Ultrasound

Generation, properties, applications

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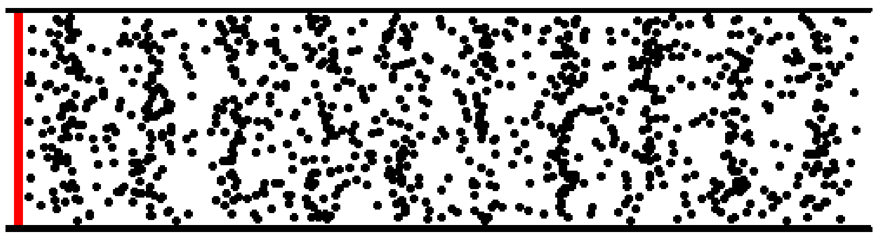
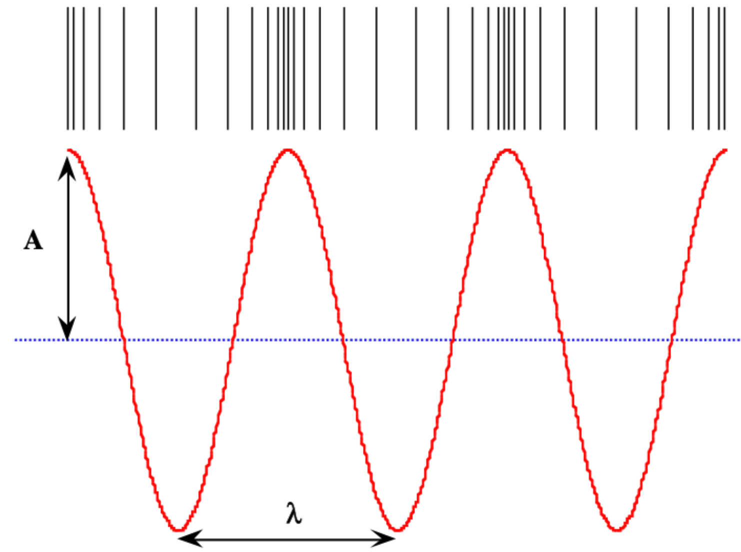
Ultrasound is a longitudinal wave



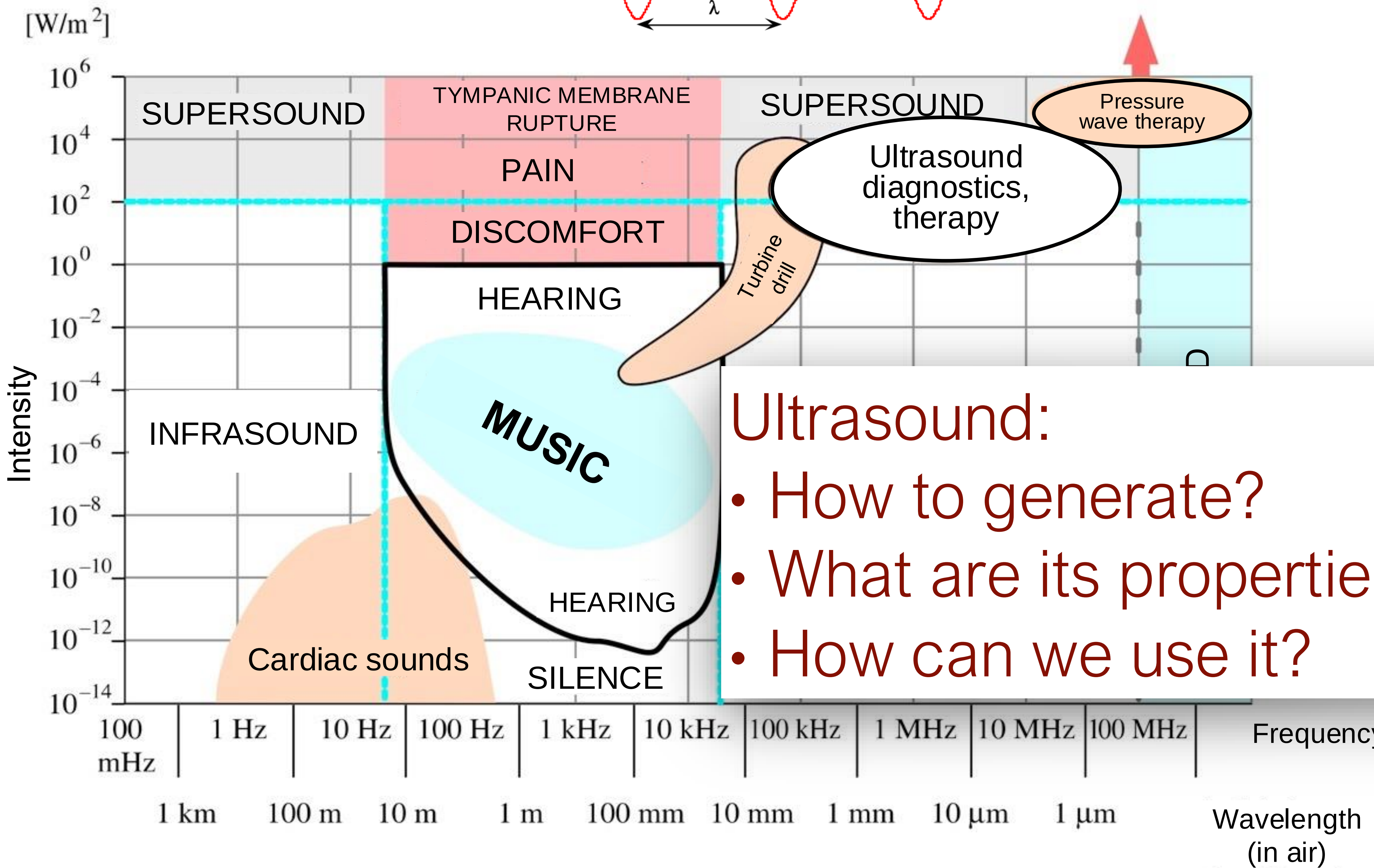
Mechanical wave (pressure wave), propagates in elastic medium



Harmonic oscillation:

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

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

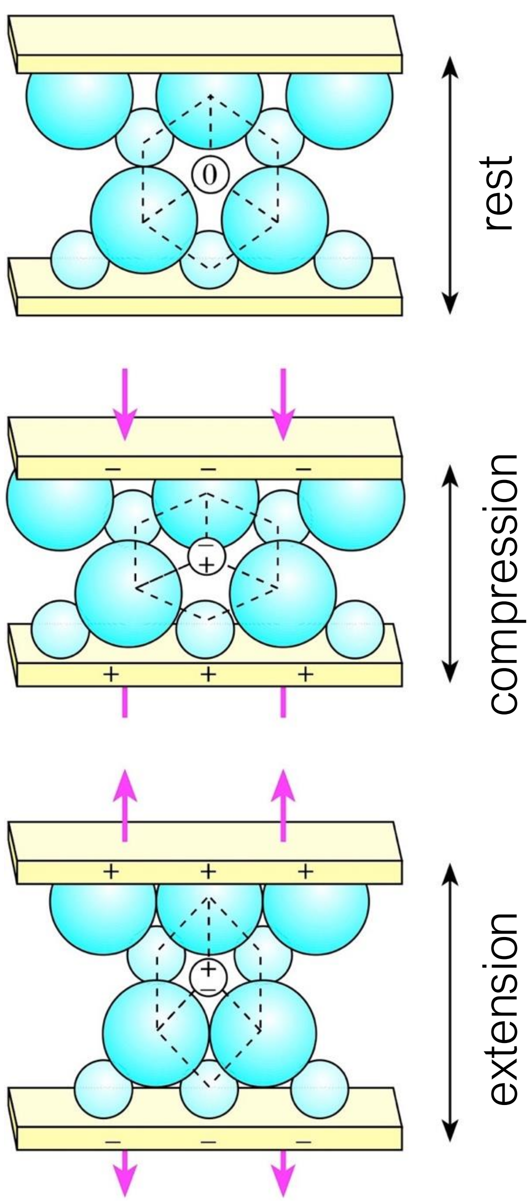


Ultrasound:

- How to generate?
- What are its properties?
- How can we use it?

Generation and detection of ultrasound: piezoelectric effect

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



Centers of + negative - charges are spatially separated.

1. **Direct piezoelectric effect**: electrical polarization (P) 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=eletric field
d=piezoelectric coefficient

Application: generation of ultrasound

Resonance: frequency of alternating voltage = Eigen (resonance) frequency of the crystal (>1 MHz).

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

Shape and size of the ultrasound transducers vary with applications.

Properties of ultrasound I: propagation

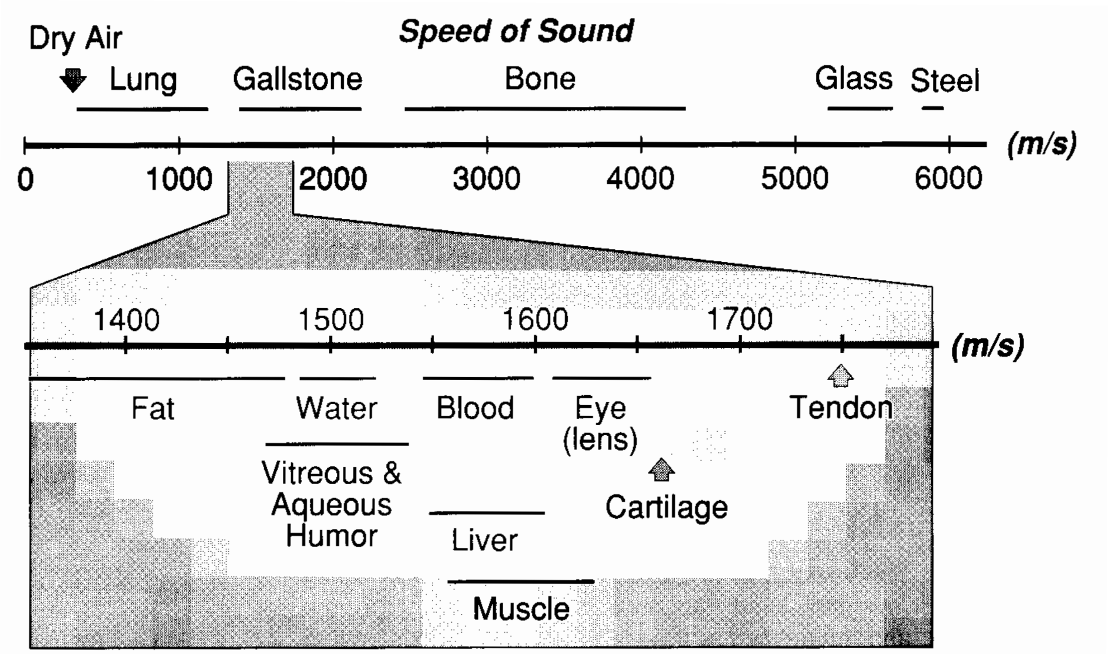
Condition: elastic medium!

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

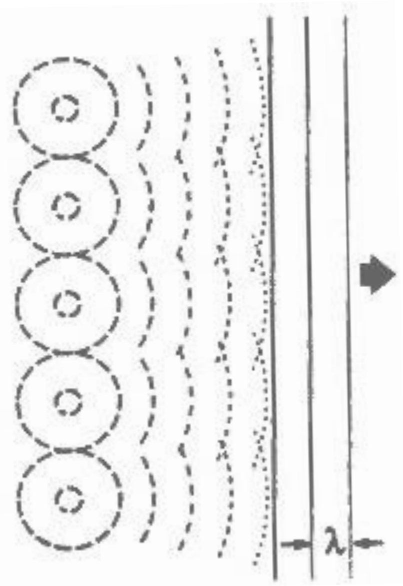
US propagates solely as a longitudinal wave in gases and liquids; in solids it may also propagate as a transverse wave.

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

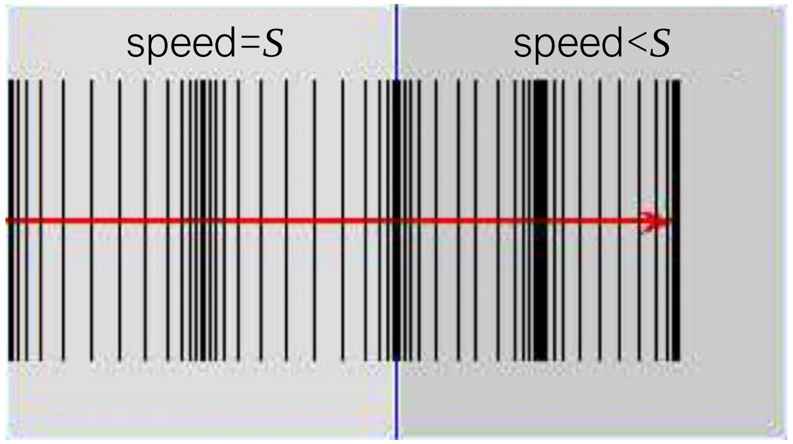
Y = Young's modulus
ρ = density of medium
k = compressibility of medium



Speed of ultrasound in different media



Formation of wavefront: based on Huygens-principle



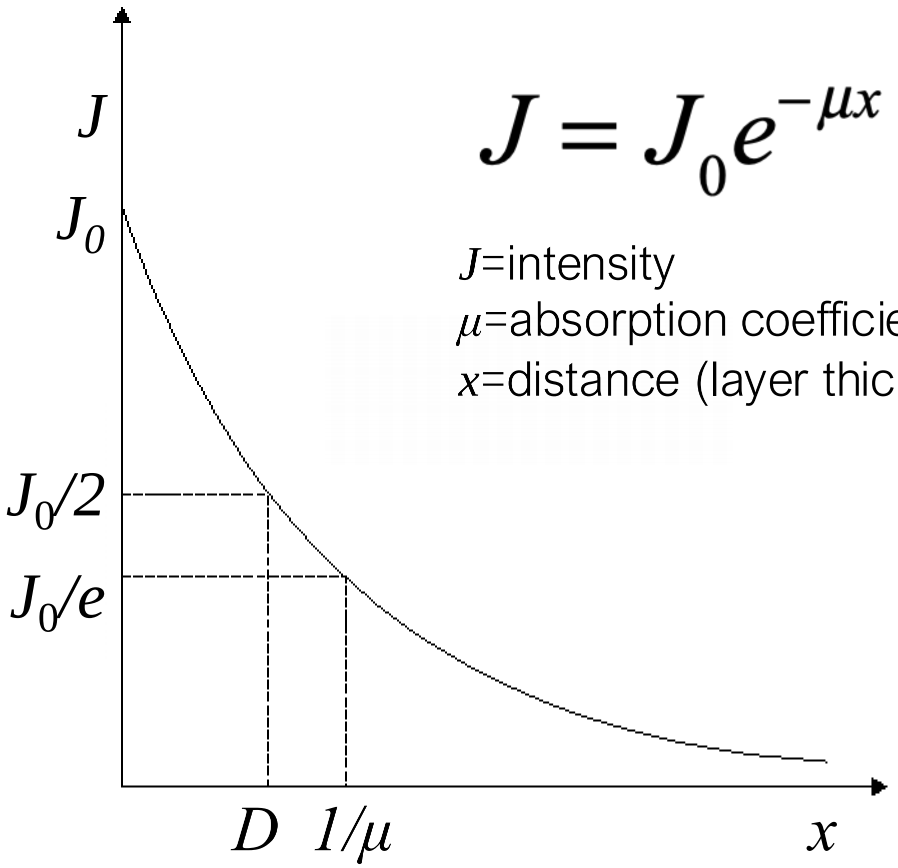
During propagation frequency is unchanged. Wavelength varies with speed.

Properties of ultrasound II: 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. rupture of interactions in viscous medium. Absorption increases with frequency.



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

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

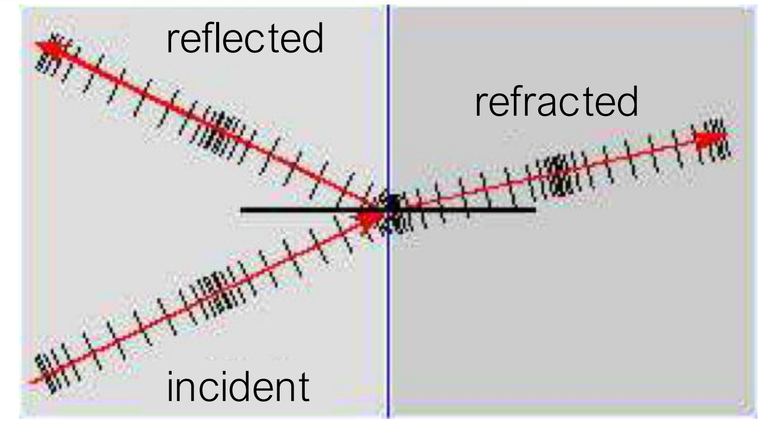
Material	D (f=1 MHz)
Air	~1 cm
Water	few m

Properties of ultrasound III: Refraction and Reflection

Refraction

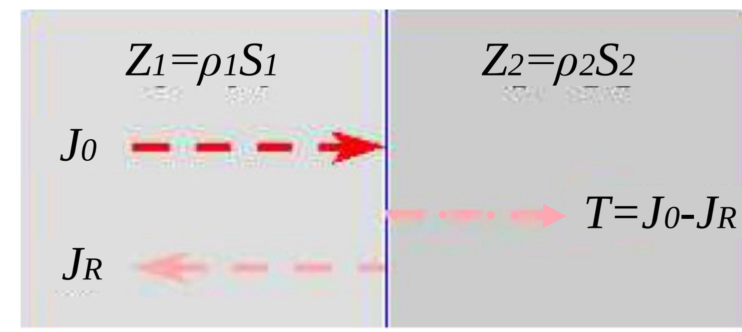
Change in the direction of propagation at surfaces bounded by media in which the speed of US propagation is different.
Refraction increases with increasing angle of incidence.
Snell's Law applies:

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



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):

$$R = \frac{J_R}{J_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

$$Z = \rho S$$

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 IV: 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.

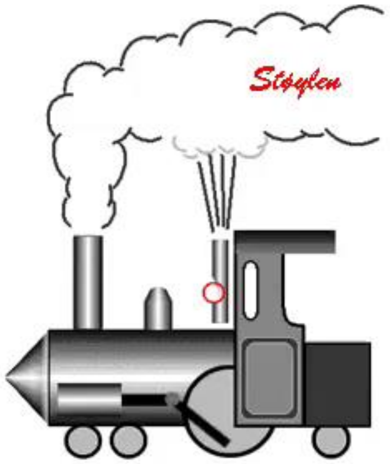
Christian Andreas Doppler
(1803 - 1853)

Frequency shift: Doppler shift

Doppler shift can be calculated:

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

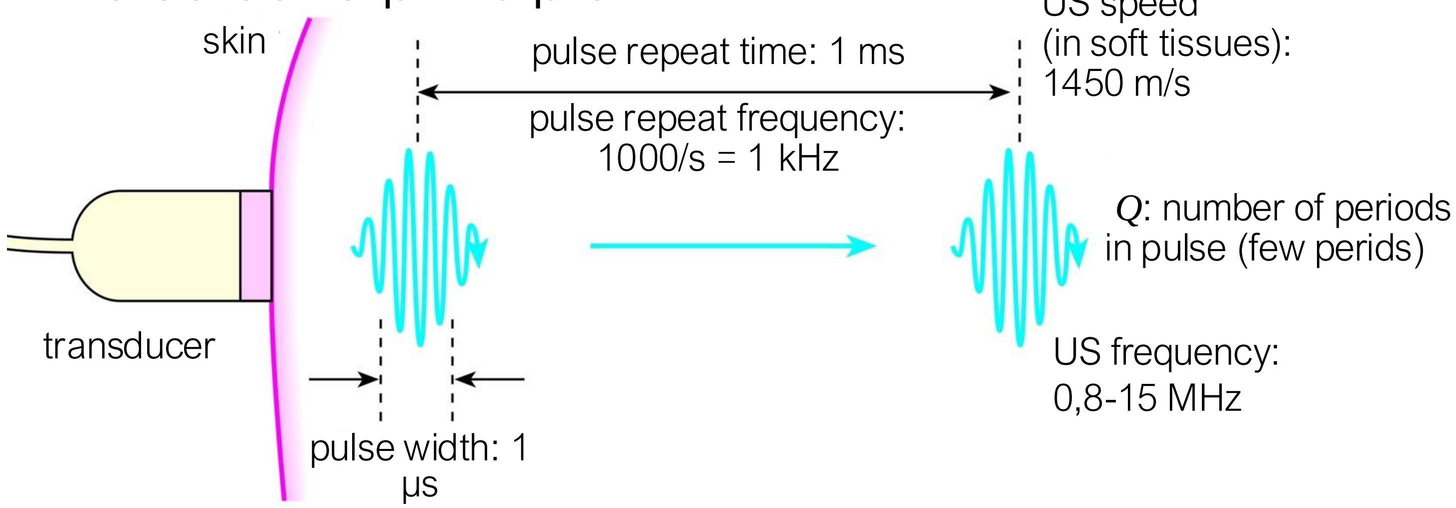
f_o: detected frequency
f_s: frequency of source
S: speed of propagation of US
v_o: speed of the observer
v_s: speed of the US source



Principles of US diagnostics

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

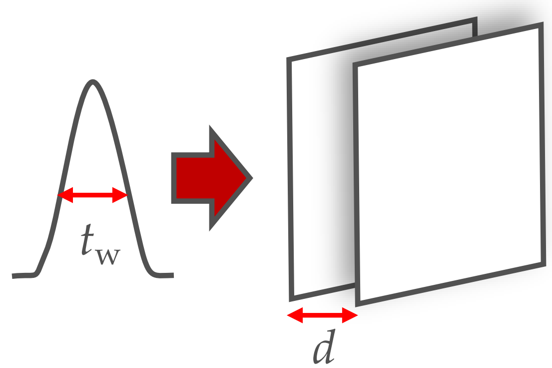


Distance measurement with ultrasound

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

D=distance between transducer and reflective surface
S=US speed in medium
T=time elapsed between pulse emision and return

2. Axial resolving power

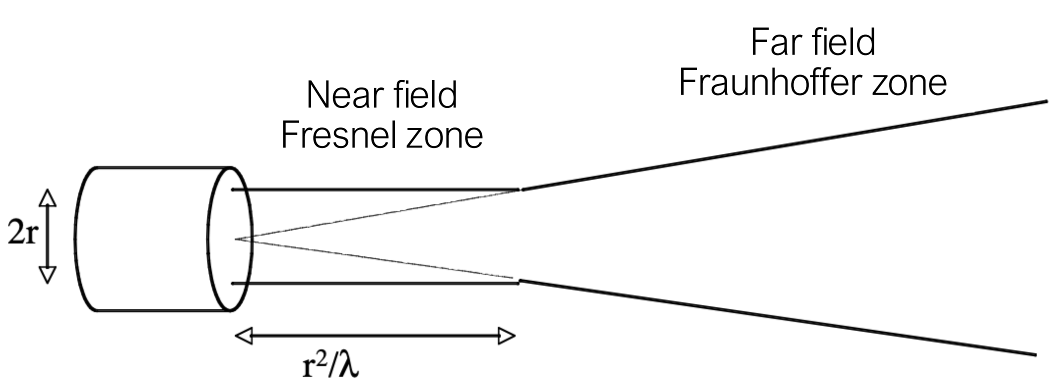


Condition of resolving smallest axial distance (d):

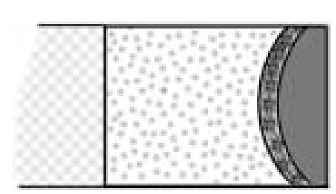
$$St_w < 2d$$

At a given f axial resolution increases with decreasing Q.
At a given Q axial resolution increases with increasing f.

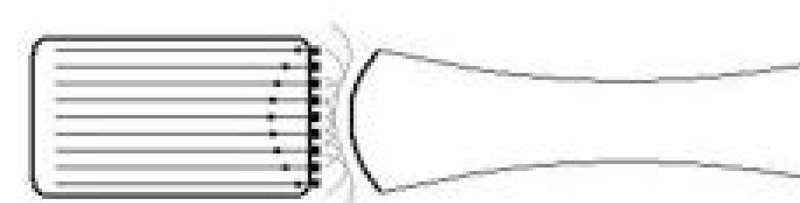
3. Ultrasound beam



Upon increasing f the Fresnel zone increases, divergence decreases: the beam may be better focused. Focusing can be achieved with US **lens** or controlled **phase shifts**.



acoustic lens



phase array

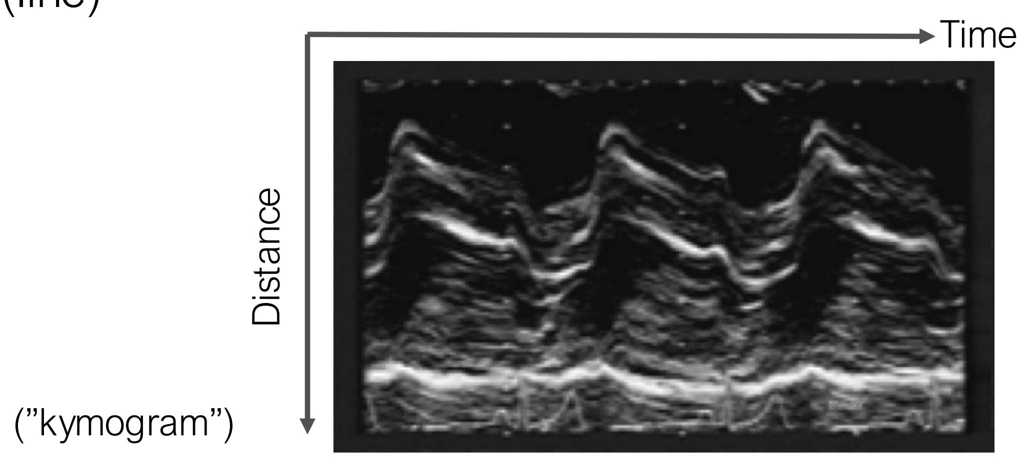
US imaging modes I.

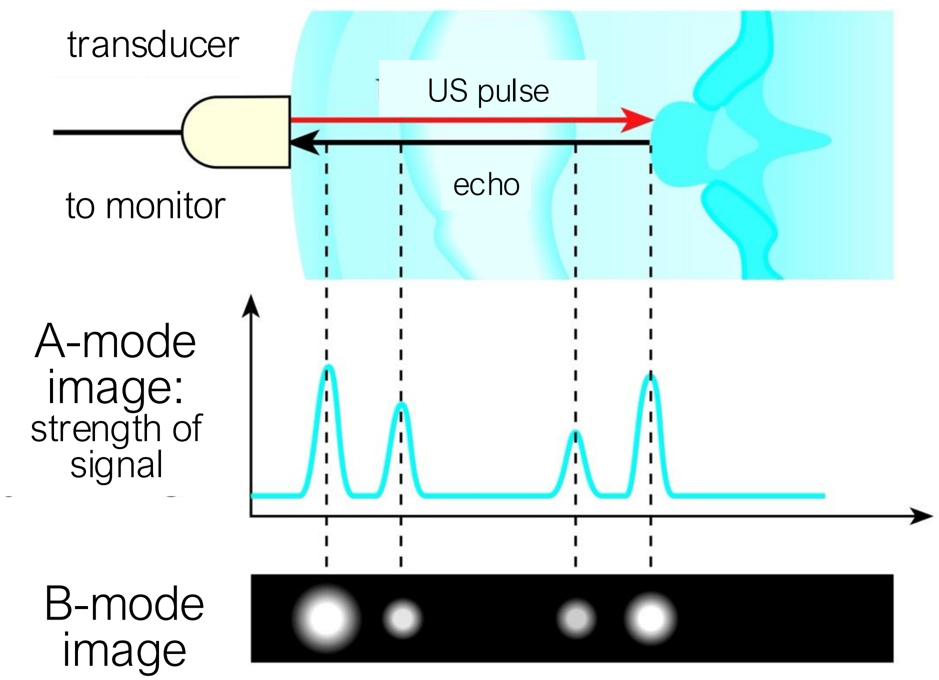
One-dimensional US

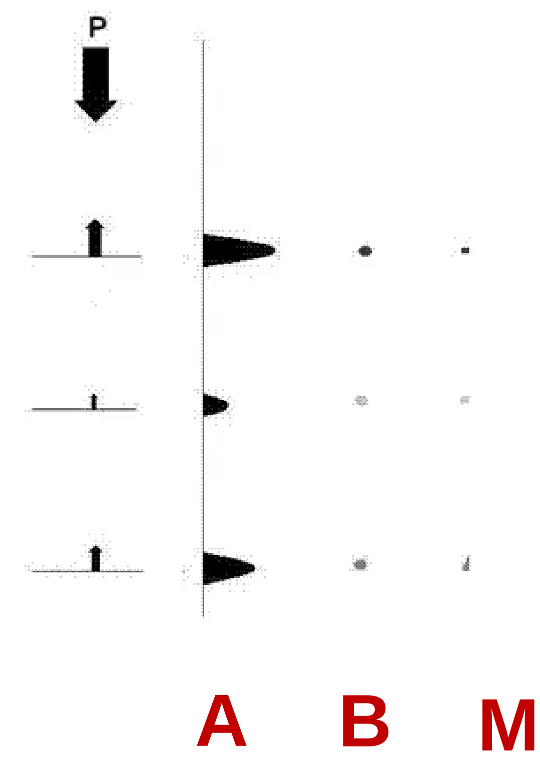
A-mode (<u>A</u>mplitude-modulated):
Single transducer; beam propagates along a single line. The echo is detected as a voltage pulse on an oscilloscope.

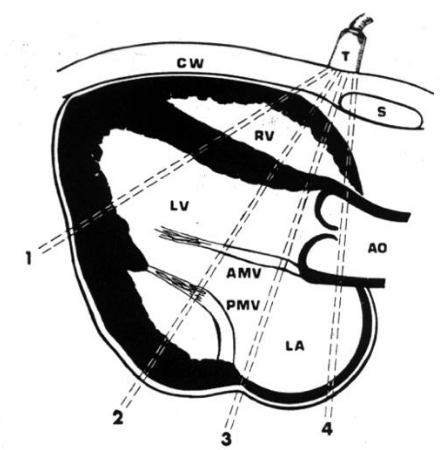
B-mode (<u>B</u>rightness):
Voltage pulses are displayed as points of varying gray level. Grayscale density is proportional to voltage amplitude: the greater the voltage the brighter the point and *vice versa*.

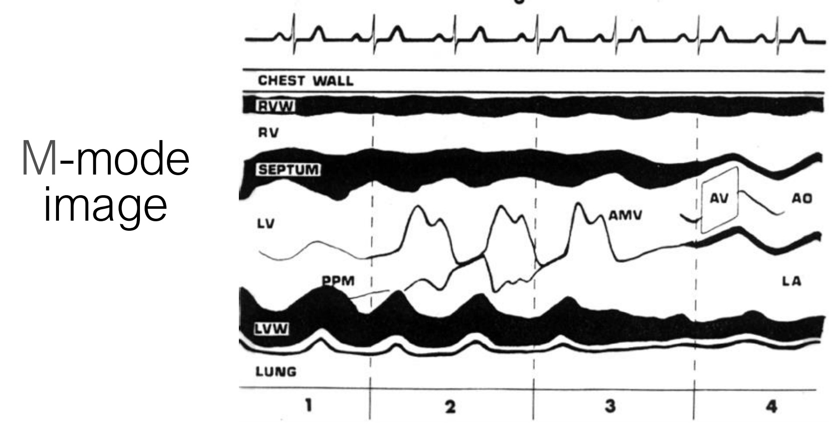
M-mode (time <u>M</u>otion): Displays periodic motions as a function of time (e.g., echocardiography). X-axis: time. Y-axis: 1-dimensional B-mode image (line)









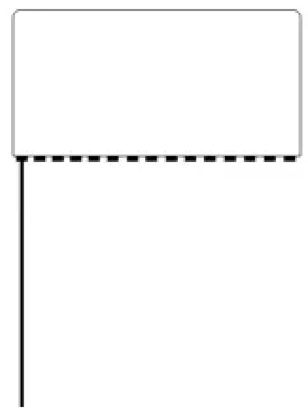


US imaging modes II.

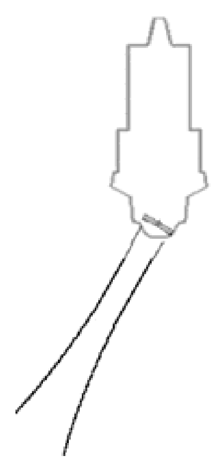
Two-dimensional B-mode (Brightness)

Scanning carried out in two dimensions

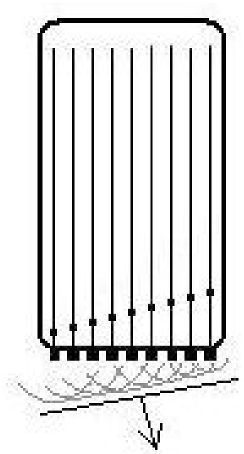
“Linear array“
(hundreds of small piezo crystals arranged linearly)



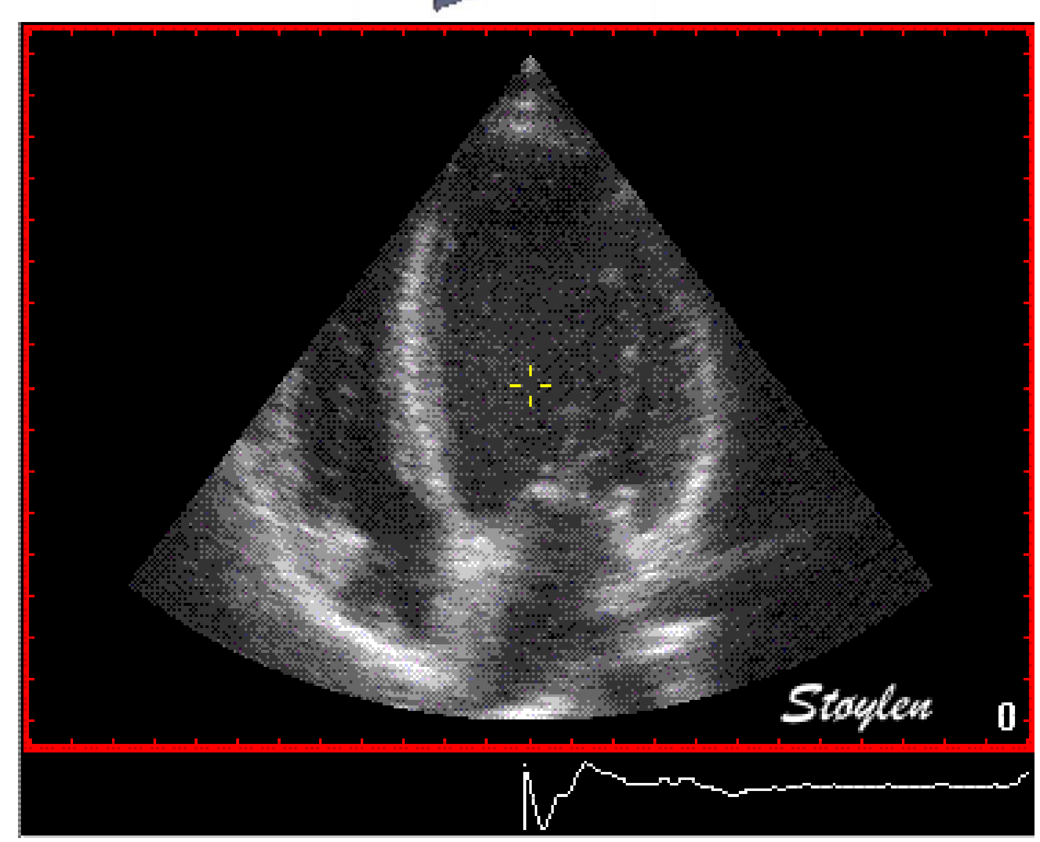
Mechanical scanning
(single piezo crystal rotated)



Electronic scanning
(phase array)



With fast scanning, real-time images may be recorded

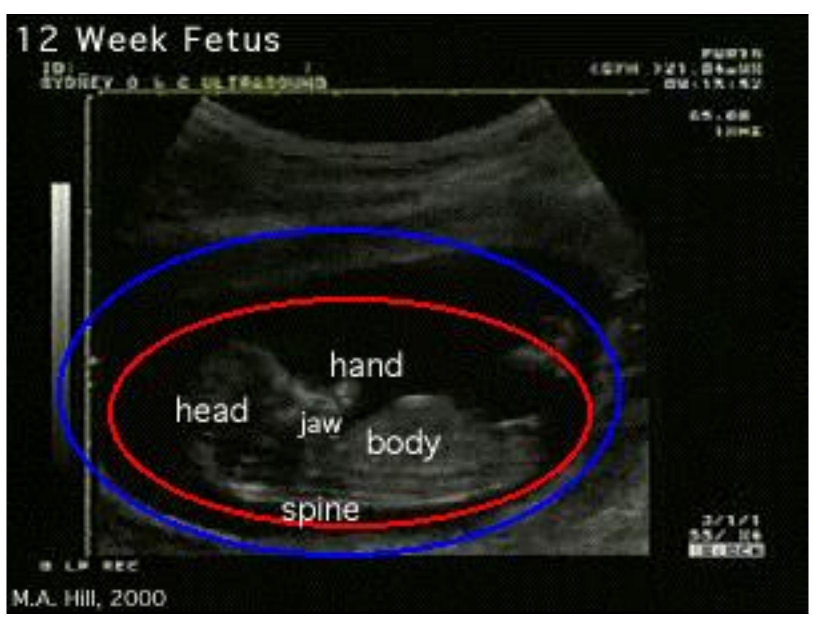


2D B-mode US in Obstetrics

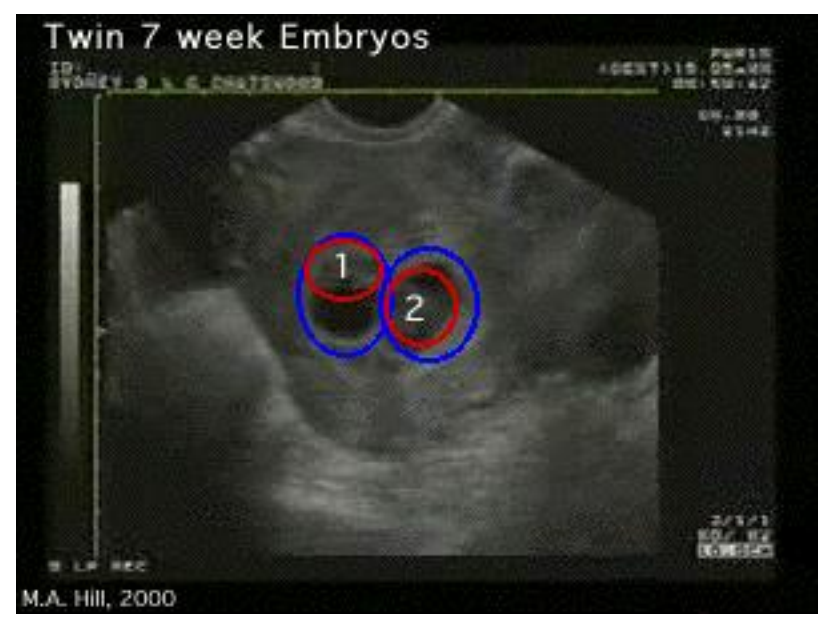
Gestational age, developmental pathology, placenta position, fetus position.

Biparietal diameter

Femur length



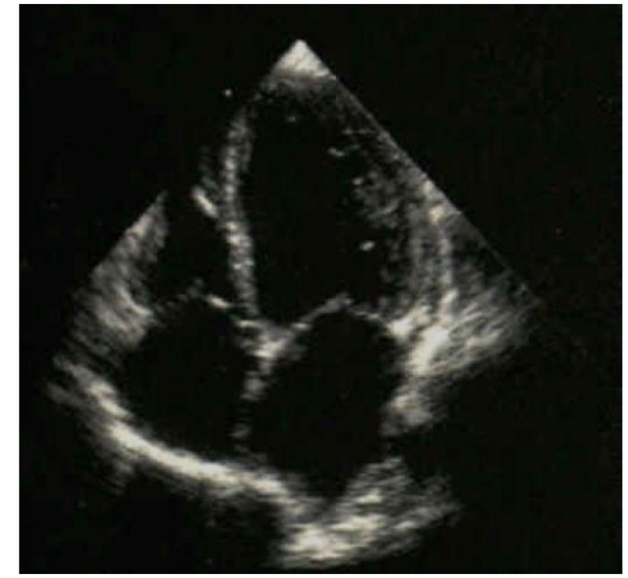
12-week fetus



7-eek twin pregnancy

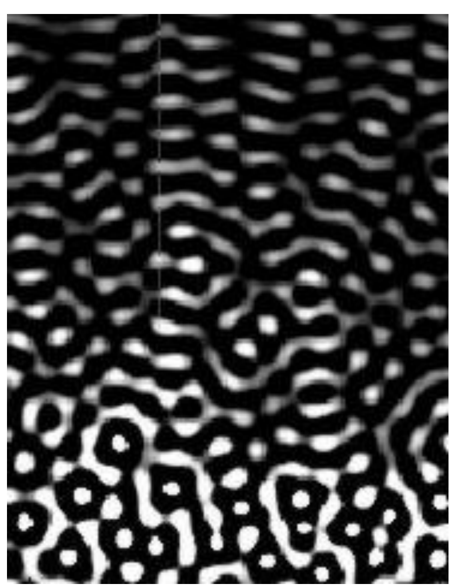
2D B-mode US in cardiolgy

Apical position

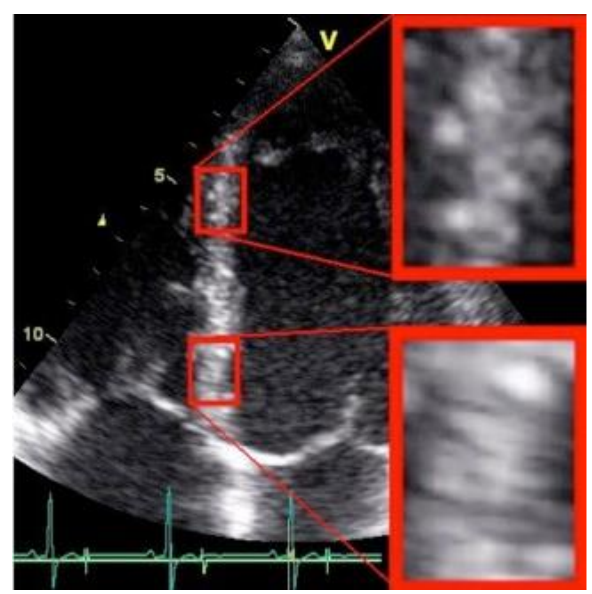


Left parasternal longitudinal position

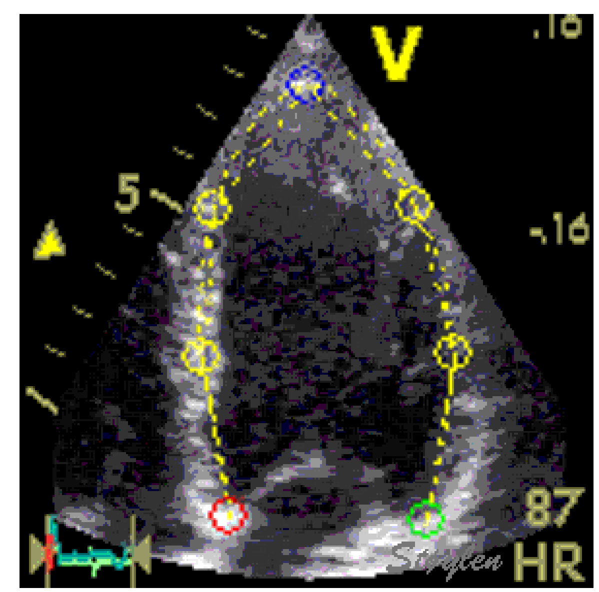
Speckle tracking



US interference pattern



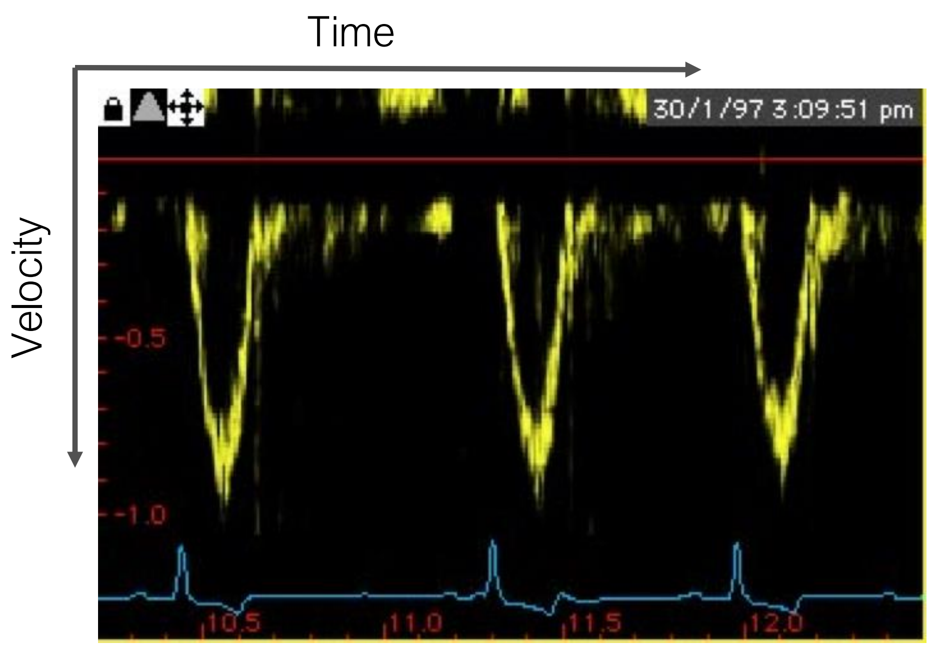
Pattern is stable and may be followed



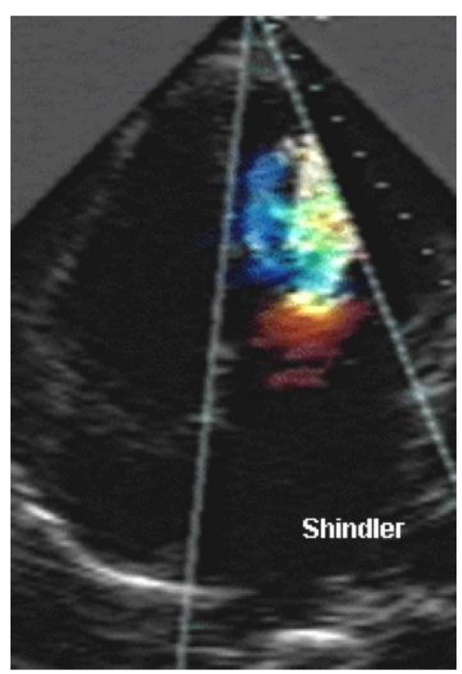
Following speckles with image analysis algorithms

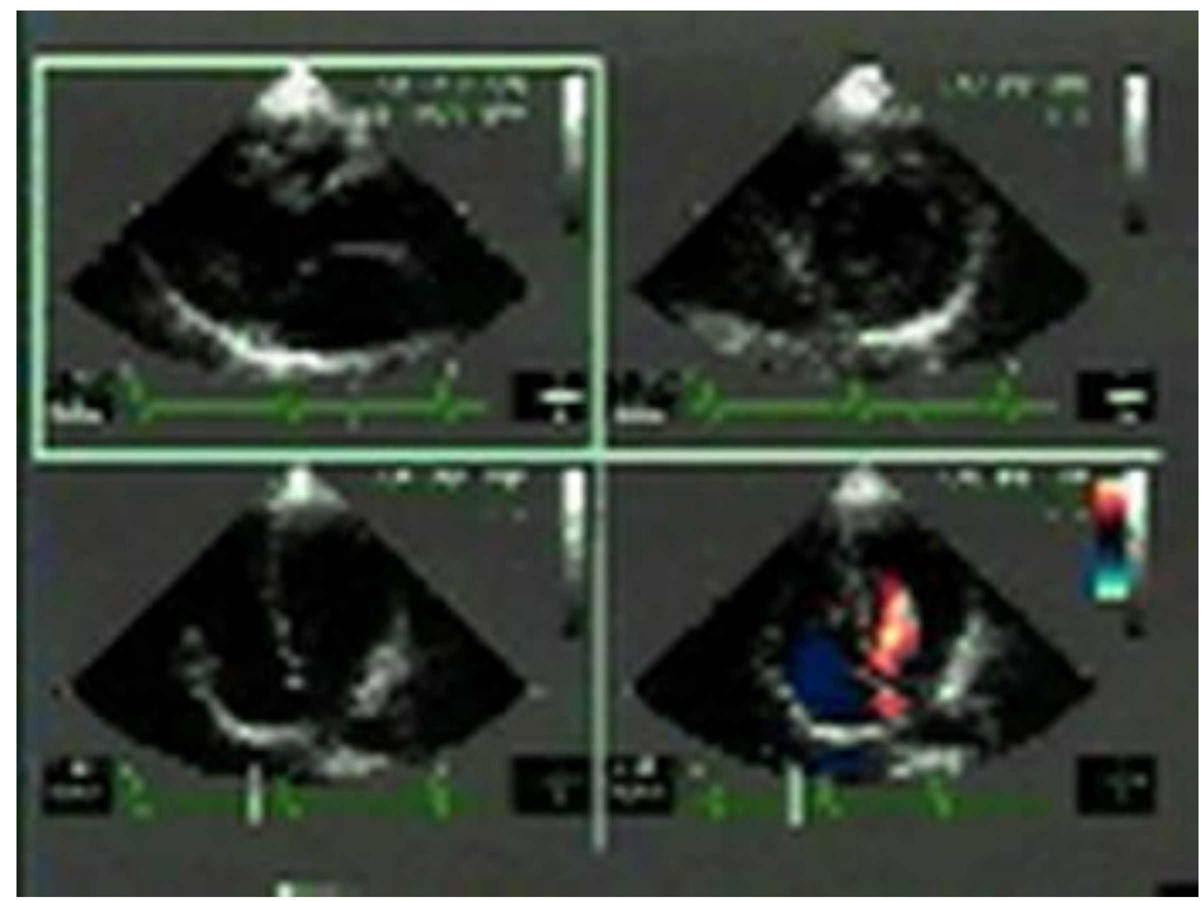
Doppler cardiography

The direction and velocity of blood flow can be displayed.



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





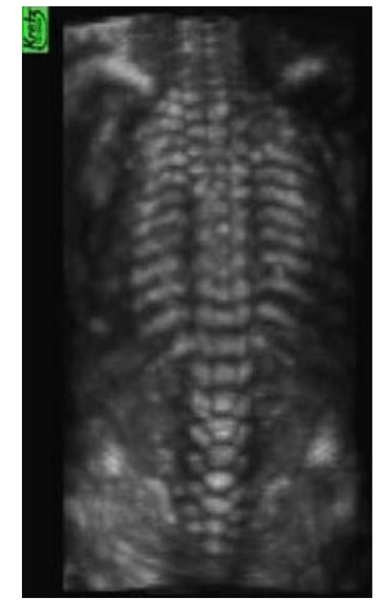
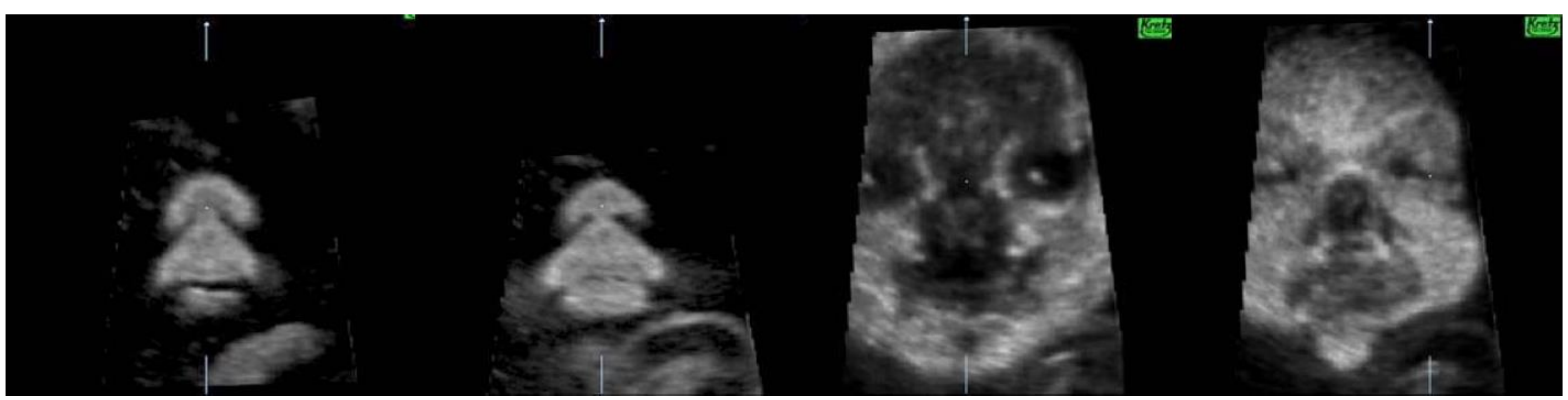
BART: Blue Away Red Towards

US imaging modes III.

Three-dimensional B-mode (Brightness)

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



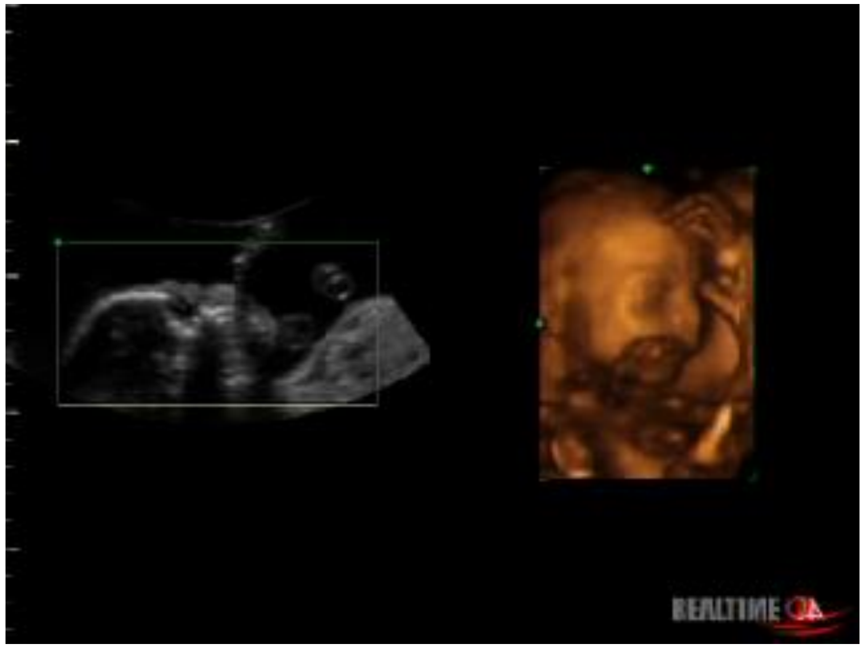

The spatially resolved images may be presented and manipulated at will.

US imaging modes IV.

Four-dimensional B-mode (Brightness): time-resolved 3D US







Therapeutic applications of ultrasound

The therapeutic applications of US deped on its physical effects

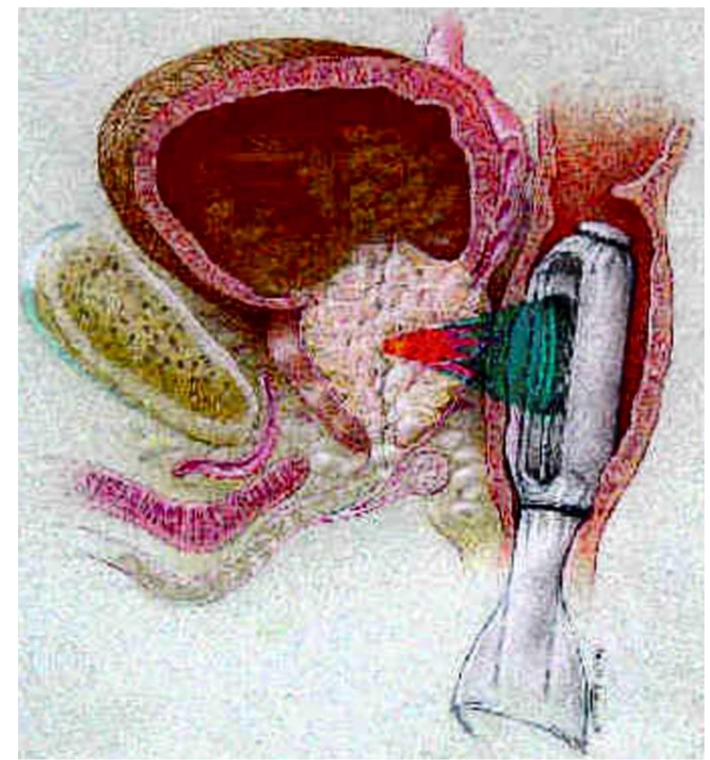
1. Local heating

2. Micromassage

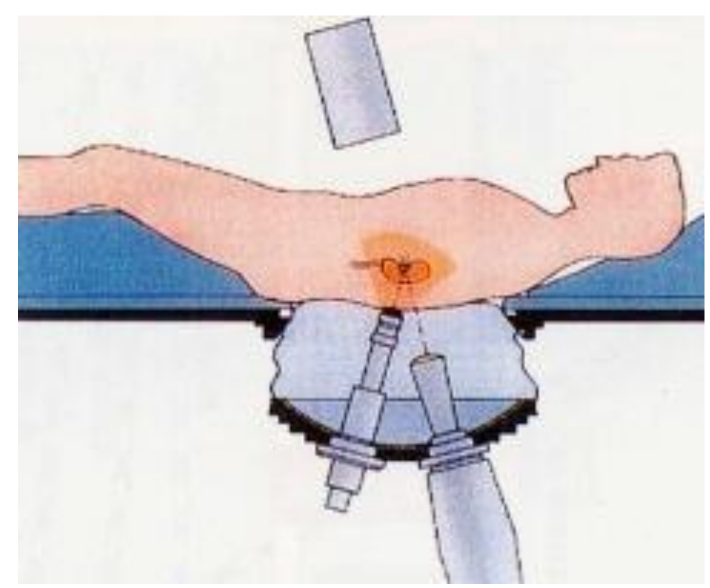
3. High Intensity Focused Ultrasound (HIFU):
Crushing of prostate tumors

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

4. Physical therapy



HIFU



ESWL

Feeedback

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