Ultrasound interference pattern



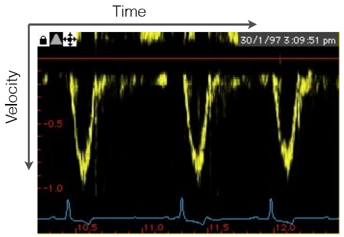
Interference pattern is stable and may be followed.

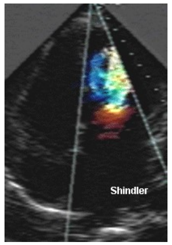


Following speckles with image analysis algorithms.

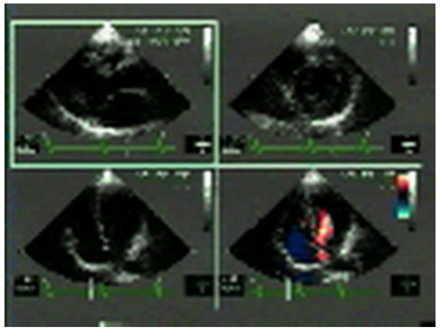
Diagnostic applications of ultrasound

Cardiological applications: Doppler cardiography





„Flow mapping": superpositioning a 2D B-mode and an M-mode image
Red: approaching blood, Blue: departing blood

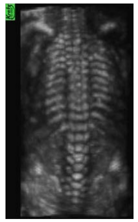


BART: Blue Away Red Towards

Diagnostic applications of ultrasound

3-dimensional ultrasound

Rapid transducer capable of rotating the fan-like beam. Computer-based image reconstruction.



Diagnostic applications of ultrasound

3-dimensional ultrasound

The spatially resolved images may be presented and manipulated at will.

Girl or boy?

Diagnostic applications of ultrasound

4-dimensional ultrasound: temporally resolved 3D ultrasound

yawning fetus

smiling fetus