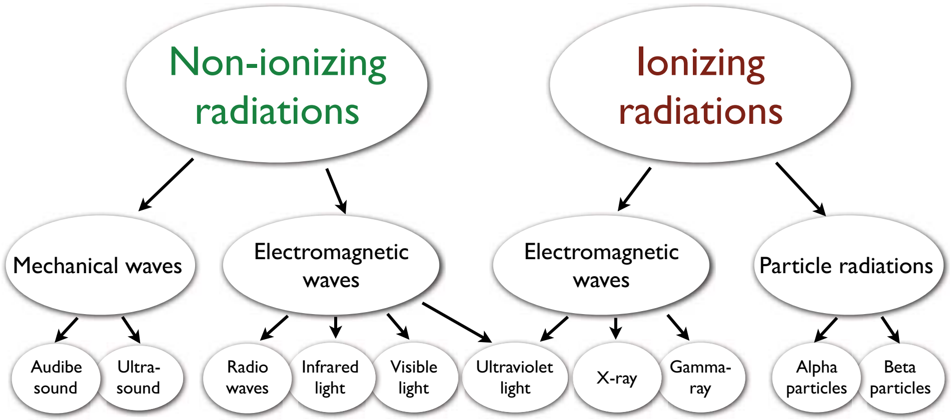
Sound, Ultrasound

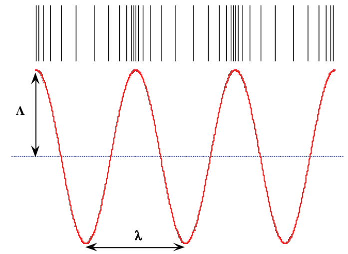
Miklós Kellermayer

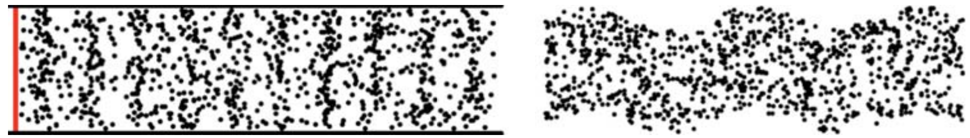
Types of radiation



Sound

Longitudinal mechanical wave (pressure wave)





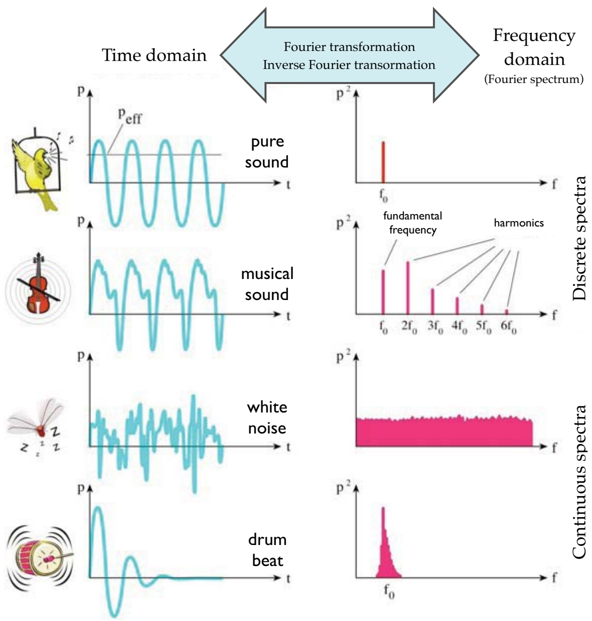
Longitudinal wave

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



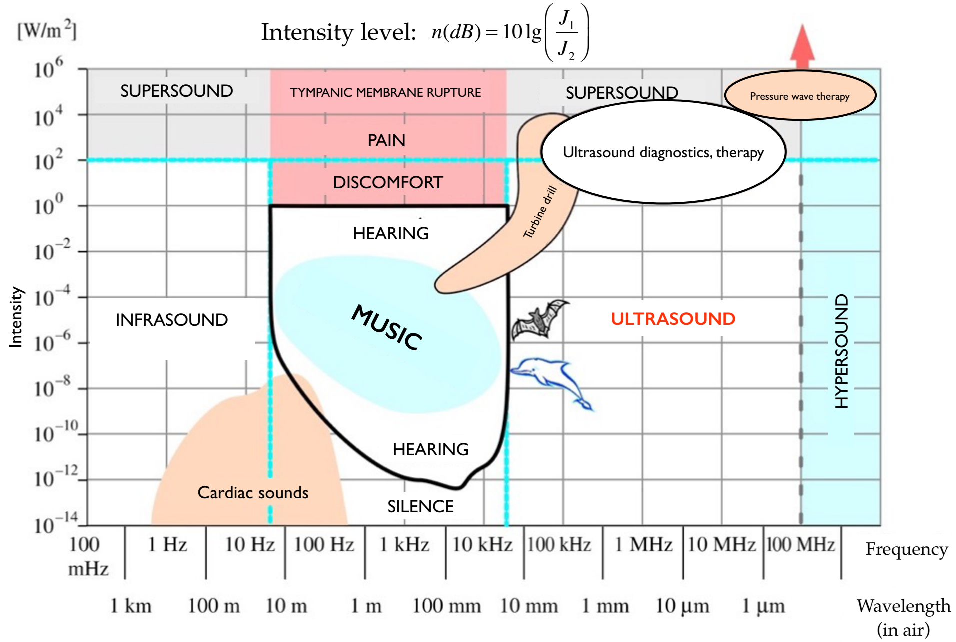
Fourier theorem:
any function can be expressed as the sum of a fundamental sine wave and its harmonics

Steps of Fourier transformation:

Octave - frequency difference with a 2:1 ratio

Frequency and intensity of sounds

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



Ultrasound

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

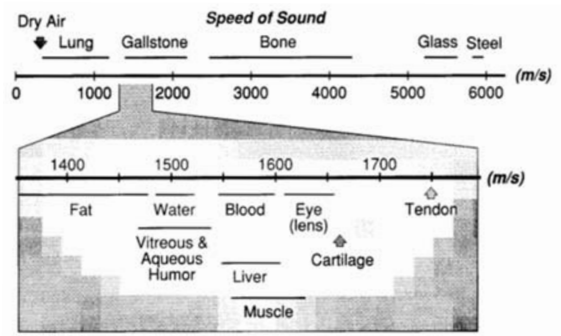
Ultrasound propagates in elastic medium

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

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

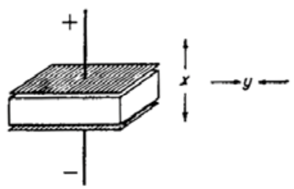
Speed depends on the properties of the medium: $S = \sqrt{\dfrac{Y}{\rho}} = \sqrt{\dfrac{1}{\kappa\rho}}$

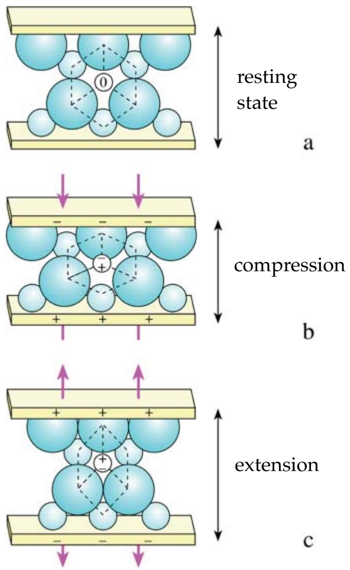
Y = Young's modulus
ρ = density of the medium
k = compressibility of the medium



Generation of ultrasound

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





In certain crystals electrical polarization occurs upon mechanical deformation.
Basis of electrical polarization: centers of mass of + and - charges become spatially separated.

Generation of ultrasound

Direct piezoelectric effect: electrical polarization (P) that occurs in certain materials upon mechanical deformation: $P = d \times \dfrac{F}{A}$

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

Up to kV voltages in piezo lighters!

Inverse piezoelectric effect: deformation that occurs in a crystal placed in electric field: $\dfrac{\Delta l}{l} = E \times d$

Δl/l= strain
E= electric field
d=piezoelectric coefficient (m/V)

Resonance occurs if the frequency of the applied alternating voltage coincides with the Eigen frequency (resonance frequency) of the crystal. Typical US frequency >1 MHz.

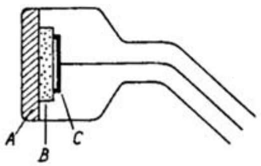
Commonly used piezoelectric crystals: quartz ($d=3\times10^{-12}$ m/V), ammonium-dihydrogen phosphate, lead-zirconium-titanate (PZT), etc.

B. Magnetostriction
Deformation of ferromagnetic materials in magnetic field. *Resonance* occurs if the frequency of the applied alternating voltage coincides with the Eigen frequency (resonance frequency) of the crystal.

Detection of ultrasound

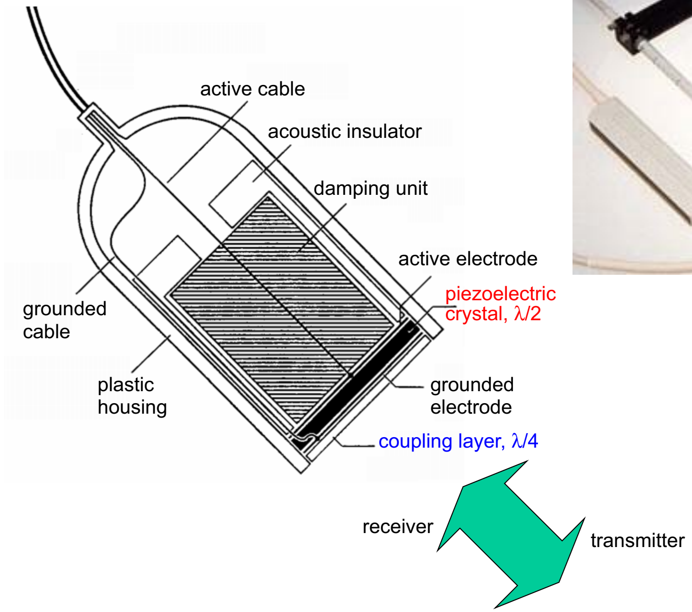
With the help of the direct piezoelectric effect.

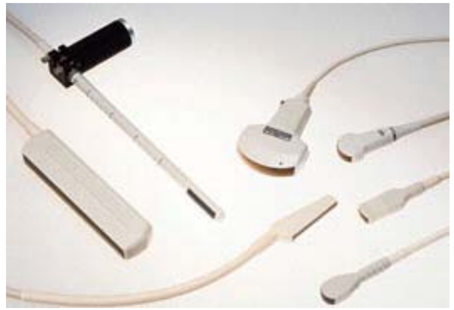
Transducer: generates and detects ultrasound.



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

The ultrasound transducer

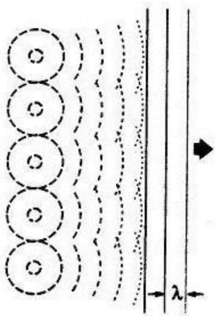


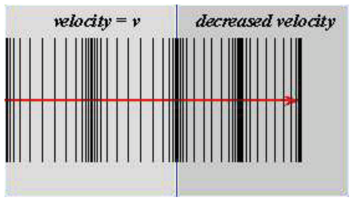


Properties of Ultrasound

A. Propagation

Diffraction - Huygens' principle (points of the wavefront are sources of new waves).
Frequency remains constant during propagation.
Wavelength changes in proportion to that of propagation velocity.





Frequency does not change, therefore wavelength decreases with decreasing velocity.

Intensity decreases with the distance of propagation.
Ultrasound is reflected from the boundary of media in which the speed of propagation of US is different.

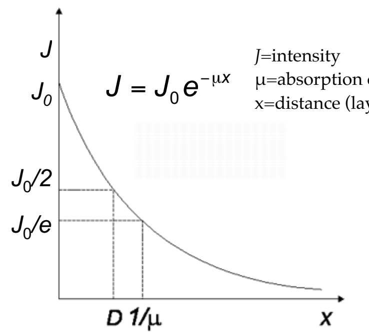
Properties of Ultrasound

B. Attenuation

Decrease of intensity

1. *1/r² 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:*
Mechanism: a. incoherent molecular motion (heat), b. viscosity of the medium



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

Absorption increases with frequency and distance of propagation.

Half-value thickness (D, @1 MHz):

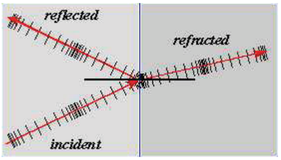
Air	1 cm
water	few meters

Properties of Ultrasound

C. Refraction

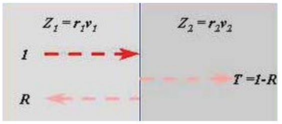
Change in the direction of propagation at surfaces bounded by media in which the speed of US propagation is different. Refracion increases with increasing angle of incidence.

Snell's Law applies: $\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$



D. 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: $R = \left(\frac{z_1 - z_2}{z_1 + z_2}\right)^2$ z= acoustic impedance

Acoustic impedance $z = \rho S$

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

Reflection (perpendicular incidence)

Reflectivity (reflection coefficient):

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

"Total" reflection:

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

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

optimal coupling:

$$Z_{\text{connecting}} \approx \sqrt{Z_{\text{source}} Z_{\text{skin}}}$$

ultrasound gel (coupling medium)

Properties of Ultrasound

E. Doppler effect

Christian Andreas Doppler (1803 - 1853)

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.

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

A. 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.
SBSL: "single bubble sonoluminescence"
Mechanism:
a. In the expansive phase of the pressure wave, bubbles are formed (5-70 μm).
b. In the compressive phase, the bubbles contract.
c. The temperature inside the bubble may reach levels up to 20.000-30.000 ˚K.
d. The excited noble gas (Ar, Xe) atoms remaining in the bubbles emit photons.

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.

Absorption increases with frequency and layer thickness.

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

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

Effects of ultrsound

B. Secondary effects

1. Mechanical
Mechanism: resonance of particles suspended in the medium (dispersion, cleaning, dentistry, etc.)

2. Chemical
Absorption -> 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

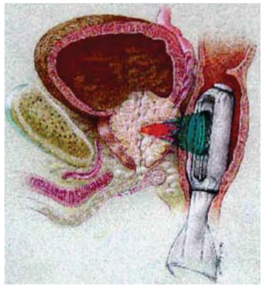
1. Local heating

2. Micromassage

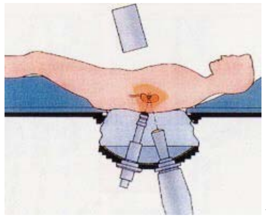
3. High Intensity Focused Ultrasound (HIFU):
Crushing of prostate tumors

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

4. Physical therapy



HIFU

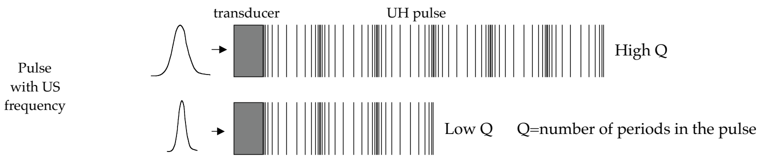


ESWL

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

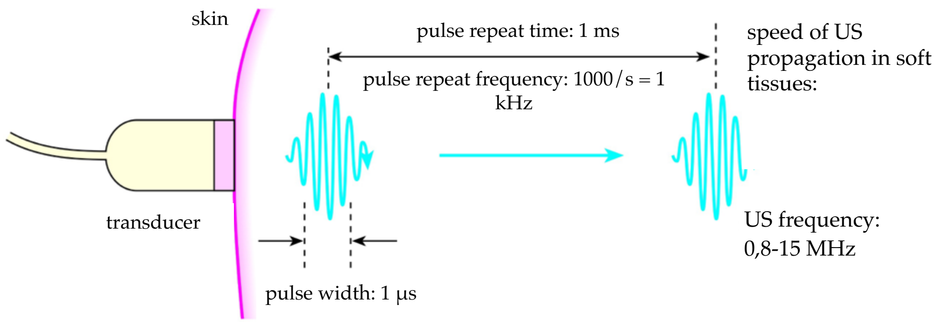
Distance: $D = \frac{vT}{2}$

D=distance between the transducer and the reflective surface
v=speed of propagation of US in the medium
T=time difference between the pulse emission and reception

US frequency: few MHz; pulse frequency: 1 kHz; pulse width: 1 μs; Q = a few periods.

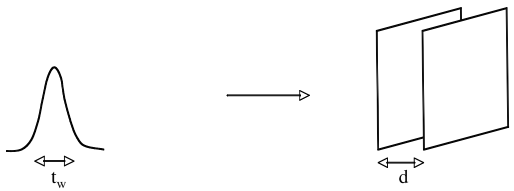
Properties of the US pulse

Transducer - transmitter and receiver in the same unit-
Basis of **temporal separation** – pulses are used instead of continuous wave.



Diagnostic applications of ultrasound

3. Axial resolving power



d axially resolved smallest distance:

$$vt_w < 2d$$

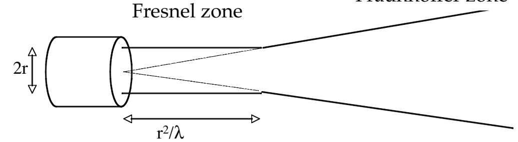
At a given frequency, axial resolution increases with decreasing Q value.
At a given Q value the axial resolution increases with increasing frequency.

Diagnostic applications of unltrasound

4. Time-gain compensation

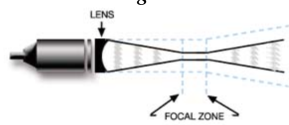
Intensity decreases with increasing distance (attenuation).
Acoustic attenuation can be partially compensated for by amplificaton of the detected signal.
After pulse emission, gain is constantly increased as a function of time.

5. Ultrasound beam

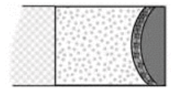


Upon increasing frequency, the length of the Frenel zone increases, divergence decreases: the beam may be better focused.

Focusing

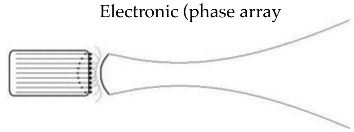


Mechanical



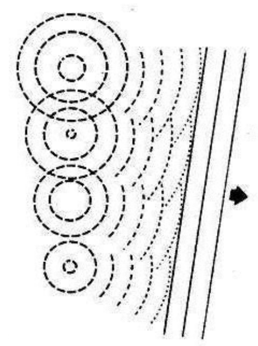
acoustic lens

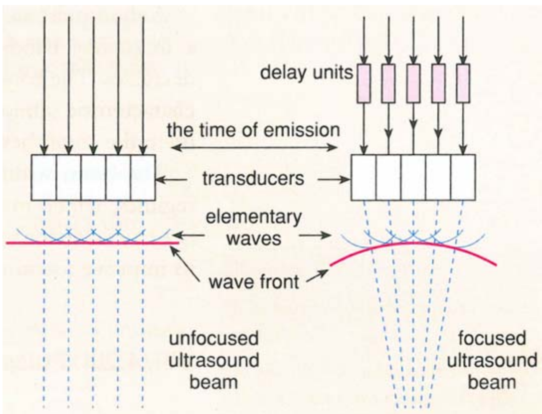
Electronic (phase array



Electronic focusing

Huygens' principle

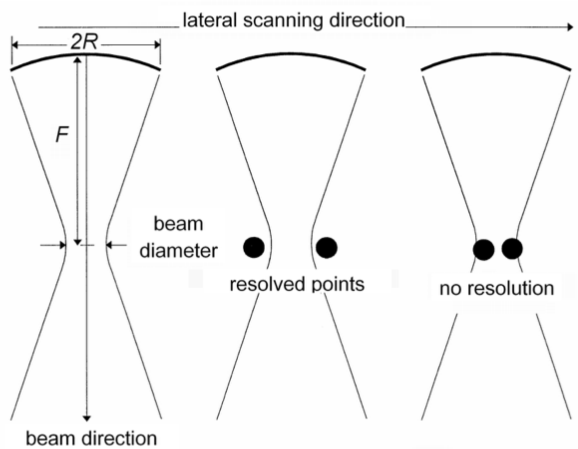




Points of the wavefront are sources of new waves: a new wavefront is formed from the envelope of the waves.

The wavefront may be manipulated and directed with phase-shift.

Lateral resolution depends on beam focusing



$$\left(\delta_{lat} \sim \frac{F}{2R} \cdot \lambda\right)$$

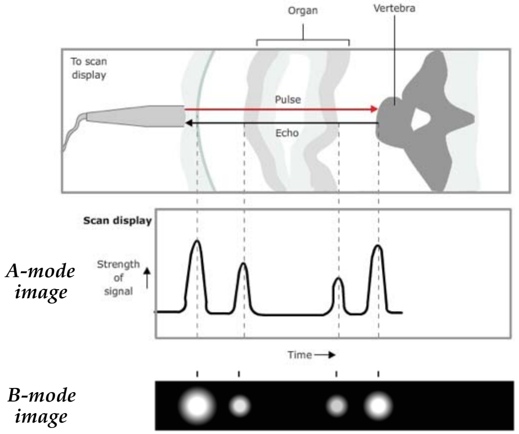
F: focal distance
2*R*: transducer diameter
λ: wavelength

Diagnostic applications of ultrasound

6. Ultrasound imaging modes:

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

B-mode (<u>B</u>rightness):
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*.

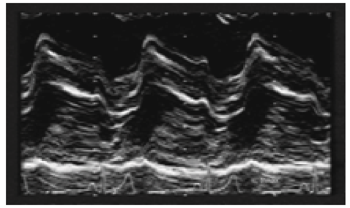


Diagnostic applications of ultrasound

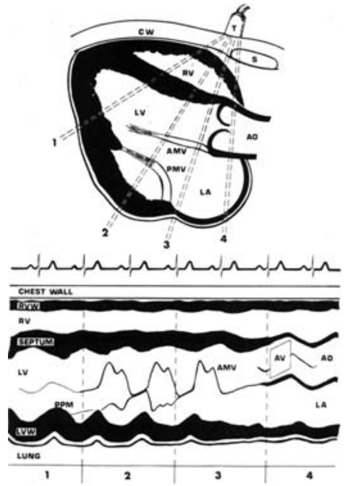
M-mode (time <u>M</u>otion)

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

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



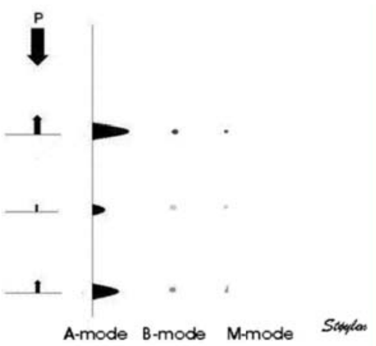
Mitral stenosis



Diagnostic applications of ultrasound

One-dimensional imaging modes - comparison

Pulse-echo principle

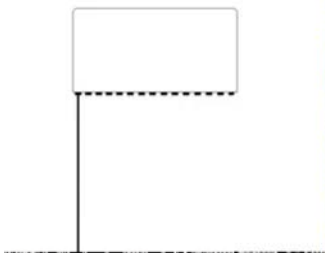


Basic imaging modes

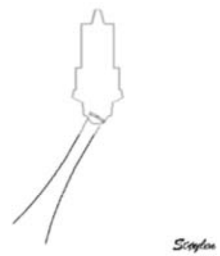
Diagnostic applications of ultrasound

2-dimensional B-mode (<u>B</u>rightness)

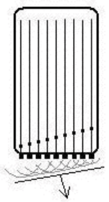
Scanning is carried out in two dimensions



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



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

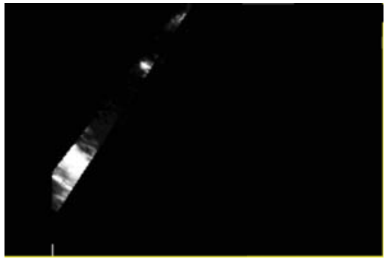


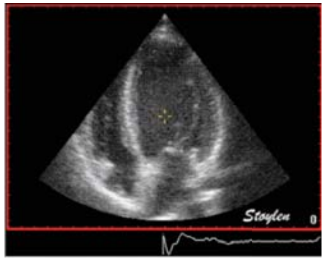
Electronic scanning
(phase array)

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

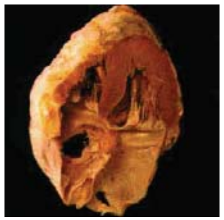
12-week fetus

7-week twin pregnancy

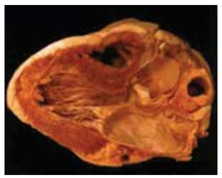
Diagnostic applications of ultrasound

A 2D B-mode in cardiology

Apical position



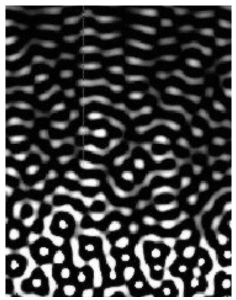
Left parasternal longitudinal position



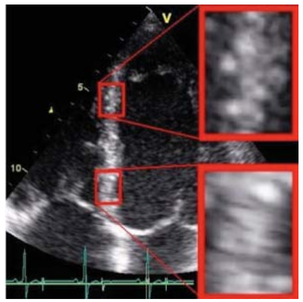
Diagnostic applications of ultrasound

A 2D B-mode in cardiology

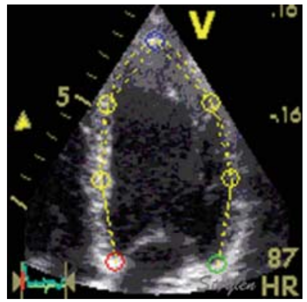
Speckle tracking



Ultrasound interference pattern



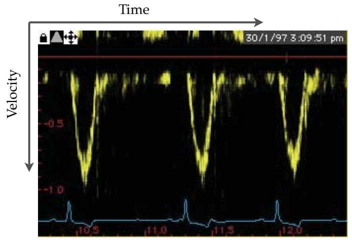
Interference pattern is stable and may be followed.



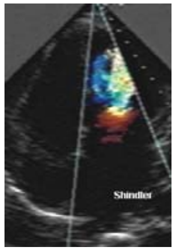
Following speckles with image analysis algorithms.

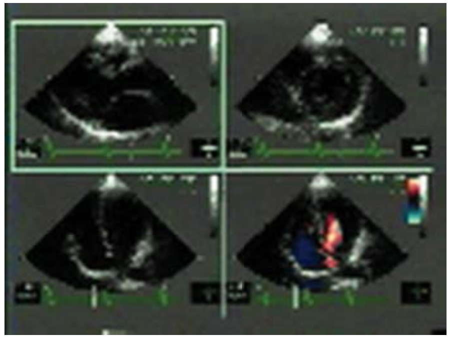
Diagnostic applications of ultrasound

Cardiological applications: Doppler cardiography



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



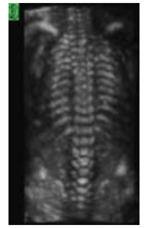


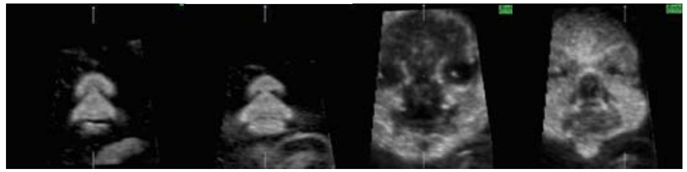
BART: Blue Away Red Towards

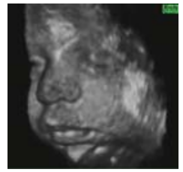
Diagnostic applications of ultrasound

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