

# Ultrasound

Generation, properties, applications

Medical Biophysics II. 4 March, 2026

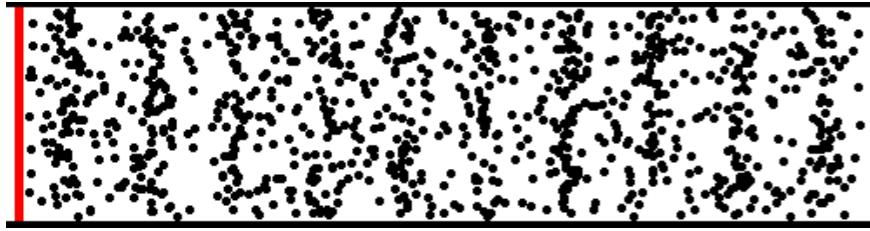
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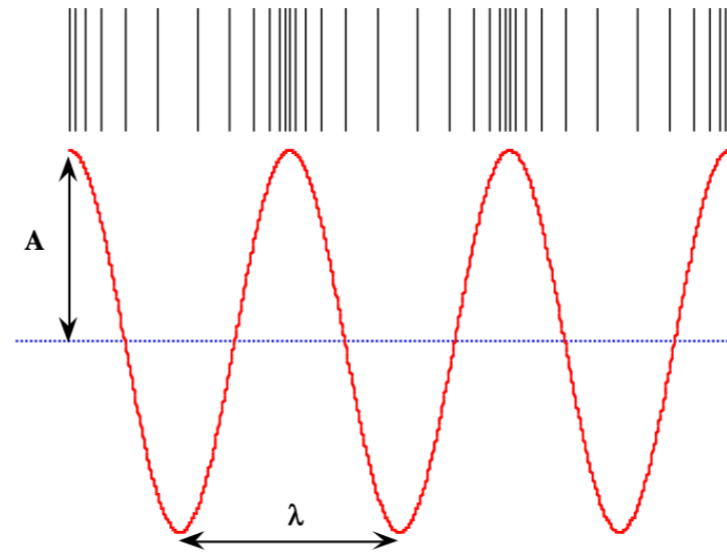


**SEMMELWEIS**  
EGYETEM 1769

# Ultrasound is a longitudinal wave

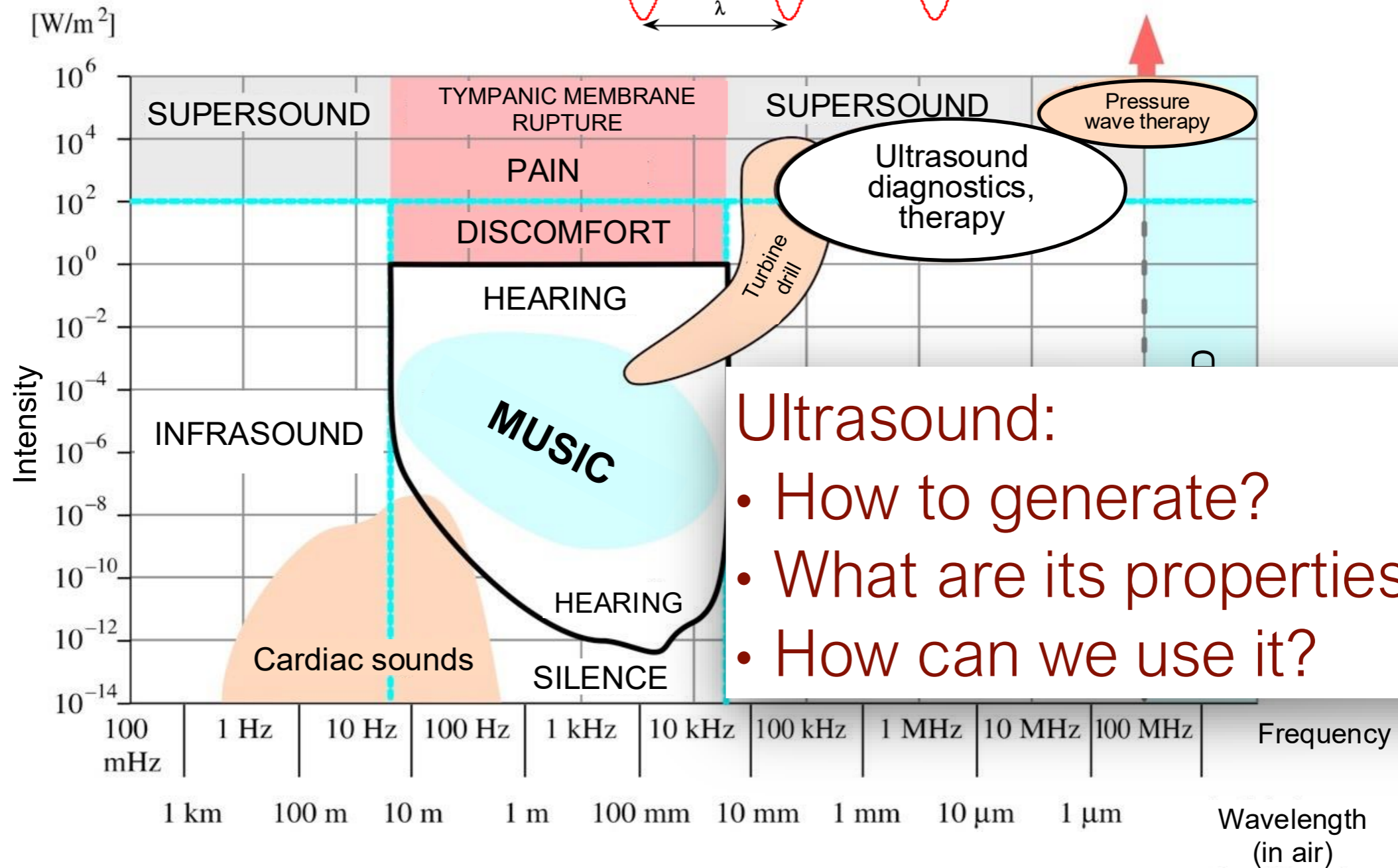


Mechanical wave (pressure wave), propagates in elastic medium



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

$y$  = actual pressure;  $t$  = time  
 $f$  = frequency (Hz);  $A$  = amplitude  
 $\varphi$  = phase shift;  $\lambda$  = wavelength

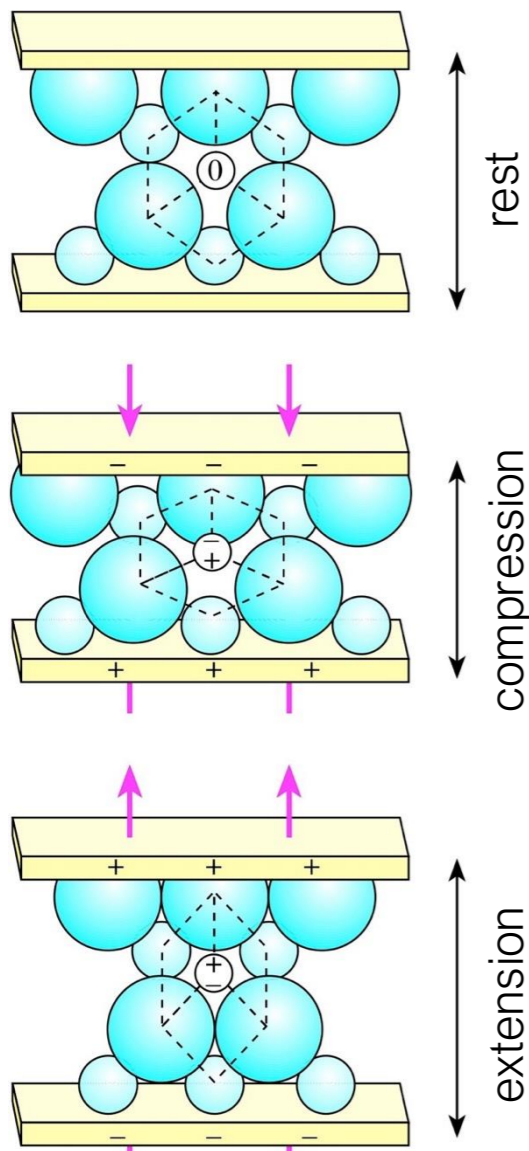


## Ultrasound:

- 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:

Application: detection of ultrasound, piezoelectric lighter

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

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



Up to kV voltage!

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

Application: generation of ultrasound

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

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

$\Delta l/l$ =strain  
 $E$ =electric field  
 $d$ =piezoelectric coefficient

"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 ( $S, v, c$ ):

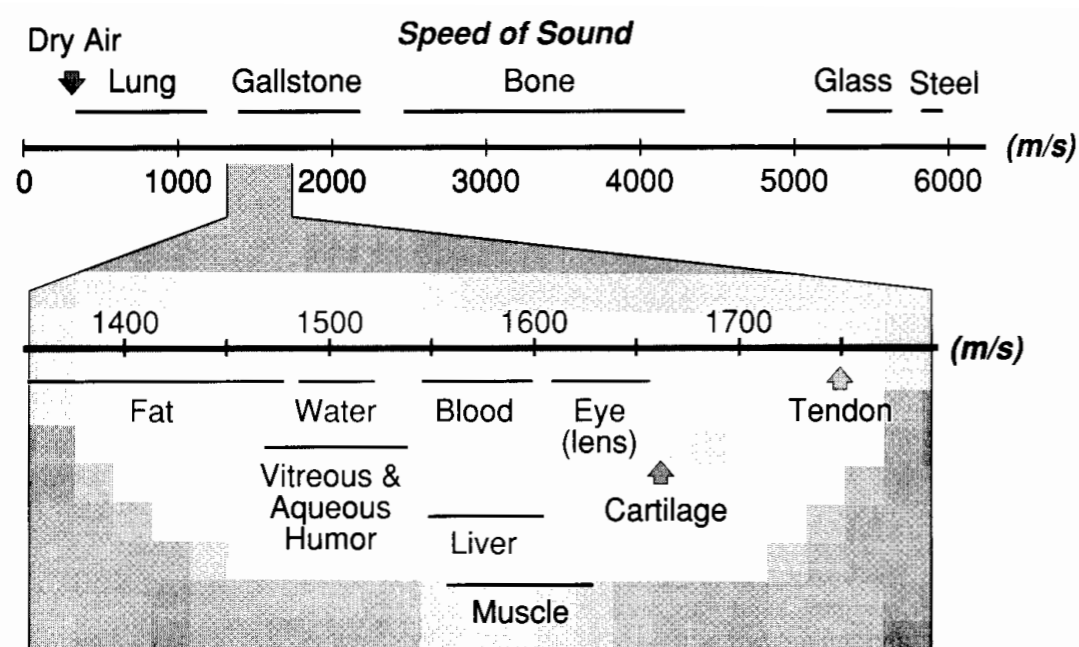
$$S = f\lambda = \frac{\lambda}{T}$$

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

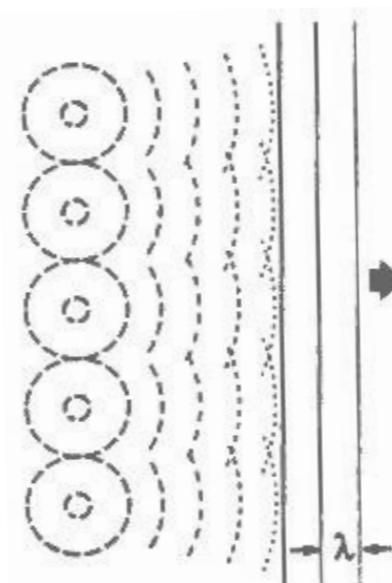
Speed depends on the properties of the medium:

$$S = \sqrt{\frac{Y}{\rho}} = \sqrt{\frac{1}{k\rho}}$$

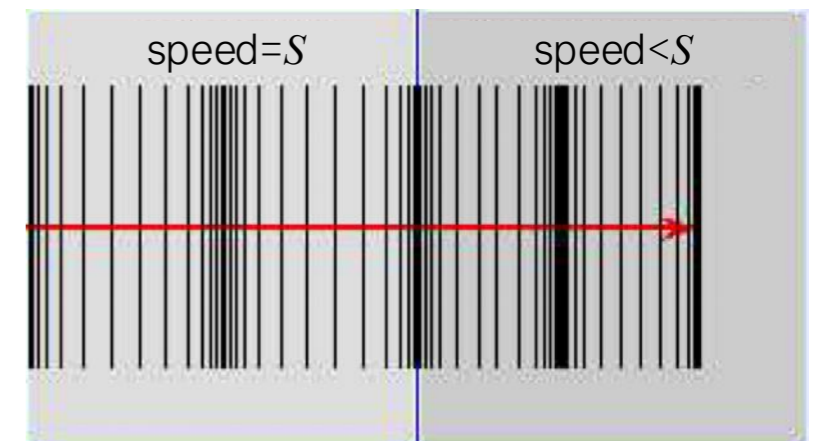
$Y$  = Young's modulus  
 $\rho$  = density of medium  
 $k$  = compressibility of medium



Speed of ultrasound in different media



Formation of wavefront: based on Huygens-principle

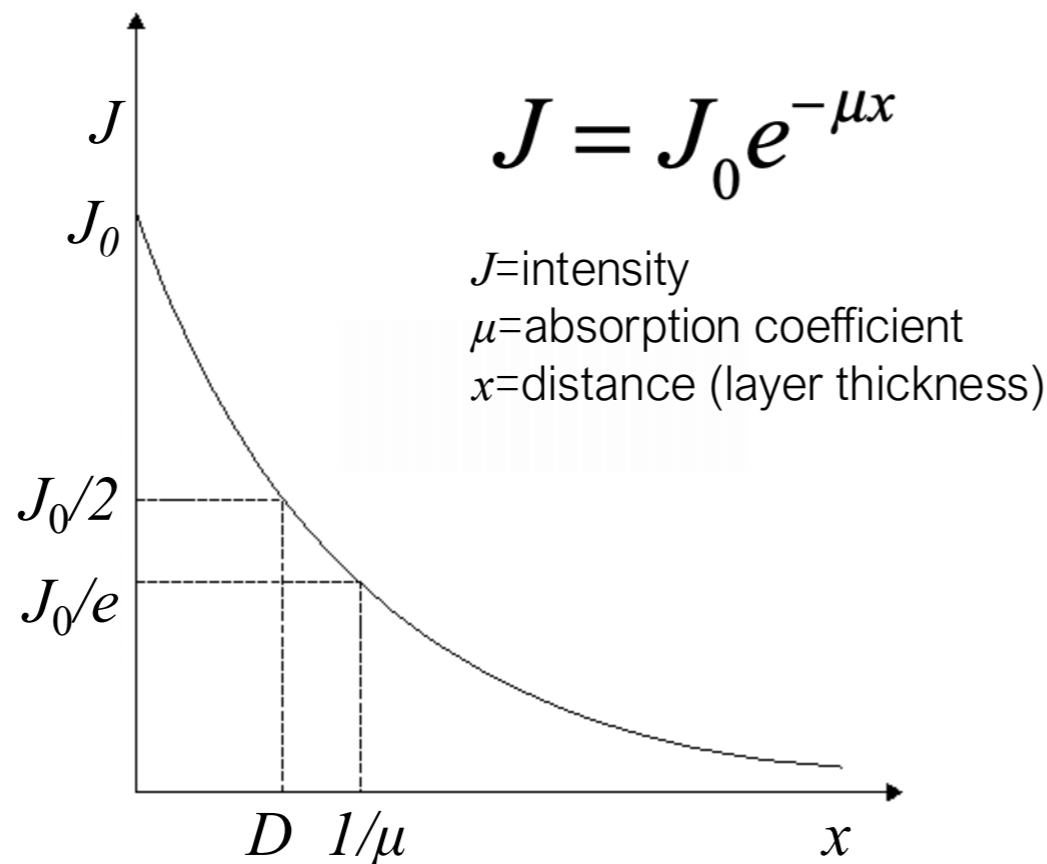


During propagation frequency is unchanged. Wavelength varies with speed.

# 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.



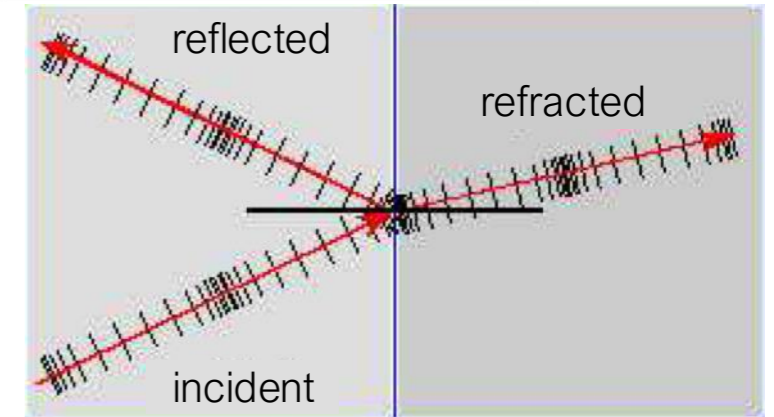
Material	$D$ ( $f=1$ MHz)
Air	~1 cm
Water	few m

# Properties of ultrasound III: Refraction and Reflection

## Refraction

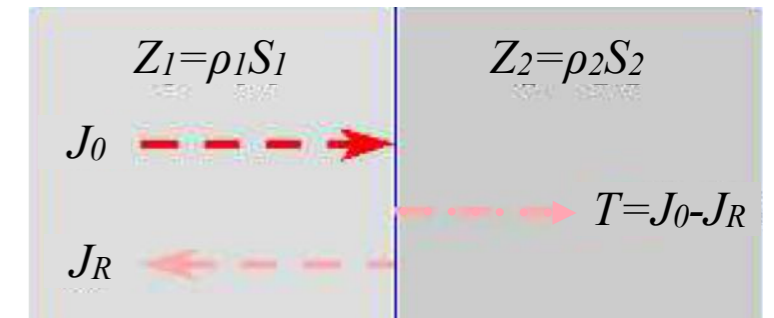
Change in the direction of propagation at surfaces bounded by media in which the speed of US propagation is different. Refraction increases with increasing angle of incidence. Snell's Law applies:

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



## 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):

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

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.

Frequency shift: Doppler shift

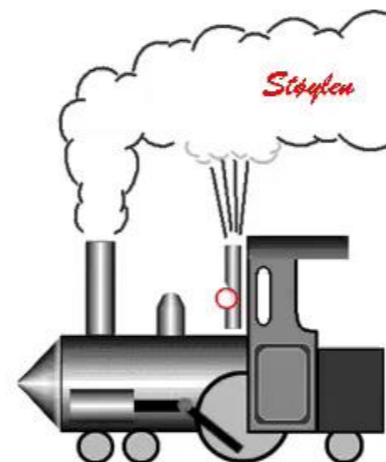
Doppler shift can be calculated:

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

$f_o$ : 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



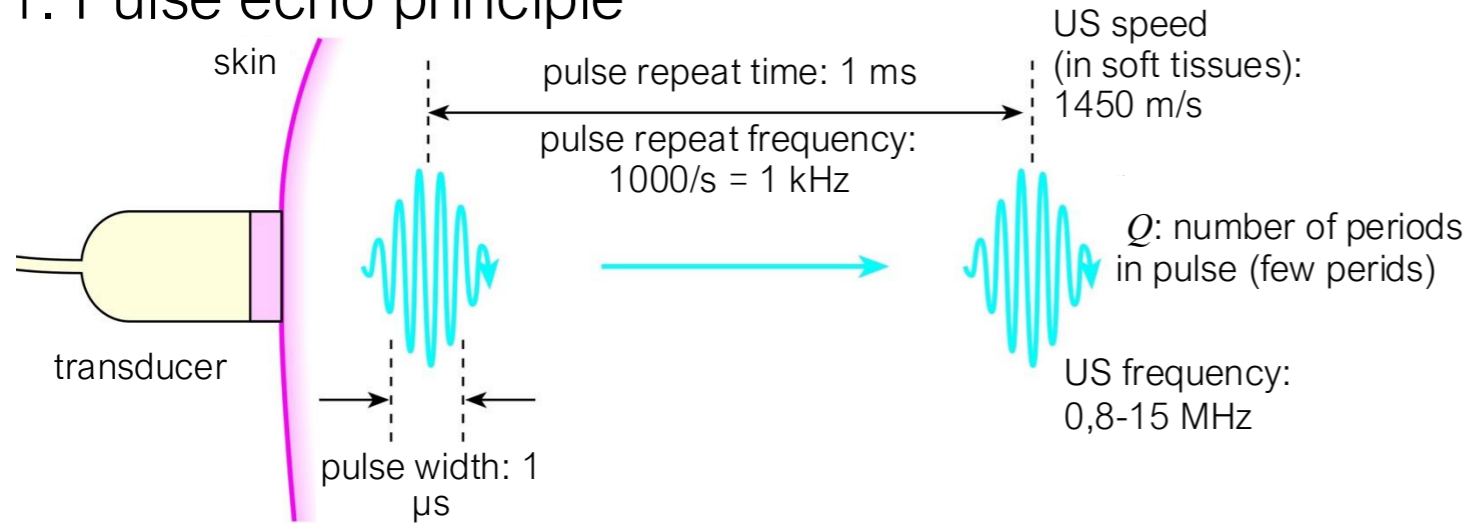
Christian Andreas Doppler  
(1803 - 1853)



# 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

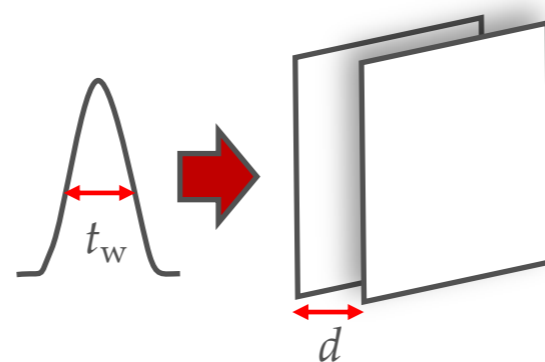


Distance measurement with ultrasound

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

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

## 2. Axial resolving power

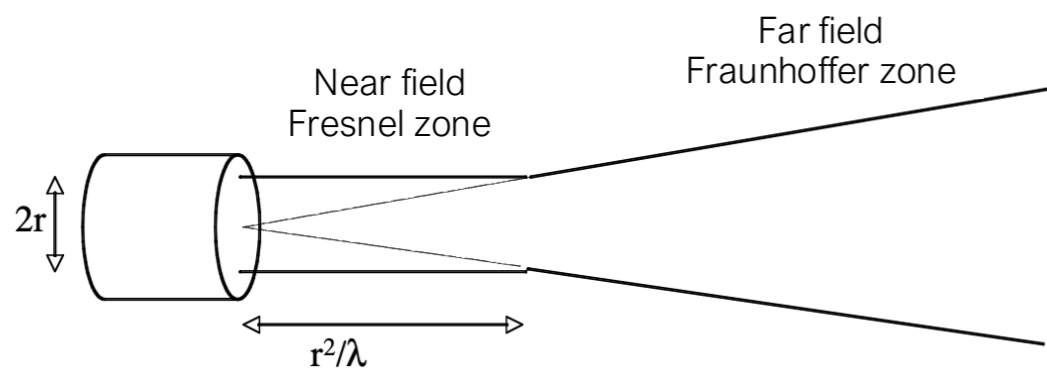


Condition of resolving smallest axial distance ( $d$ ):

$$St_w < 2d$$

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

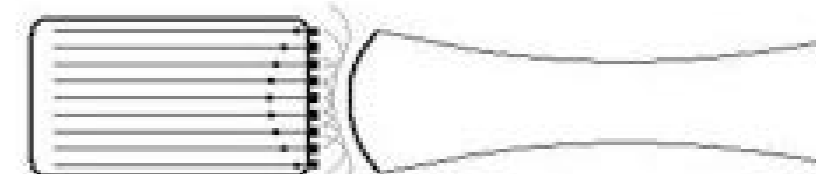
## 3. Ultrasound beam



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

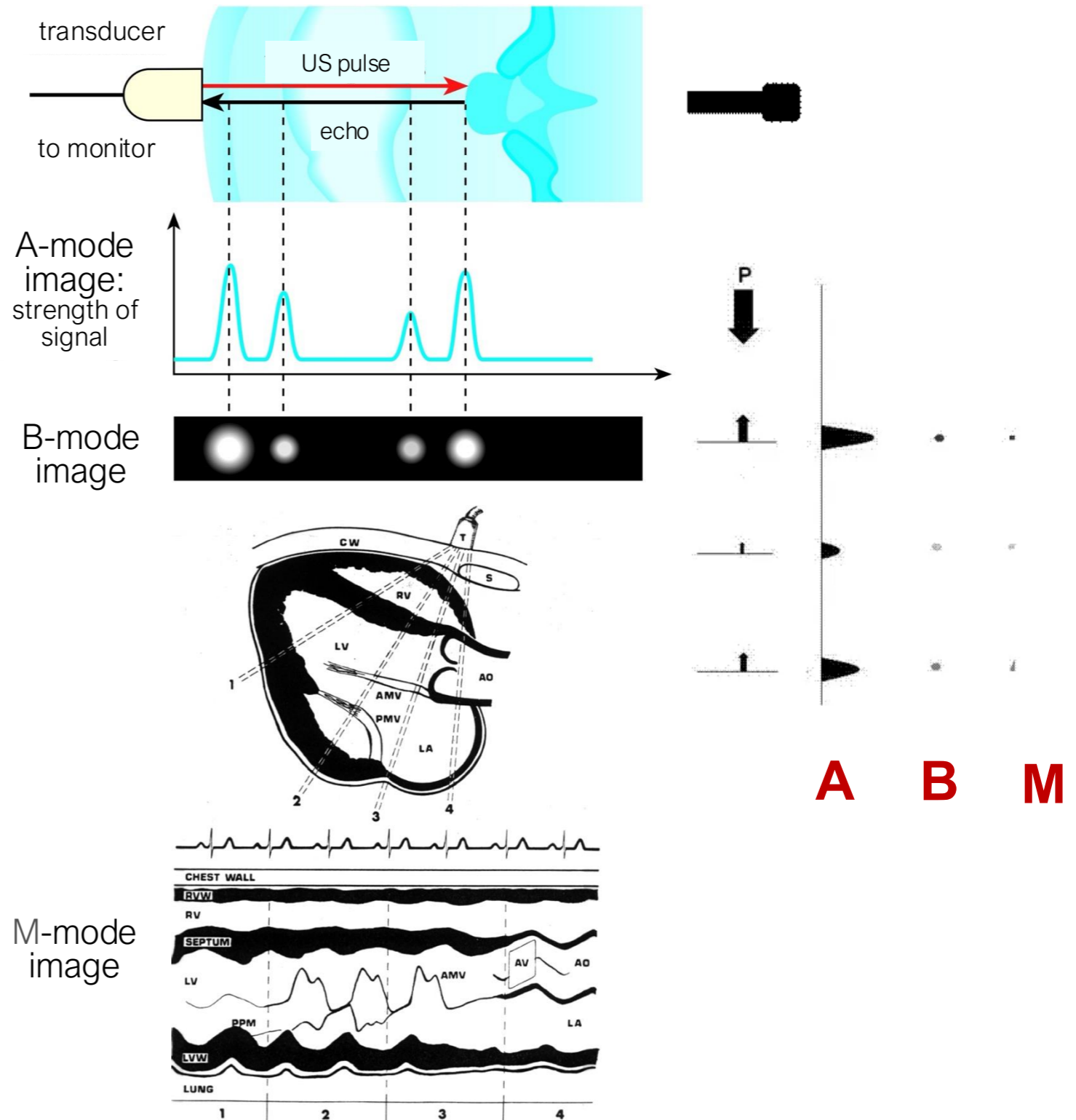
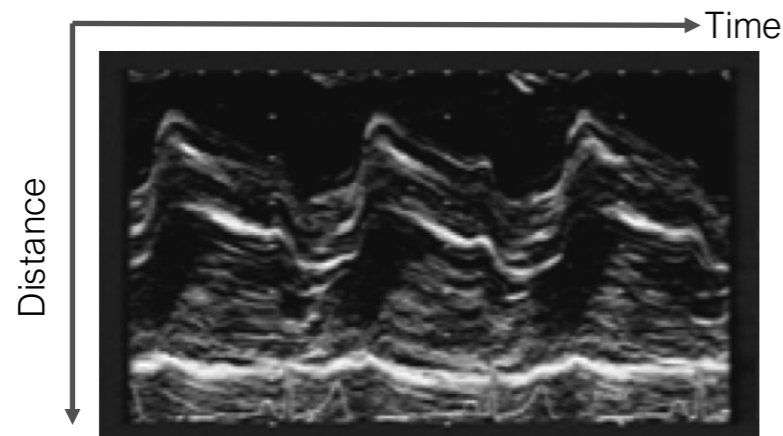
### A-mode (Amplitude-modulated):

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*.

**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)



# US imaging modes II.

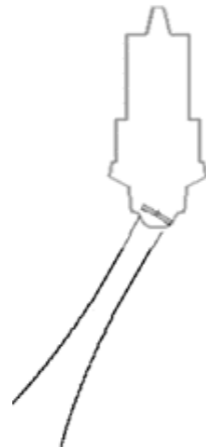
## Two-dimensional B-mode (Brightness)

Scanning carried out in two dimensions

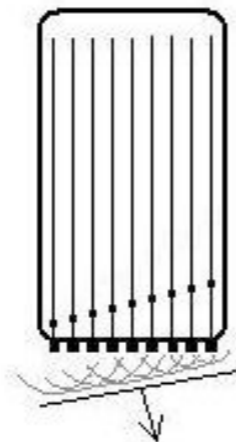
“Linear array”  
(hundreds of small piezo crystals arranged linearly)



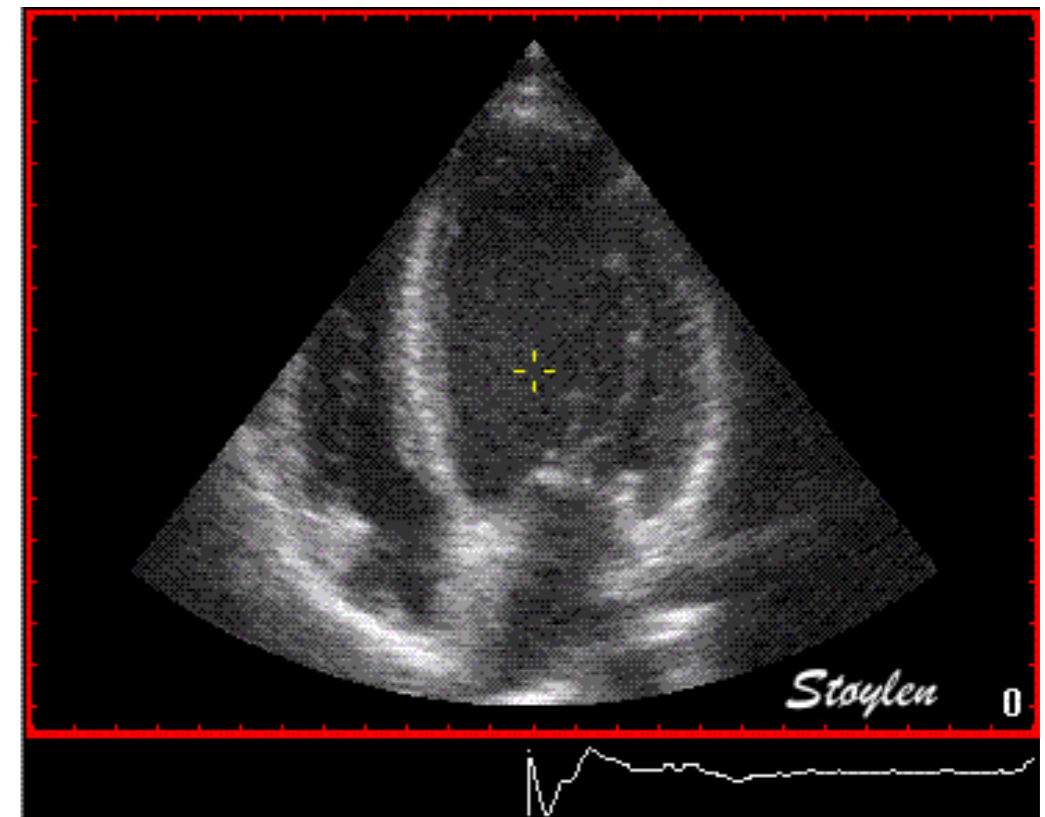
Mechanical scanning  
(single piezo crystal rotated)



Electronic scanning  
(phase array)



With fast scanning, real-time images may be recorded

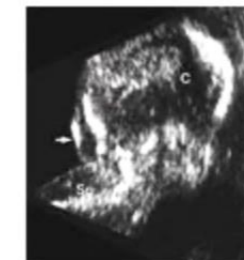


# 2D B-mode US in Obstetrics

Gestational age, developmental pathology, placenta position, fetus position

„Genetic” ultrasound:  
Analysis of the morphological features associated with genetic diseases and chromosome aberrations

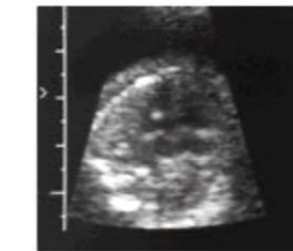
21 trisomy (Down syndrome)



Nuchal thickening



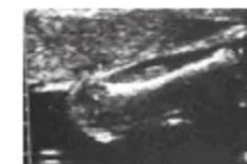
Mild ventricular dilatation



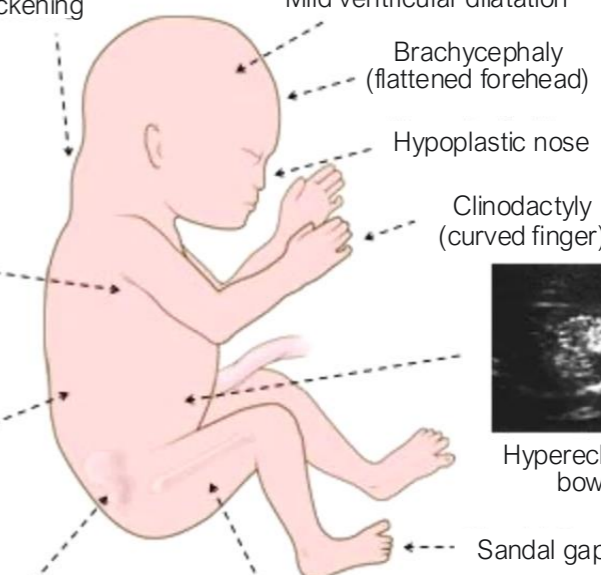
Hyperechogenic intracardiac reflections



Pyelectasis (dilatation of renal pelvis)



Short limbs



Brachycephaly (flattened forehead)

Hypoplastic nose

Clinodactyly (curved finger)



Hyperechogenic bowels

Sandal gap

Widened pelvis



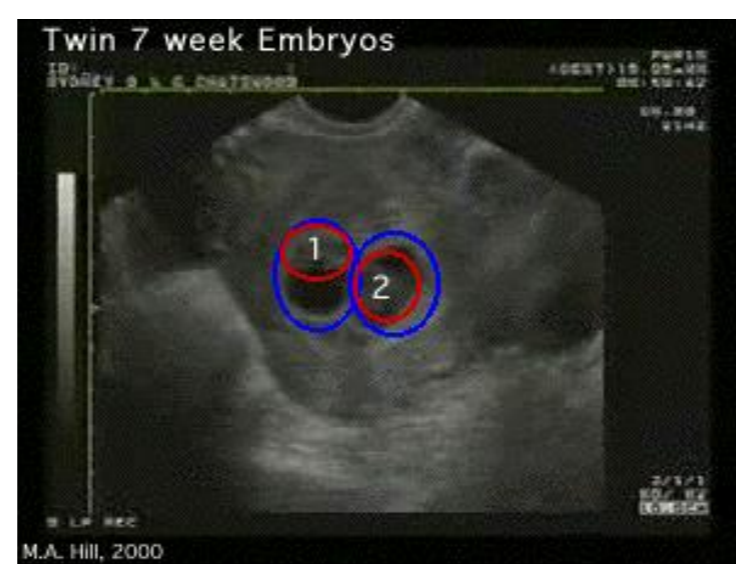
Biparietal diameter



Femur length



12-week fetus



7-week twin pregnancy

# 2D B-mode US in cardiology

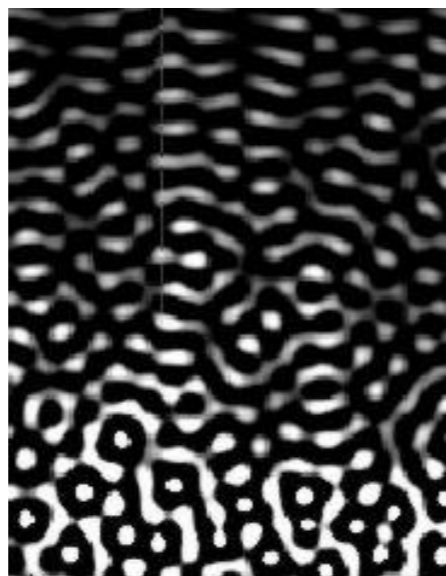
Apical position



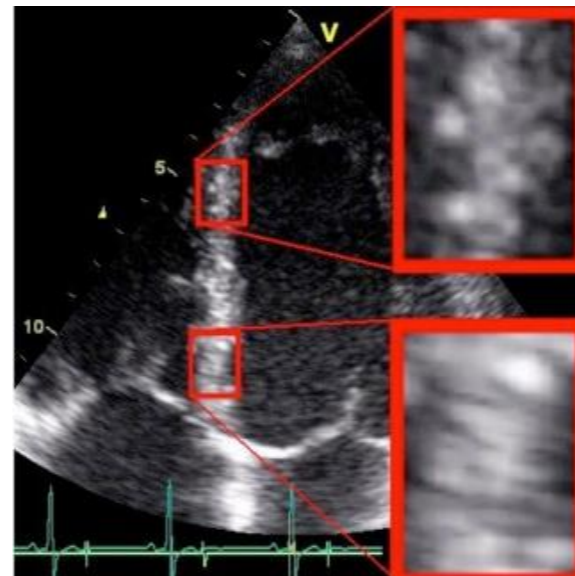
Left parasternal longitudinal position



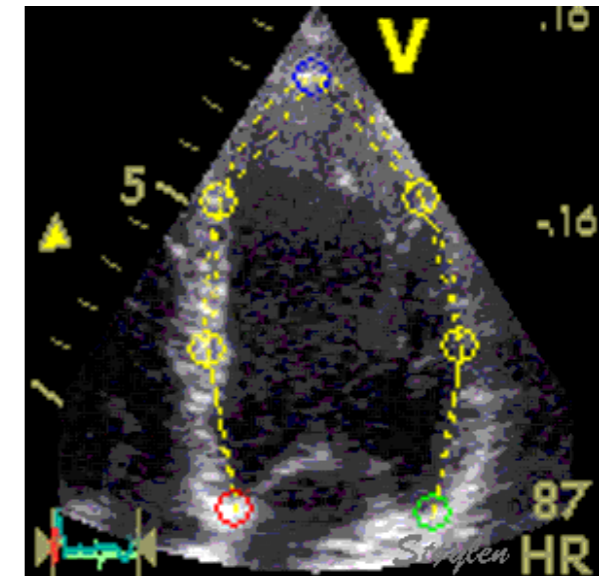
Speckle tracking



US interference pattern



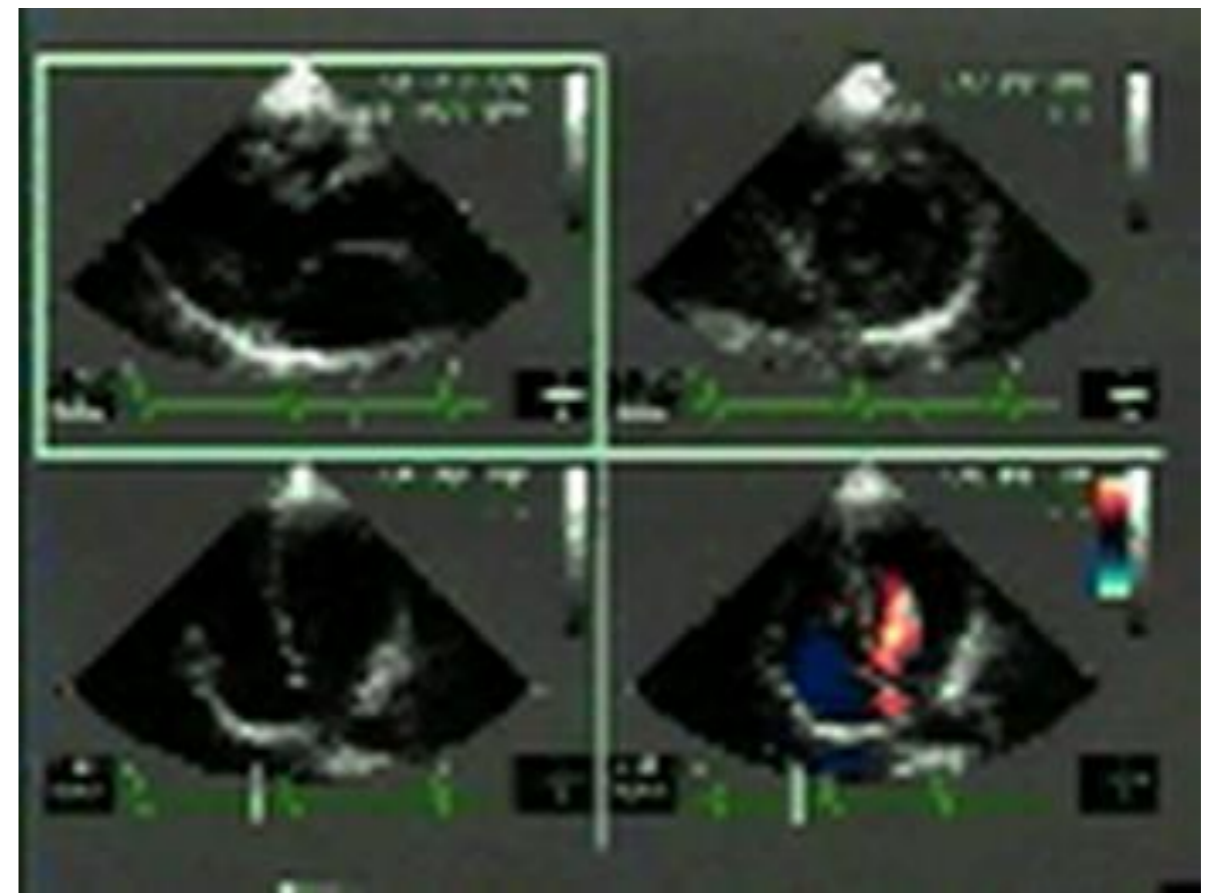
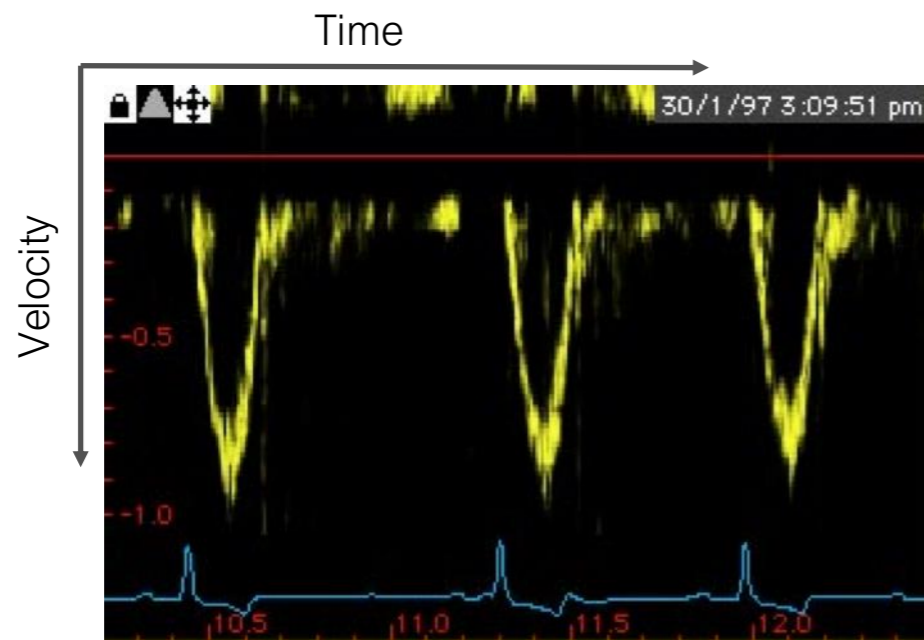
Pattern is stable and may be followed



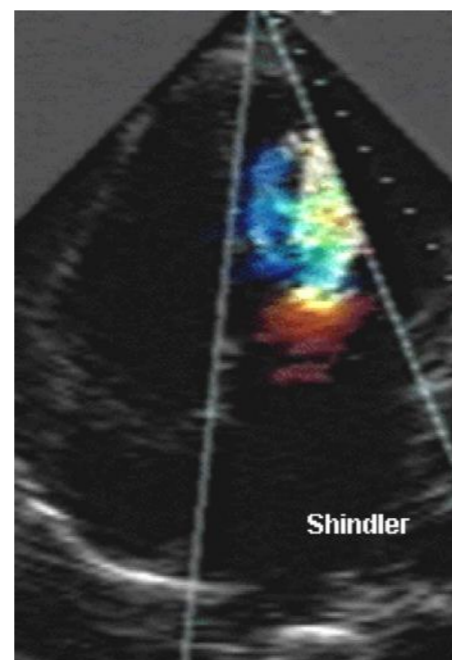
Following speckles with image analysis algorithms

# 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

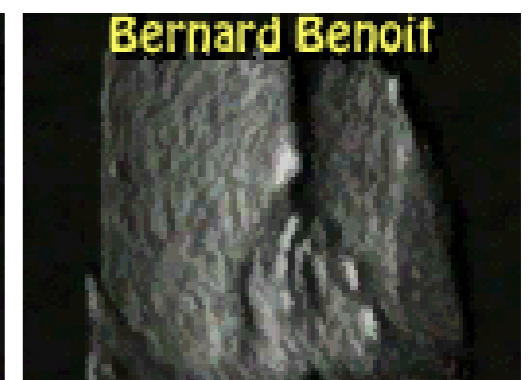
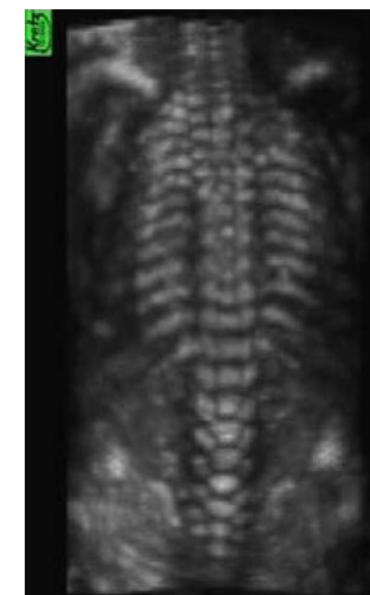


BART: Blue Away Red Towards

# 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



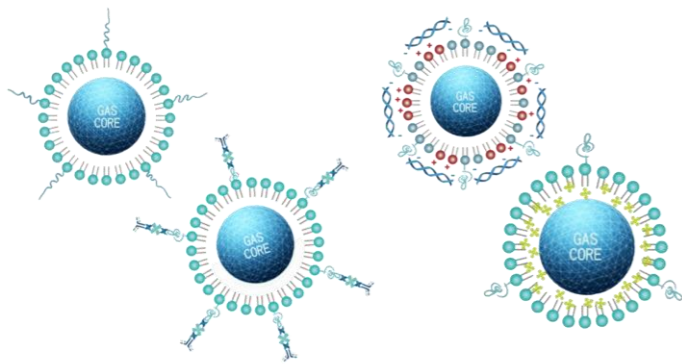
Five-dimensional ultrasound (5D UH, 4D Virtual HD)



High-resolution imaging technology; enhances 4D scans with lighting, depth perception, and realistic skin tones. Marketing term for a software solution (not a technological mode).

# Ultrasound contrast agents

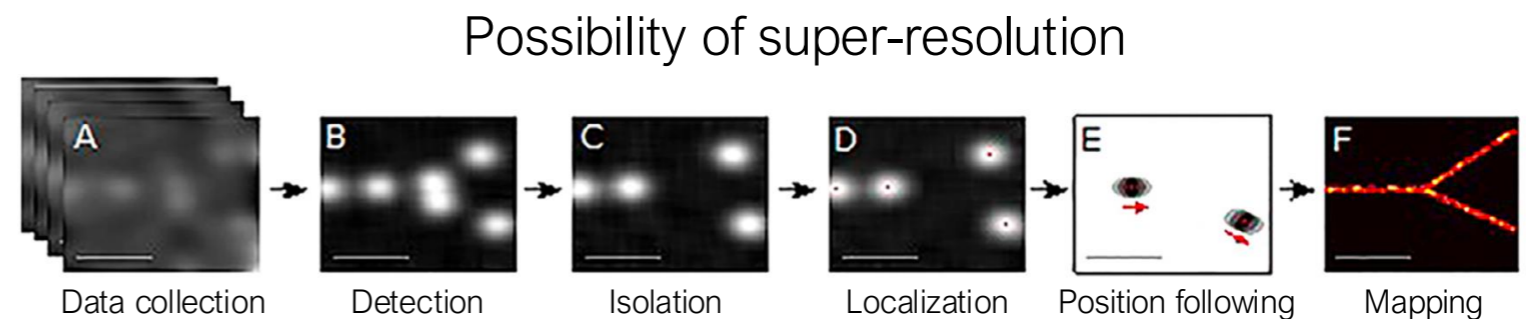
## Microbubbles filled with gas



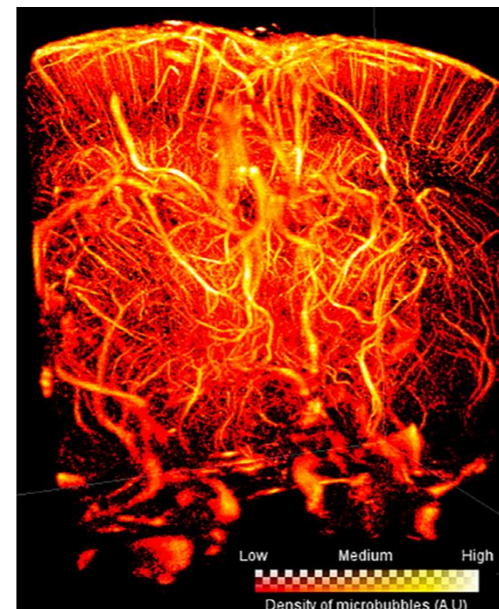
- Gas-filled core: air, perfluorocarbon, nitrogen
- Shell can be functionalized: proteins, sugars, lipids, polymers
- Size: 1-2  $\mu\text{m}$
- Large reflection coefficient



Hepatic vasculature



- Greater resolution can be achieved than with diffraction
- Based on changes in capillary flow, functional imaging can be achieved.



Capillary network in rat brain



Effect of whisker stimulation in the mouse brain

# Therapeutic applications of ultrasound

The therapeutic applications of US depend on its physical effects

## 1. Physical therapy

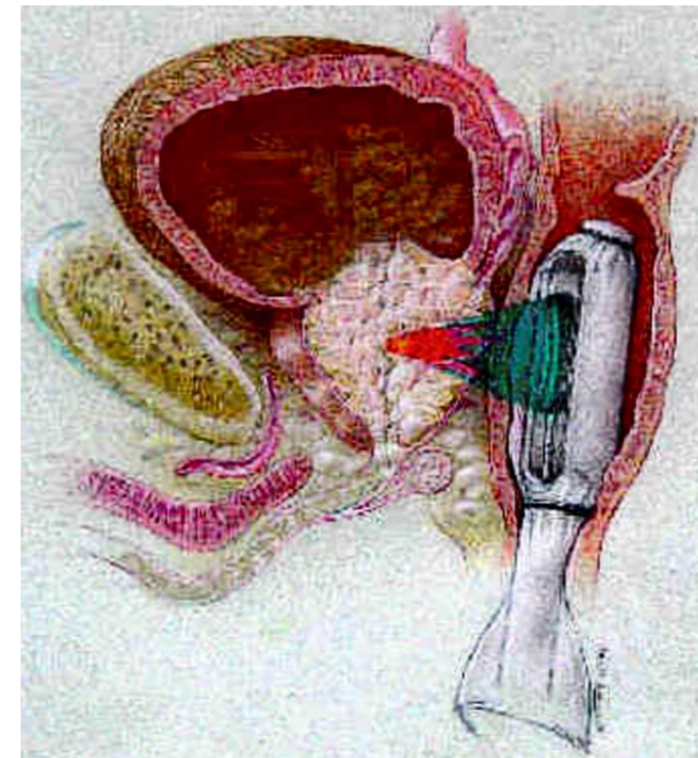
Local heating  
Micromassage

## 2. High Intensity Focused Ultrasound (HIFU):

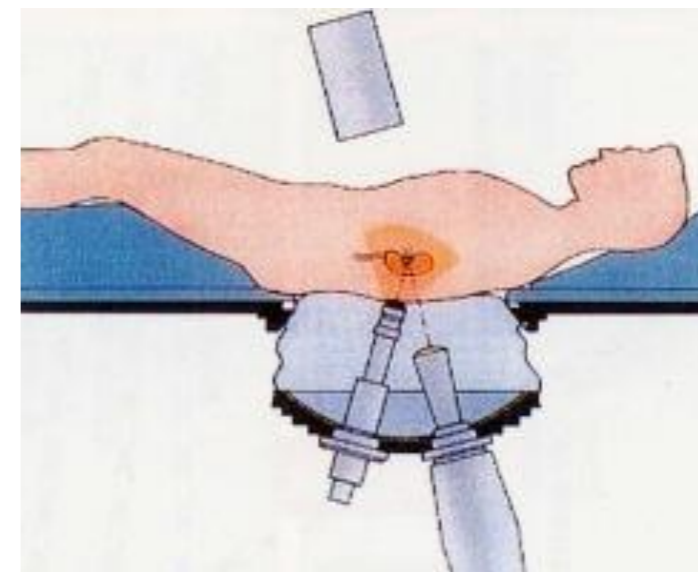
Crushing of prostate tumors  
(Not US: Shock wave therapy, ESWL –  
Extracorporeal Shockwave Lithotripsy, crushing  
of kidney stones)

## 3. Ultrasound-facilitated gene therapy

By using low-frequency, focused US, the blood-brain barrier can be transiently opened, thereby facilitating therapeutic gene delivery into the central nervous system.



HIFU



ESWL

# Feedback



<https://feedback.semmelweis.hu/feedback/index.php?feedback-qr=XUWJT5UFZ885TYB3>