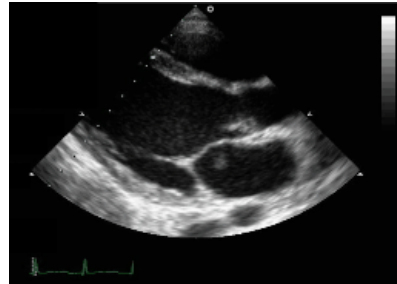
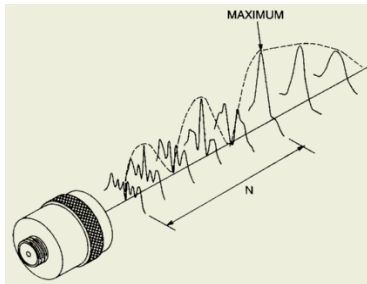


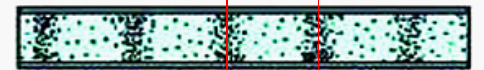
# Physics of ultrasonography



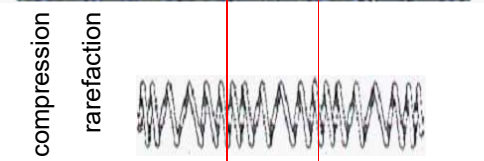
KAD 2021.03.04

## Sound: mechanical wave (model)

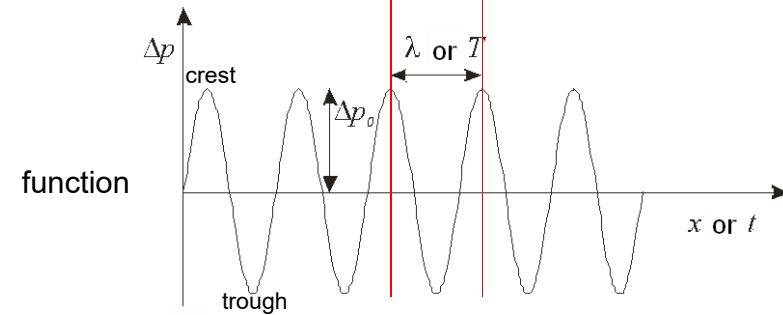
whistle



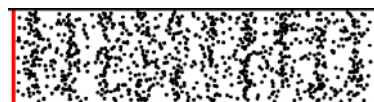
spring



spatial and temporal periodicity



2



**longitudinal wave**  
(in the interior of liquids and gases only this type)



**transverse wave**

hydrostatic pressure    pressure change, sound pressure

$$p_{\text{total}} = p_{\text{hydrostat}} + \Delta p$$

pressure DC    + AC    amplitude    phase

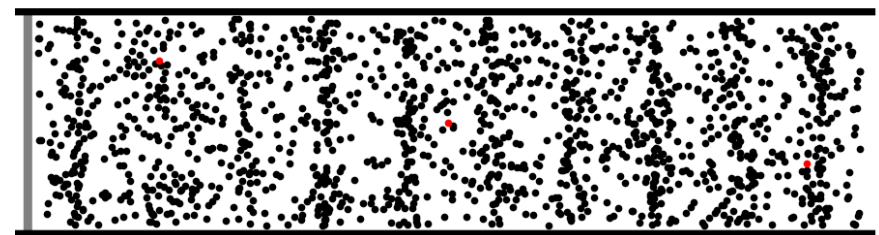
$$\Delta p(t, x) = \Delta p_{\text{max}} \sin \left[ 2\pi \left( \frac{t}{T} - \frac{x}{\lambda} \right) \right]$$



$$c \cdot T = \lambda, \quad c = f \cdot \lambda$$

3

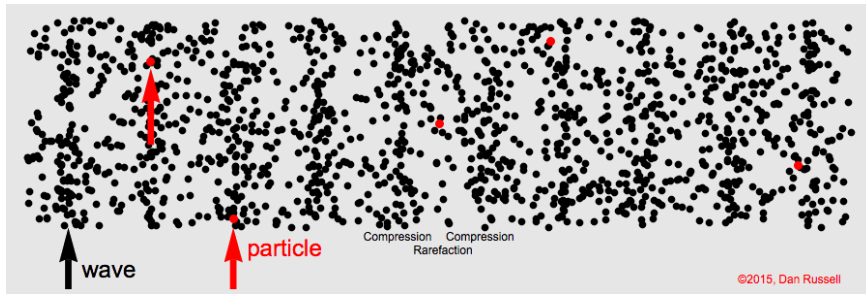
longitudinal wave



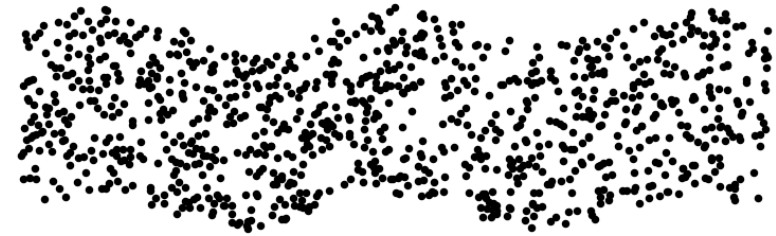
©2011. Dan Russell

moving surface (source of wave)

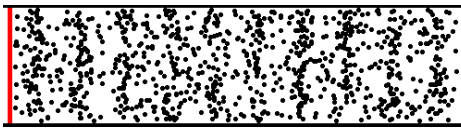
longitudinal wave



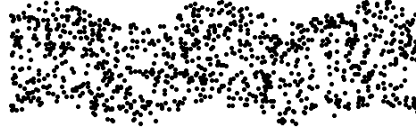
transverse wave



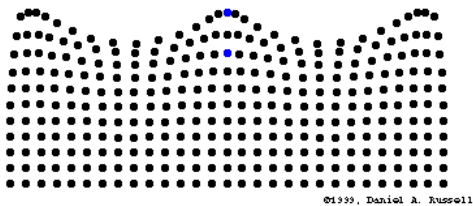
longitudinal wave



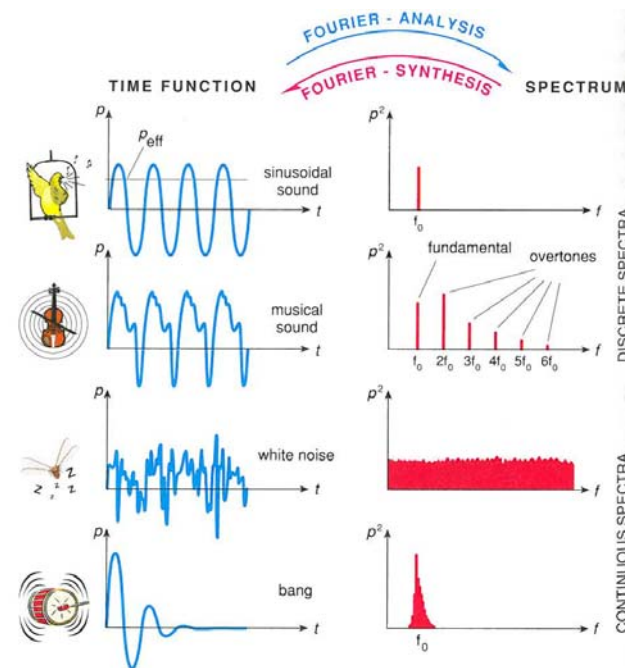
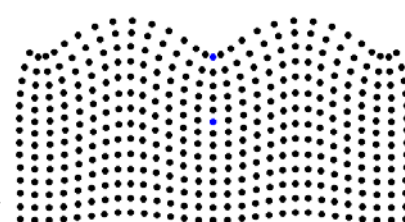
transverse wave



surface wave



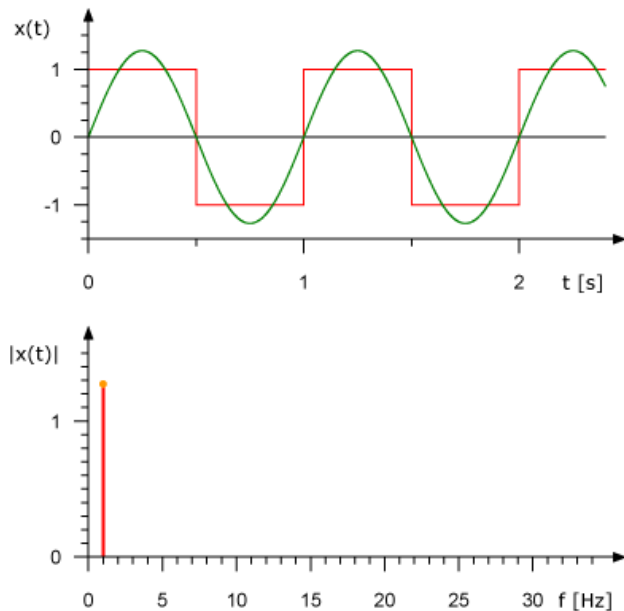
Rayleigh wave



Biophysics textbook, Fig. IV.23.

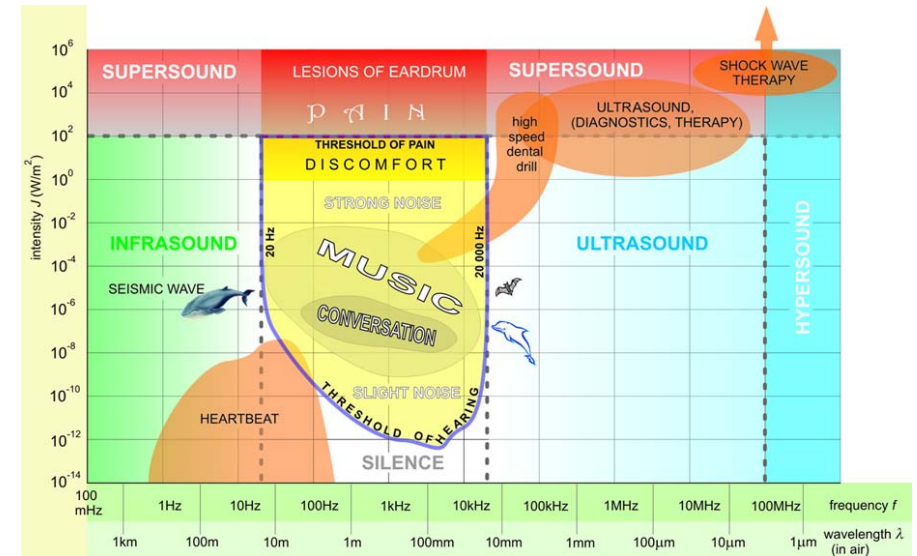
**pitch:**  
frequency of the  
fundamental

**timbre (tone colour):**  
relative strengths of  
overtones/harmonics  
(spectrum)



9

## Frequency and intensity regions of sounds



Laboratory manual, Audiometry

10

## The role of elastic medium

$$\kappa = -\frac{\Delta V}{V \Delta p}$$

**compressibility**  
relative volume decrease  
over pressure



$$c = \frac{1}{\sqrt{\rho \kappa}}$$

**speed of sound**

$$Z = \frac{p}{v} = \frac{p_{\max}}{v_{\max}}$$

**acoustic impedance**  
(definition)

$$Z_{\text{el}} = \frac{U}{I}$$

$$Z = c\rho = \sqrt{\frac{\rho}{\kappa}}$$

**acoustic impedance**  
(useful form)

Supplementary material

## Acoustic impedance (way to the useful form)

$$y = y_{\max} \sin\left[\omega\left(t - \frac{x}{c}\right)\right]$$

$$p = p_{\max} \sin\left[\omega\left(t - \frac{x}{c}\right)\right]$$

$$\frac{\Delta y}{\Delta t} = v = y_{\max} \omega \cos\left[\omega\left(t - \frac{x}{c}\right)\right]$$

$$Z = \frac{p}{v} = \frac{p_{\max}}{v_{\max}}$$

$$\frac{\Delta p}{\Delta t} = a = -y_{\max} \omega^2 \sin\left[\omega\left(t - \frac{x}{c}\right)\right]$$

$$\rho y_{\max} \omega^2 \sin\left[\omega\left(t - \frac{x}{c}\right)\right] = \frac{\Delta p}{\Delta x}$$

$$-\rho y_{\max} \omega c \cos\left[\omega\left(t - \frac{x}{c}\right)\right] = p$$

$$p_{\max} = \rho y_{\max} \omega c = \rho v_{\max} c$$

$$ma = F$$

$$\frac{1}{V} ma = \frac{1}{A \Delta x} F$$

$$\rho a = -\frac{\Delta p}{\Delta x}$$

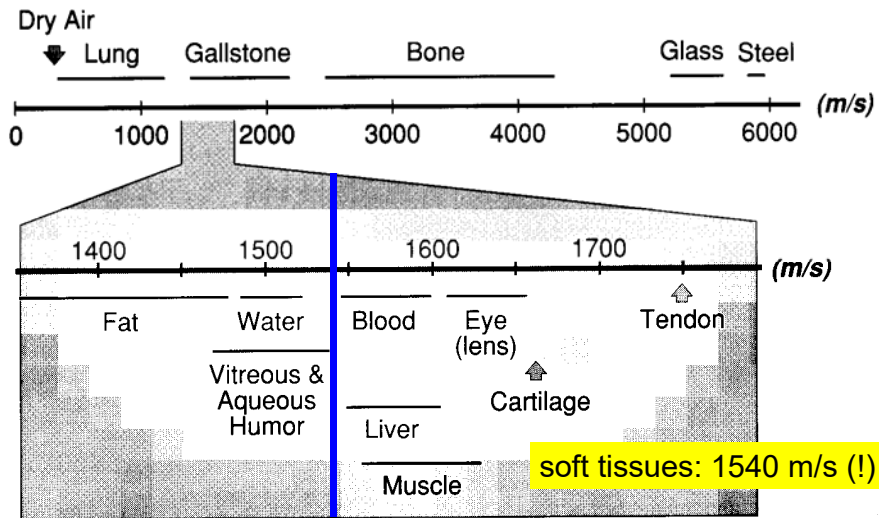
$$\frac{p_{\max}}{v_{\max}} = \rho c = Z$$

11

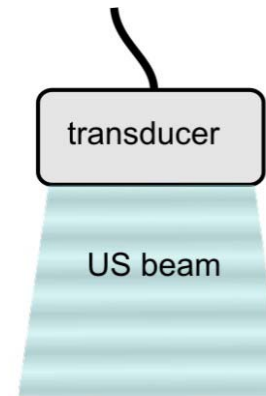
12



## Speed of sound/US in different media



3

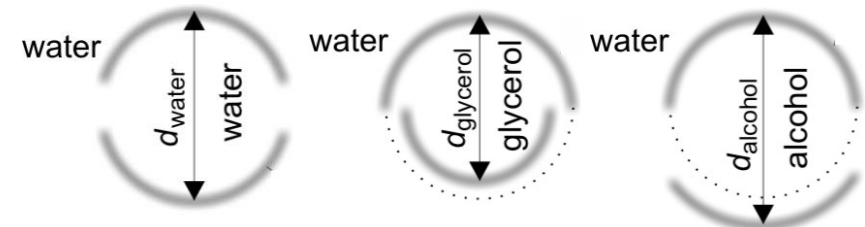


## Assuming constant speed of US → Artefacts

The image of the back-wall reflection appears in different distances, depending on the material in the finger of the rubber gloves

$$C_{\text{water}} = 1540 \text{ m/s}, C_{\text{glycerol}} = 1900 \text{ m/s}, C_{\text{alcohol}} = 1200 \text{ m/s}$$

contours of the rubber glove finger on the screen



Laboratory manual, US, Figure 15

14

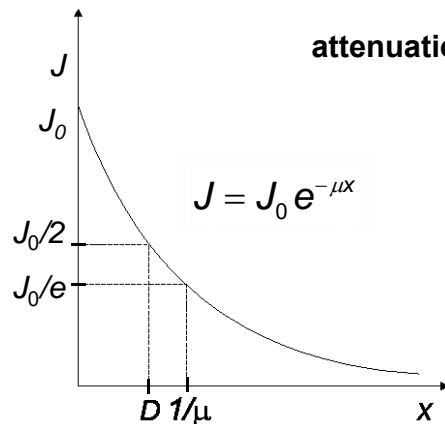
## Intensity of US

$$J = \frac{1}{Z} \Delta p_{\text{eff}}^2$$

$$P_{\text{el}} = \frac{1}{Z_{\text{el}}} U_{\text{eff}}^2$$

intensity = energy-current density    electric analogy

## Loss of energy during propagation (absorption)



attenuation:  $\alpha = 10 \cdot \lg \frac{J_0}{J} \text{ dB}$   
 $\alpha = 10 \cdot \mu \cdot x \cdot \lg e \text{ dB}$   
 $\mu$  is proportional to frequency in the diagnostic range

specific attenuation:  $\frac{\alpha}{f \cdot x}$

15

$\mu$  is proportional to frequency in the diagnostic range

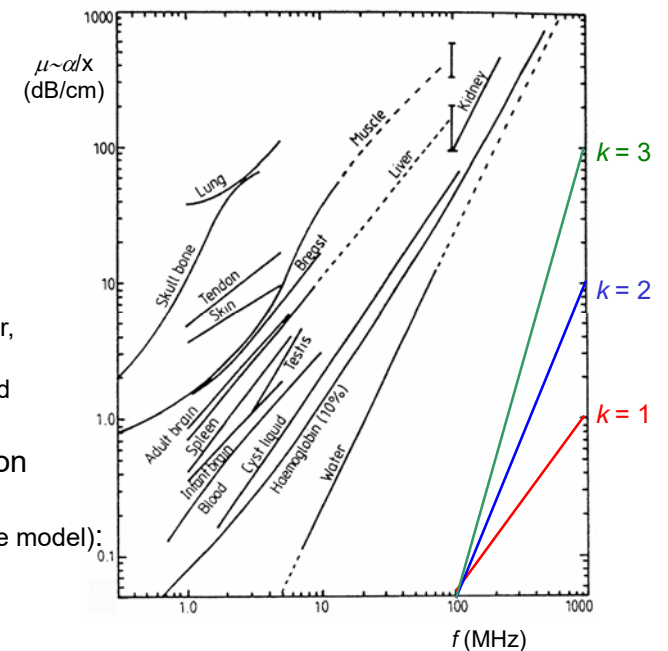
$$\mu \sim f^k, \quad k \sim 1(?)$$

$$\log \mu \sim k \log f$$

if the graph is a linear, the power function approximation is valid

specific attenuation for soft tissues (homogeneous tissue model):

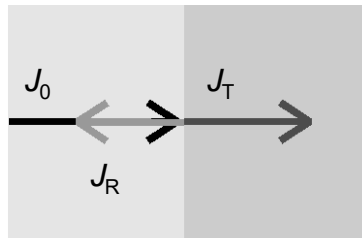
$$\frac{\alpha}{f \cdot x} \sim 1 \frac{\text{dB}}{\text{cm MHz}}$$



16

## Phenomena at the boundary of different media

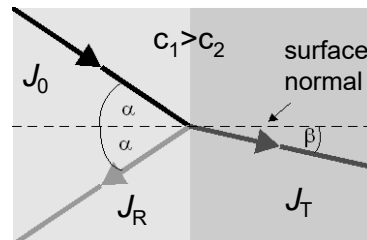
normal/perpendicular incidence



$$J_0 = J_R + J_T$$

reflection and transmission  
(penetration)

skew incidence



$$\frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2}$$

Snellius-Descartes

## Reflection (normal incidence)

reflectivity:

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

“full” reflection:

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

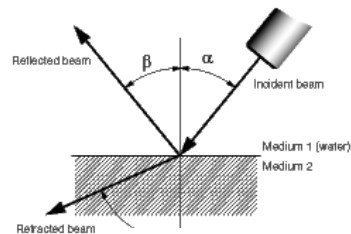
optimal coupling:

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



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

Supplementary material



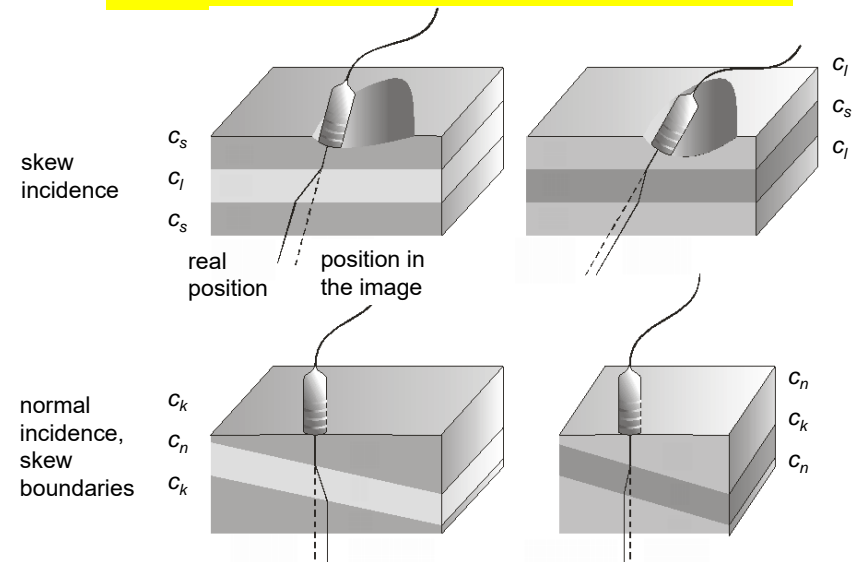
Skew incidence

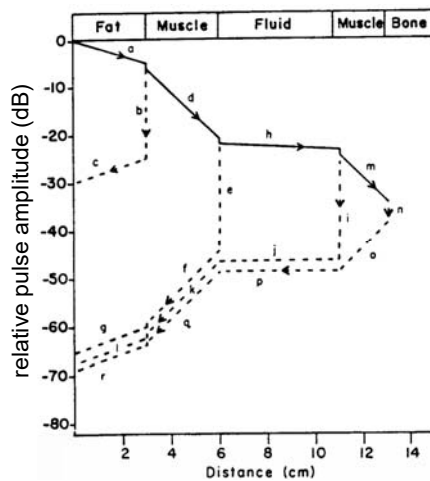
$$\text{Reflexion coefficient} = R = \left[ \frac{Z_2 \cos \alpha - Z_1 \cos \gamma}{Z_2 \cos \alpha + Z_1 \cos \gamma} \right]^2$$

$$\text{Refraction coefficient} = D = \frac{4 Z_1 Z_2 \cos^2 \alpha}{(Z_2 \cos \alpha + Z_1 \cos \gamma)^2}$$

$$\text{Refraction angle} = \gamma = \text{asin} \left( \frac{c_2 \sin \alpha}{c_1} \right)$$

## Phenomenon of skew incidence or normal incidence and skew boundaries





## Absorption and reflection

the later comes back the reflection, the deeper lays the reflecting surface and the weaker is the intensity

run time dependent amplification

TGC: time gain compensation

DGC: depth gain control

boundary surface	$R$	$10\lg R$ (dB)	$T$	$10\lg T$ (dB)
fat/muscle	0.01	-20.0	0.990	-0.044
muscle/blood	0.001	-30.0	0.999	-0.004
muscle/bone	0.41	-3.9	0.590	-2.291

21

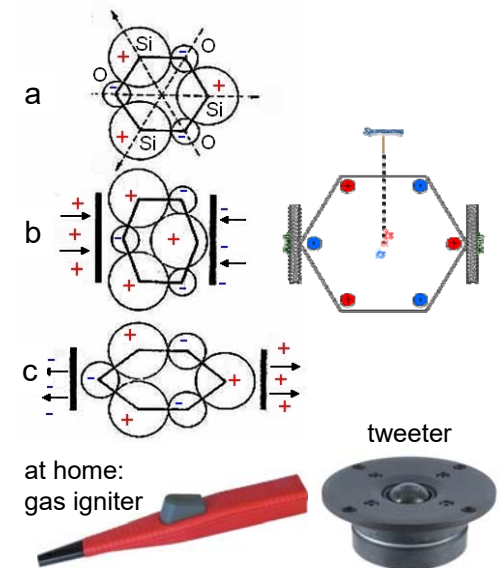
## Generation of US. Piezoelectric effect

source of electric signal  
(sine wave oscillator)+  
transducer (piezo-crystal)

(a) Center of charge of positive and negative charges coincides.

(b) and (c) As a result of pressure, the charge centers are separated, i.e. a potential difference arises (direct ~).

The crystal is deformed when voltage is applied (inverse ~).



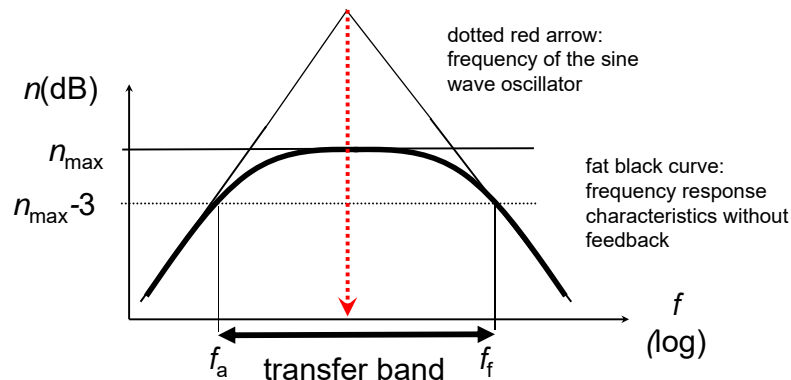
production: inverse ~  
detection: direct ~

## Source of electric signal : sine wave oscillator

amplifier with positive feedback

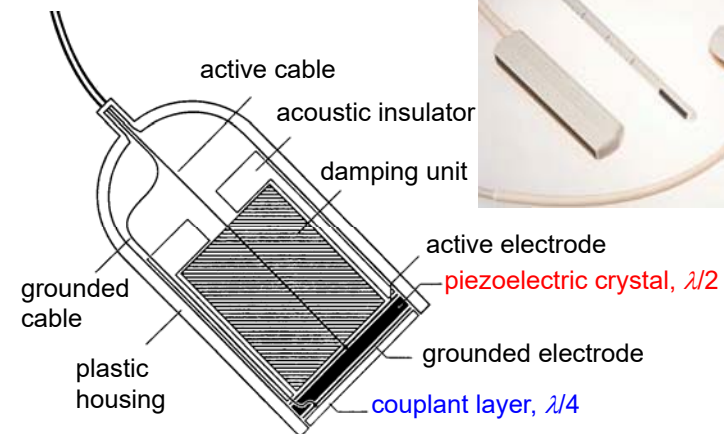
$$A_{U, \text{feedback}} = \frac{A_U}{1 - \beta A_U}$$

$\beta A_U = 1$ , amplification = „infinity“ → sine wave oscillator  
no input signal, output signal: sine voltage



23

## Ultrasound transducer

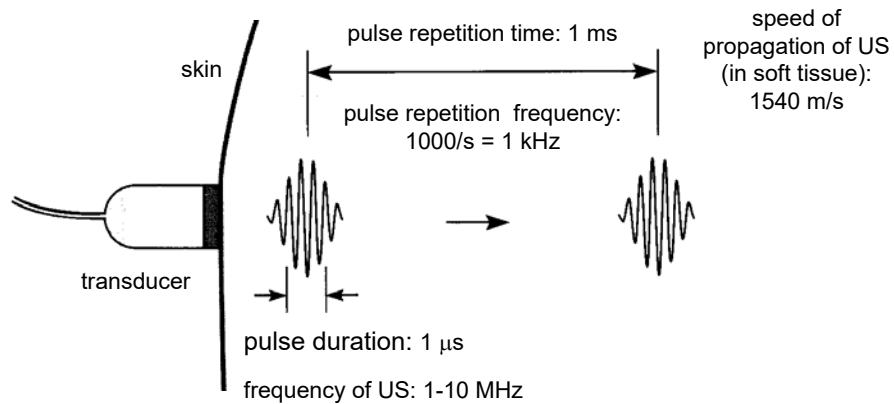


24

## Characteristic of US pulses

transducer: transmitter and receiver is the same unit

**time sharing** mode: pulses instead of continuous wave US



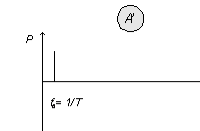
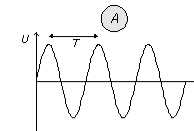
Biophysics textbook, Fig. VIII.32.

25

## Time function

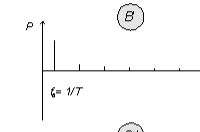
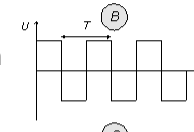
## Spectrum

sine function



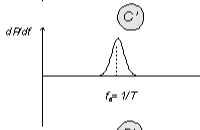
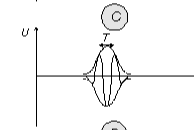
line spectrum (1 line)

square function



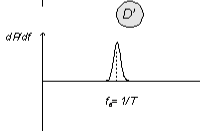
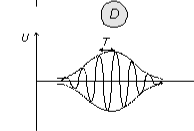
line spectrum

sine wave pocket (some „periods”)



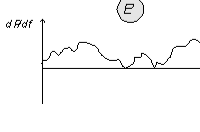
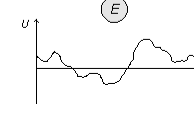
band spectrum

sine wave pocket (several „periods”)



band spectrum

aperiodic function

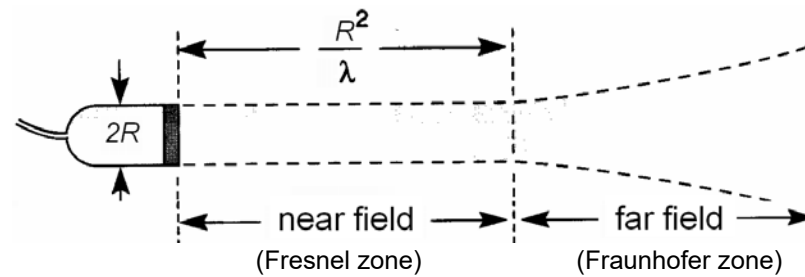


continuous spectrum

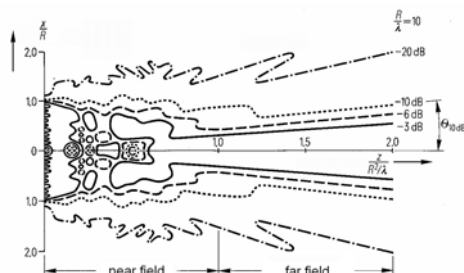
**US pulse**

26

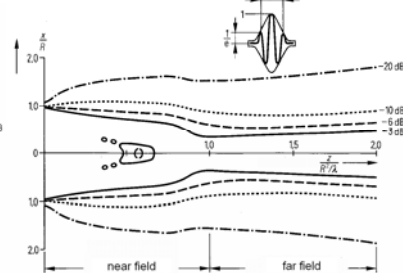
## US beam shape (simplified version)



Beam shape, continuous wave US

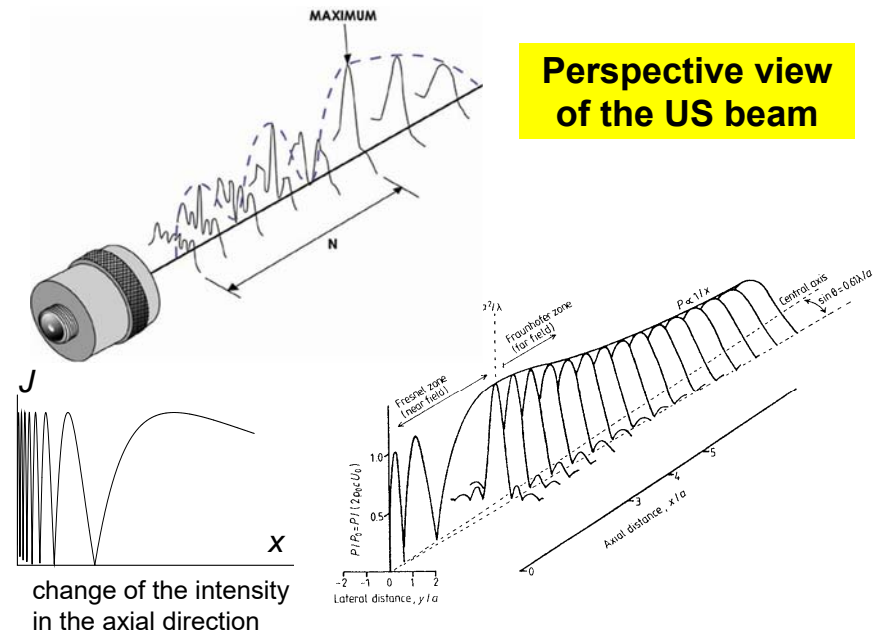


Beam shape, pulsed wave US



27

## Perspective view of the US beam



cf. Textbook. Fig. on p.505

28

## Resolving limit, resolution

**Resolving limit** is the distance between two object details which can be just resolved as distinct objects (the smaller the better).

**Resolution (resolving power):** the reciprocal of the resolving limit (the greater the better)

**Axial resolving limit** depends on the pulse length. Pulse length is inversely proportional to the frequency.

**Lateral resolving limit** is the minimum separation of two interfaces aligned along a direction perpendicular to the ultrasound beam. It depends on the beam width

<b>Typical values</b>	frequency (MHz):	2	15
	wavelength (in muscle) (mm):	0.78	0.1
	penetration depth (cm):	12	1.6
	lateral resolving limit (mm):	3.0	0.4
	axial resolving limit (mm):	0.8	0.15

29

## Axial resolving limit

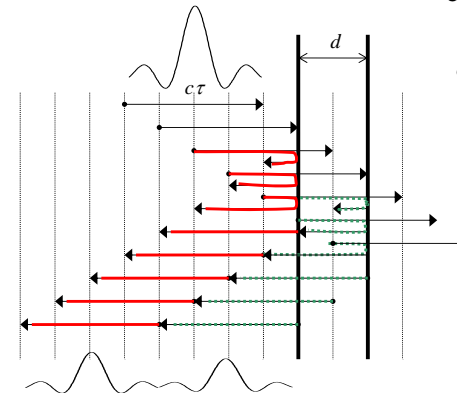
$\tau$  : pulse duration

$c_1\tau \cong c_2\tau = c\tau$  pulse length

$\delta_{ax} = d = \frac{c\tau}{2}$  resolving limit

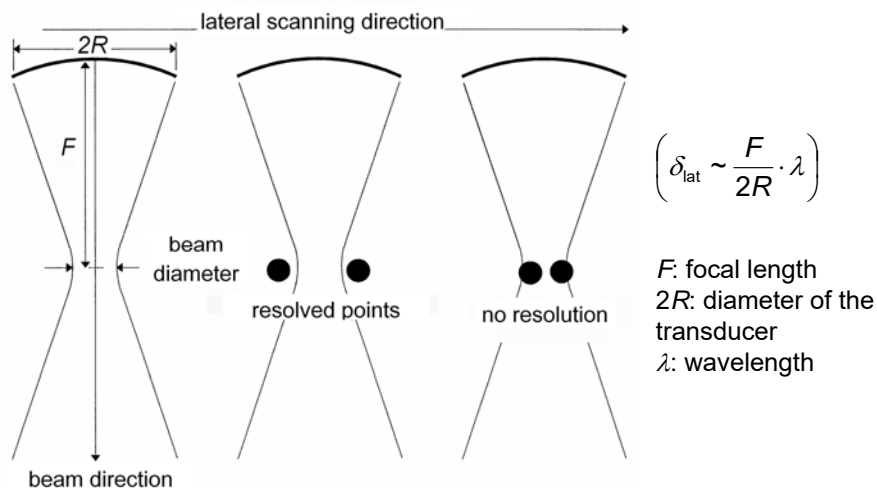
The axial resolving limit is the half of the pulse length. The echos from the adjacent surfaces in this case just hit another.

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



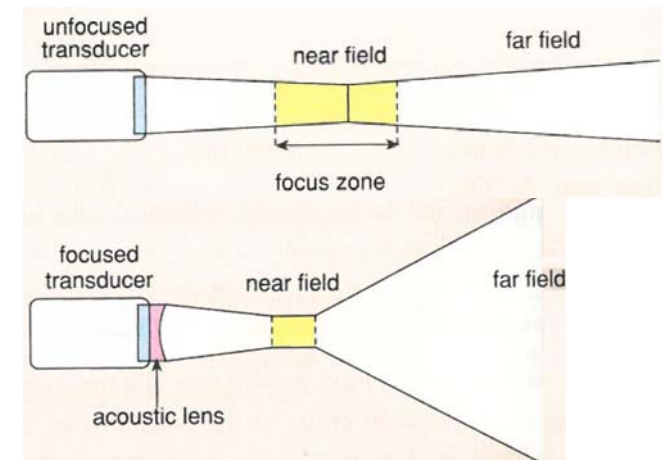
30

## Lateral resolving limit



31

## Focusing of the beam

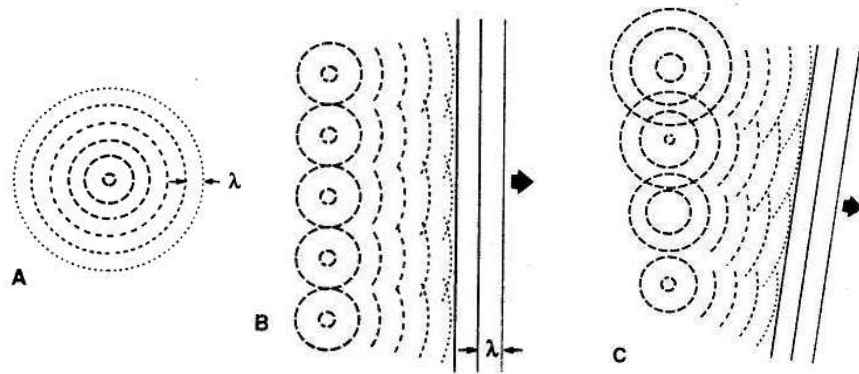


Focusing increases the divergence of the beam in the far field regime and reduces the depth sharpness.

cf. Textbook Fig. on p.506

32

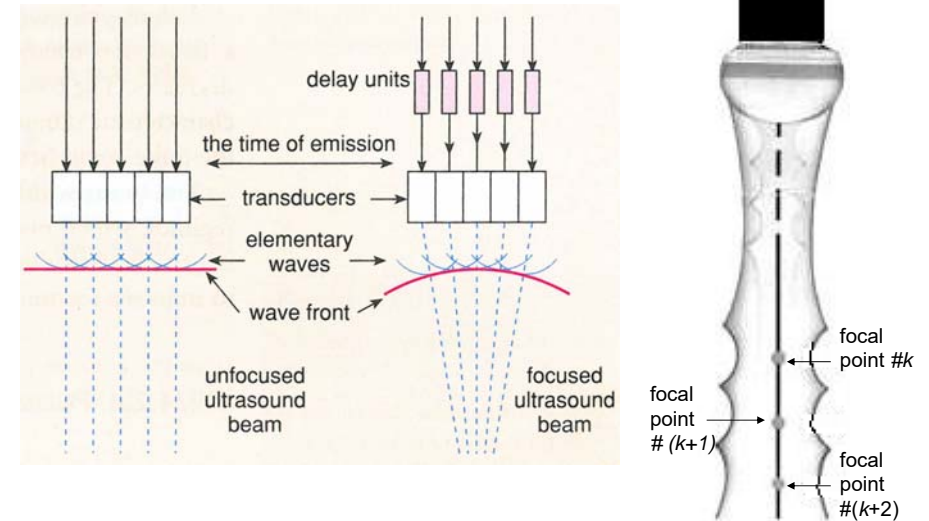
## Huygens' principle



Any wave propagates so, that each point on a primary wavefront serves as the source of spherical secondary wavelets that advance with a speed and frequency equal to those of the primary wave. The primary wavefront at some later time is the envelope of these wavelets.

33

## Electronic focusing

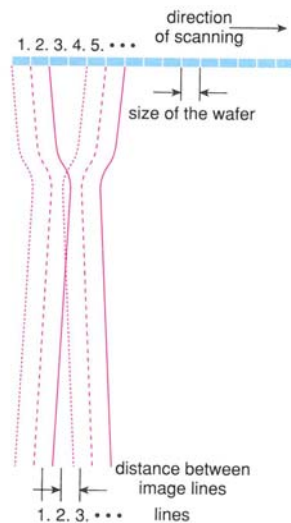


cf. Textbook Fig. on p.507

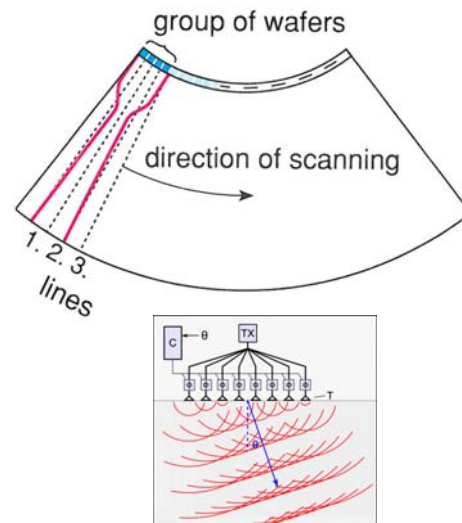
34

## Scanning

multi unit linear array



multi unit curved array



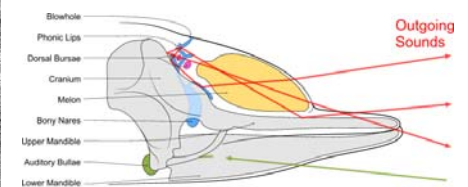
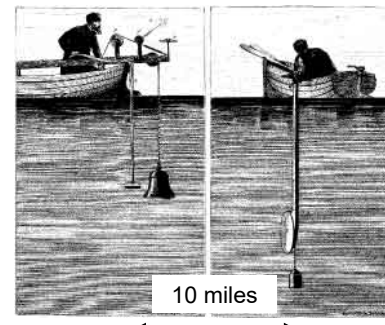
cf. Textbook Fig. VII. 36-37

35

## Echo principle

1794 Spallanzani:  
bat's navigation

1822 Colladen  
measured the speed of  
sound in water

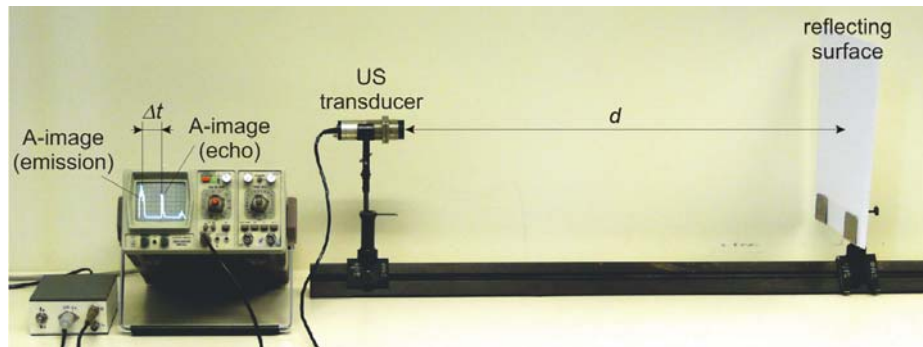


bottlenose dolphin

36

## Echo principle

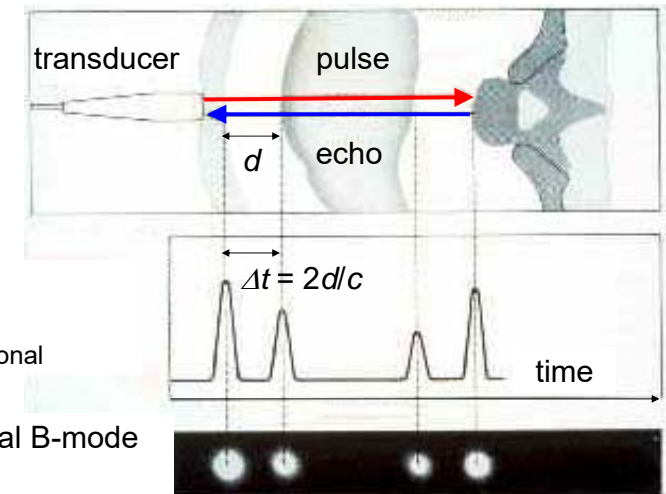
using a special US-head, short pulses are emitted in the air towards a reflecting surface, and the same US-head detects the echo signal



$$c\Delta t = d + d = 2d$$

37

## Receiving the echos



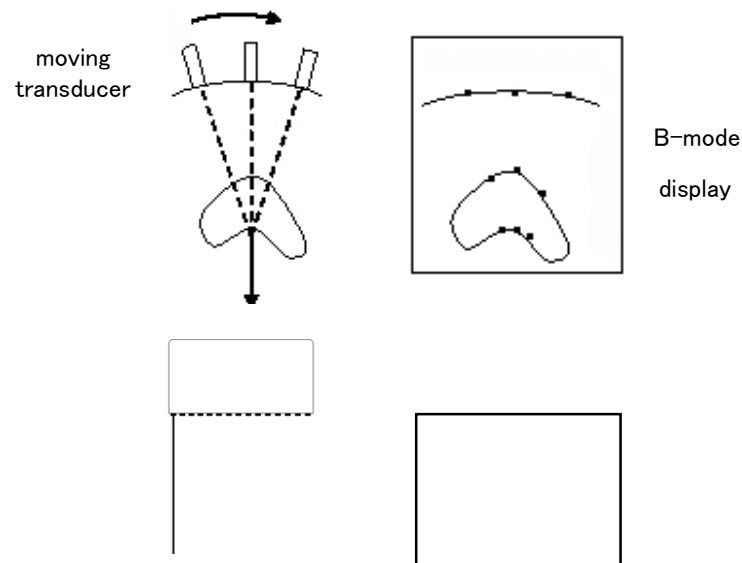
A-mode  
(**A**mplitude)  
only 1-dimensional

1-dimensional B-mode  
(**B**rightness)

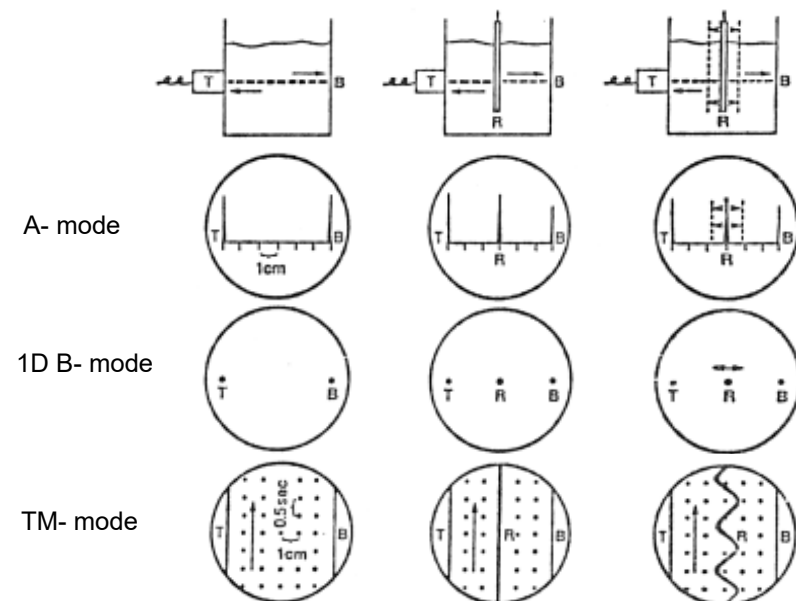
cf. Textbook Fig. VIII.33

38

## 2-dimensional B-mode



39

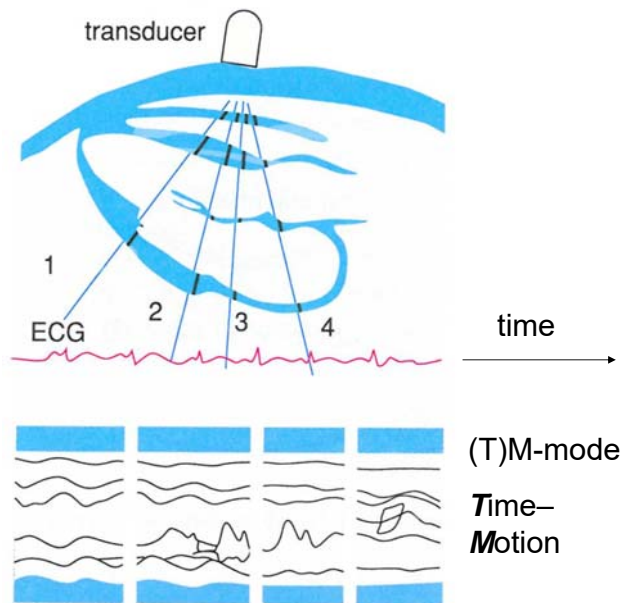


40

## TM-mode

ECG signal  
for reference

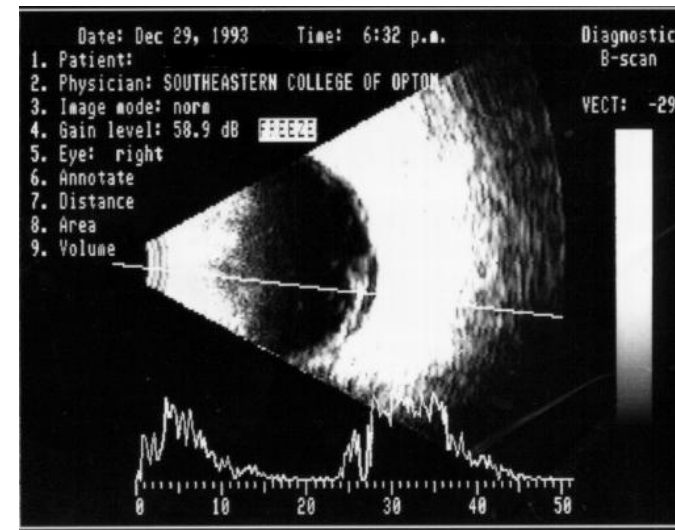
(vertical)  
time-dependent  
1-dimensional  
B-mode



Textbook Fig. VIII.34

41

## 2-dimensional B-mode and A-mode (used in ophthalmology)



real speed of  
propagation for  
the accurate  
determination of  
distances:

cornea: 1641 m/s

aqueous humour:  
1532 m/s

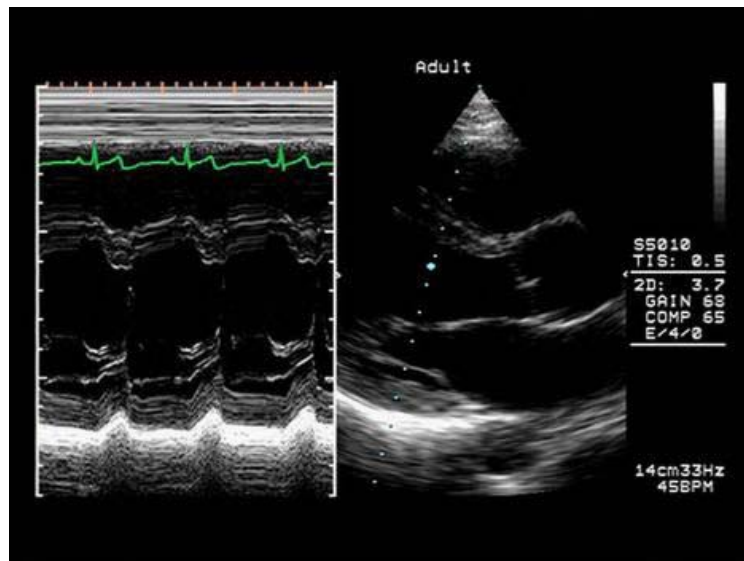
crystalline lens:  
1641 m/s

vitreous body:  
1532 m/s

42

TM-mode

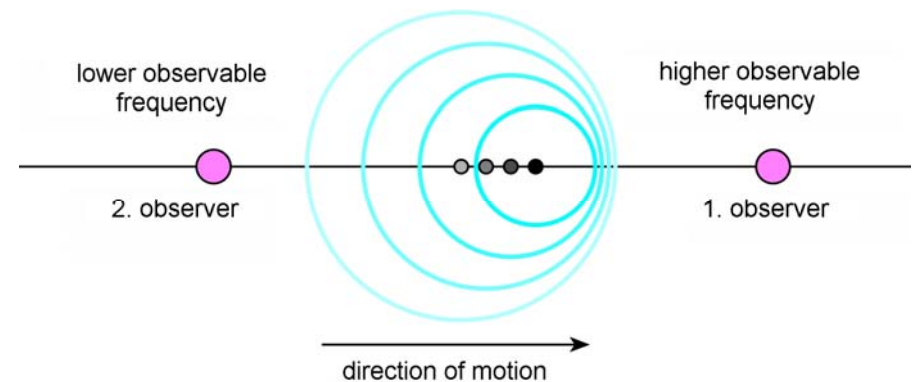
B-mode



43

## Doppler phenomenon

„The pitch of a train whistle seems to get higher as it approaches, then seems to lower as the train whistle moves away.” (C. Doppler, 1842)



Textbook Fig. VIII.39

44

$f'$ : **observed frequency**,  $f$ : original frequency

- (a) standing source and moving observer ( $v_o$ )  
 +: observer approaches the source  
 -: observer moves away from the source

$$f' = f \left( 1 \pm \frac{v_o}{c} \right)$$

- (b) moving source and standing observer  
 (if  $v_s \ll c$ , then „same” as (a))

$$f' = \frac{f}{1 \mp \frac{v_s}{c}}$$

- (c) moving source and moving observer

$$f' = f \frac{1 \pm \frac{v_o}{c}}{1 \mp \frac{v_s}{c}}$$

- (d) moving reflecting object (surface),  
 (if  $v_R \ll c$ )

$$f' = f \left( 1 \pm \frac{2v_R}{c} \right)$$

45

**Doppler frequency** = frequency change = frequency shift

if  $v_i, v_R \ll c$  (i= S or O)

rearranging equation (a)

**moving source or observer:**

$$\Delta f = f_D = \pm \frac{v_i}{c} f$$

rearranging equation (d)

**moving reflecting object  
or surface:**

$$\Delta f = f_D = \pm 2 \frac{v_R}{c} f$$

if  $v$  and  $c$  are not parallel, then  $v \cos \theta$  should be used  
 instead of  $v$  (remark: if  $\theta = 90^\circ$ ,  $f_D = 0$ )

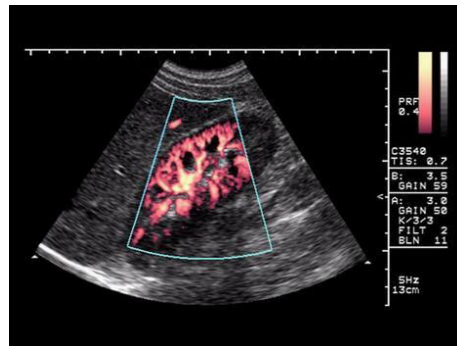
46

## Colour coding

towards the transducer: warm colours  
 away from the transducer: cold colours



BART: Blue Away Red Towards



power Doppler

47

## 1-dimensional CW Doppler apparatus for measuring average flow velocity. Red blood cells as sound scatterers

CW: continuous wave

source and detector are separated

$$|f_D| = 2 \frac{v_R \cos \theta}{c} f$$

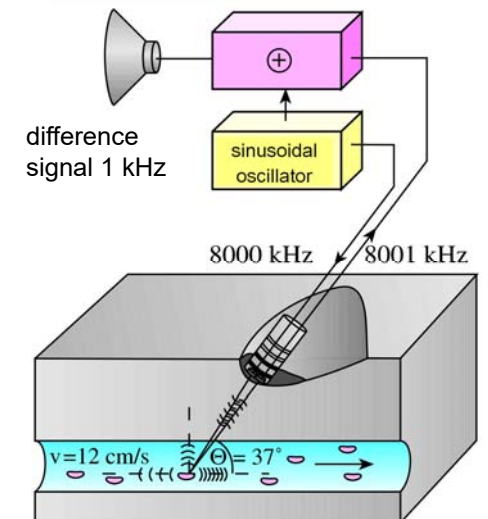
e.g.  $f = 8000$  kHz

$v = 12$  cm/s

$c = 1600$  m/s

$\theta = 37^\circ$

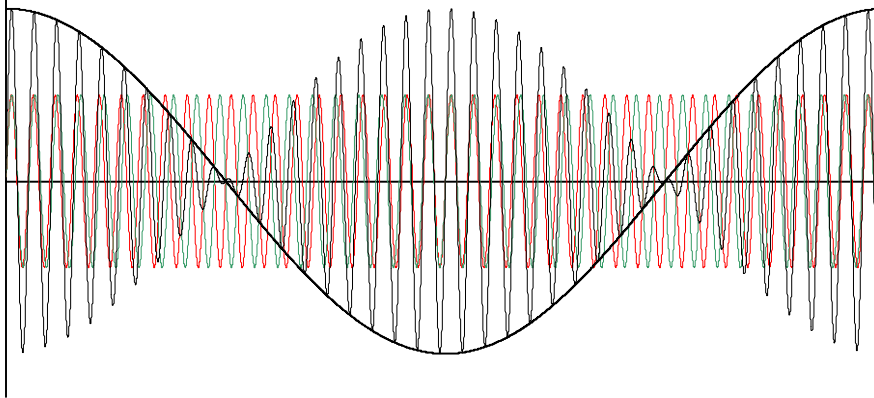
$\Rightarrow f_D = 1$  kHz  
 (beating phenomenon)



48

## Beating phenomenon

$f_{\text{red}} \geq f_{\text{green}}$  the beating frequency equals to the difference of the two interfering frequency

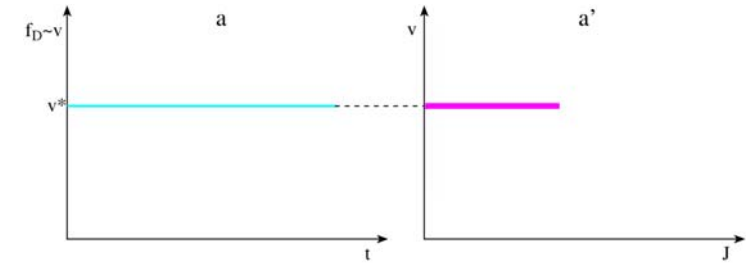


reminder:  $\sin \alpha + \sin \beta = 2 \sin \frac{\alpha + \beta}{2} \cos \frac{\alpha - \beta}{2}$

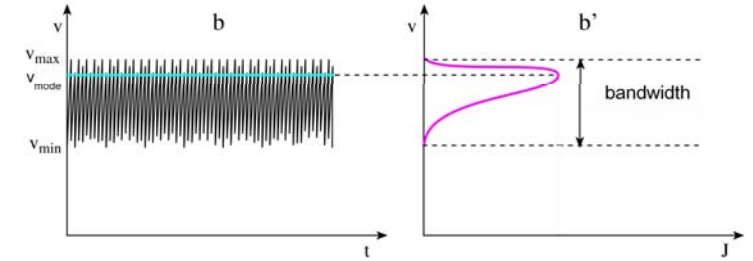
49

## Doppler curves

one constant velocity ( $v^*$ )



frequency distribution (with  $v_{\text{mode}}$ )



velocity distribution in TM-mode

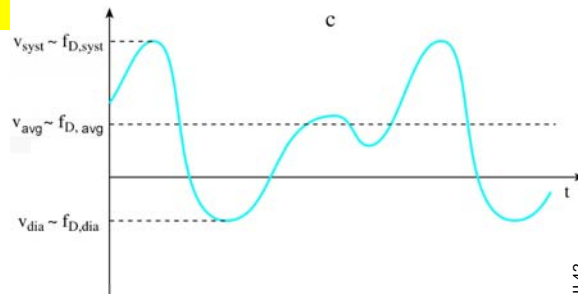
velocity distribution at a certain time

Textbook Fig. VIII.42

50

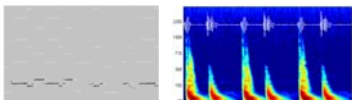
## Doppler curves

flow can be represented by one velocity in each moment

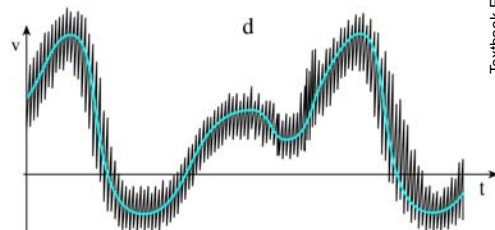


Textbook Fig. VIII.42

flow can be represented by a velocity distribution in each moment

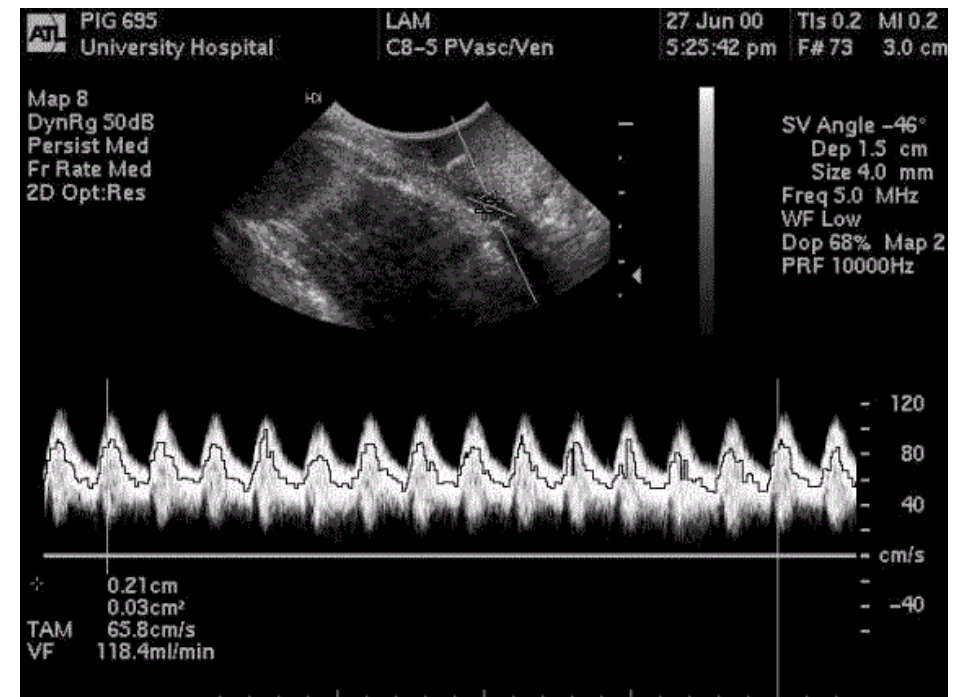


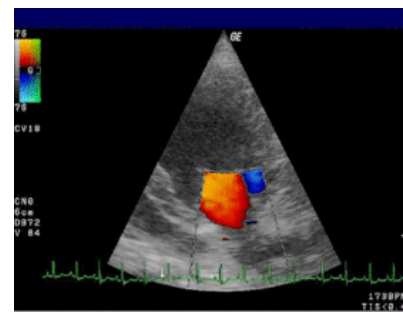
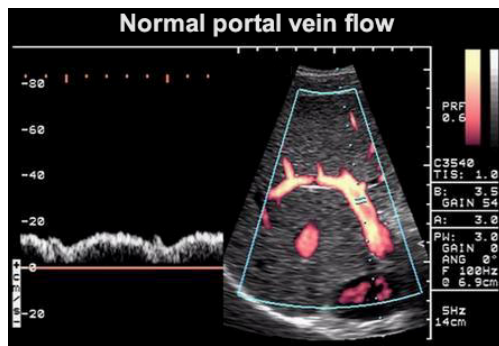
cf. voiceprint, music/heart beats in time-frequency representation



velocity distribution in TM-mode

51





Mitral valve

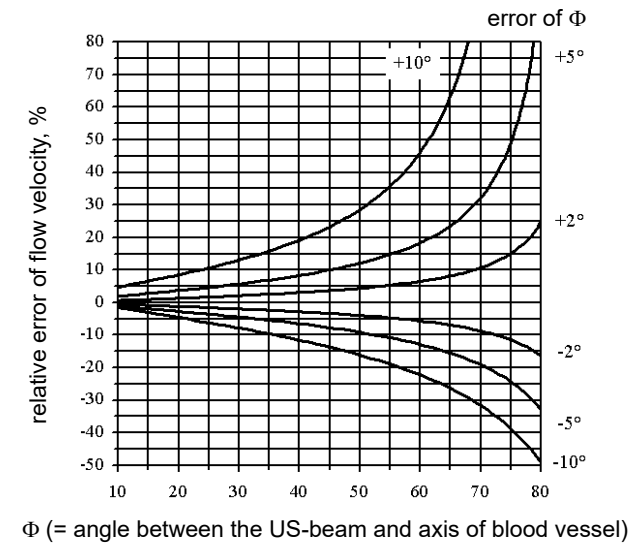


EF: ejection fraction



## Supplementary material

Error of measuring the angle between the US-beam and axis of blood vessel influences the error of the flow velocity



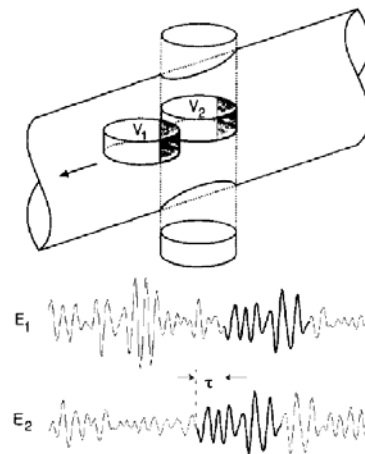
## Speckle tracking/Time domain correlation method (CVI = color velocity imaging)

If the reflecting surface and/ or the scatterer are moving then the US signal at a fixed position depends on time.

Similar US pattern can be measured at a certain distance from the earlier position (where the reflecting surface/scatterer moved).

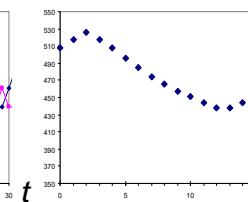
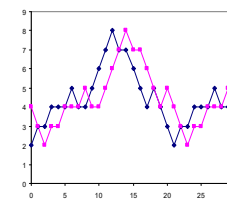
How can be compared the similarity of different functions?

The advantage of speckle tracking is the **angle independency**.



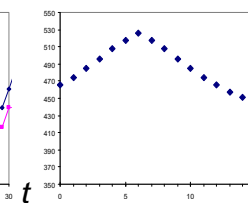
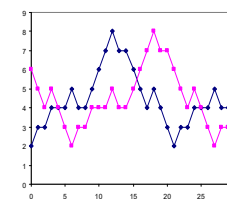
time domain

correlation function

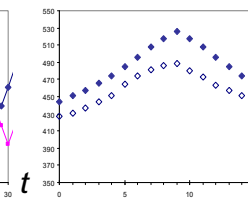
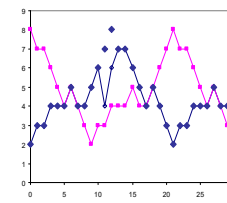


$$f_{\text{blue}}(t) = f_{\text{pink}}(t + \tau^*)$$

$$\tau^* = 2u$$

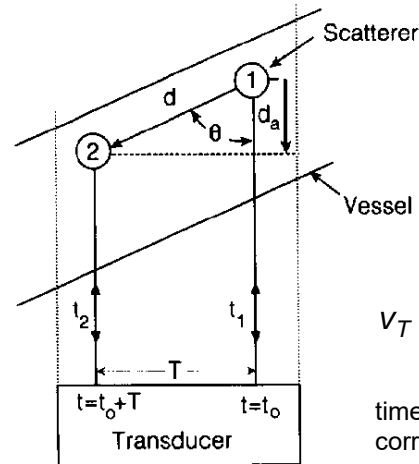


$$\tau^* = 6u$$



$$\tau^* = 9u$$

$$f_{\text{empty}}(t) \cong f_{\text{blue}}(t)$$



$$d_a = \frac{(t_1 - t_2)c}{2}$$

$$d = \frac{(t_1 - t_2)c}{2\cos\theta}$$

$$v_T = \frac{(t_1 - t_2)c}{2T\cos\theta}$$

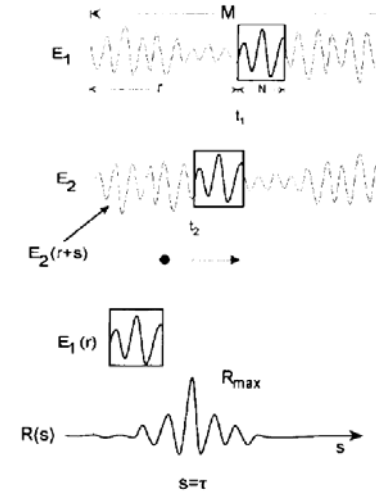
time domain  
correlation method

$T$ : pulse repetition  
time

$$v_D = \frac{f_D c}{2f\cos\theta}$$

cf.: Doppler  
method

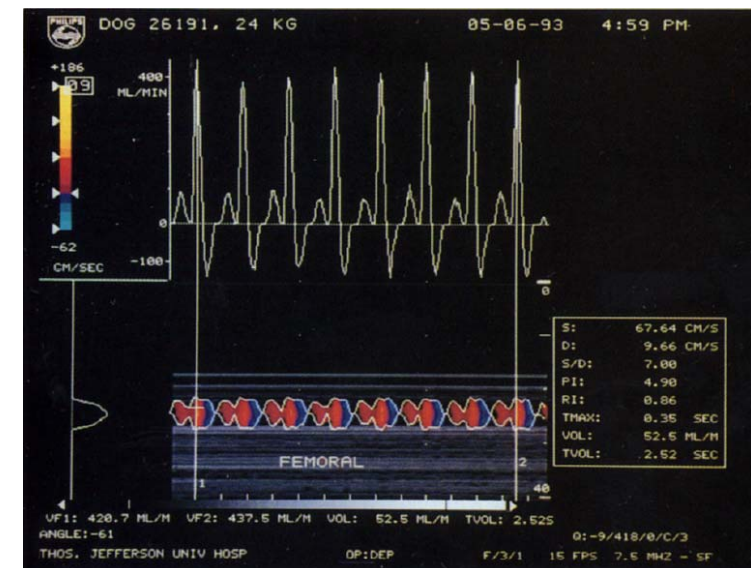
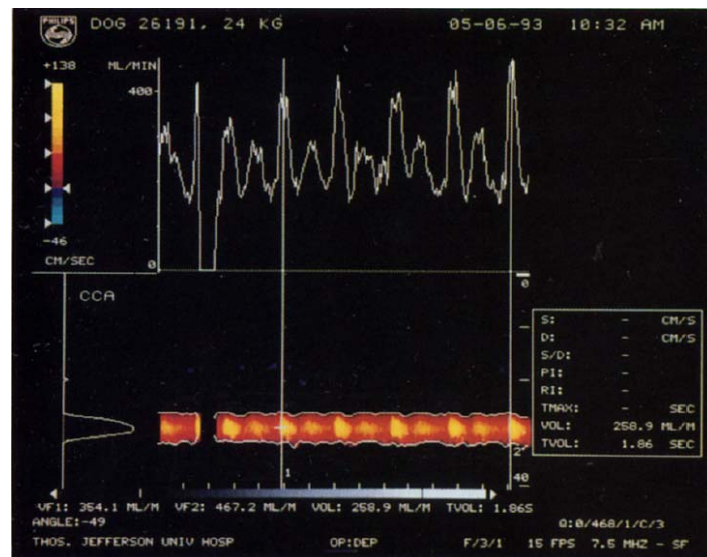
$f$ : frequency of US



correlation procedure  
consists of removing a  
window of width N at  
desired range from on echo  
signal  $E_1$

$E_1$  is correlated at different  
locations along another  
echo signal  $E_2$

the value of s producing the  
maximum corresponds to  $s = \tau$



## Sono-CT

image reconstruction from several multidirectional B-images

SonoCT yields better results than conventional B-mode sonography in terms of delineation, visualization of borders and artefact-free representation

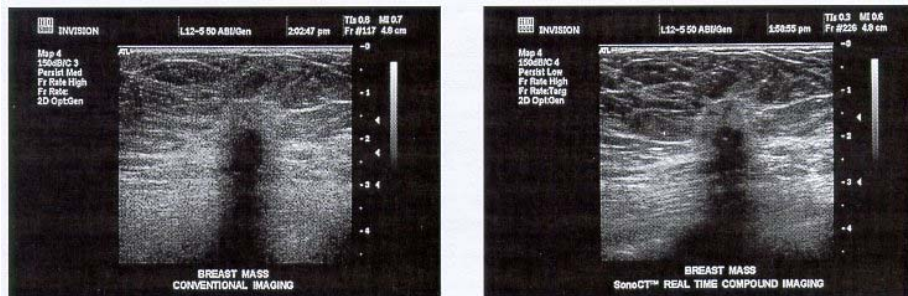
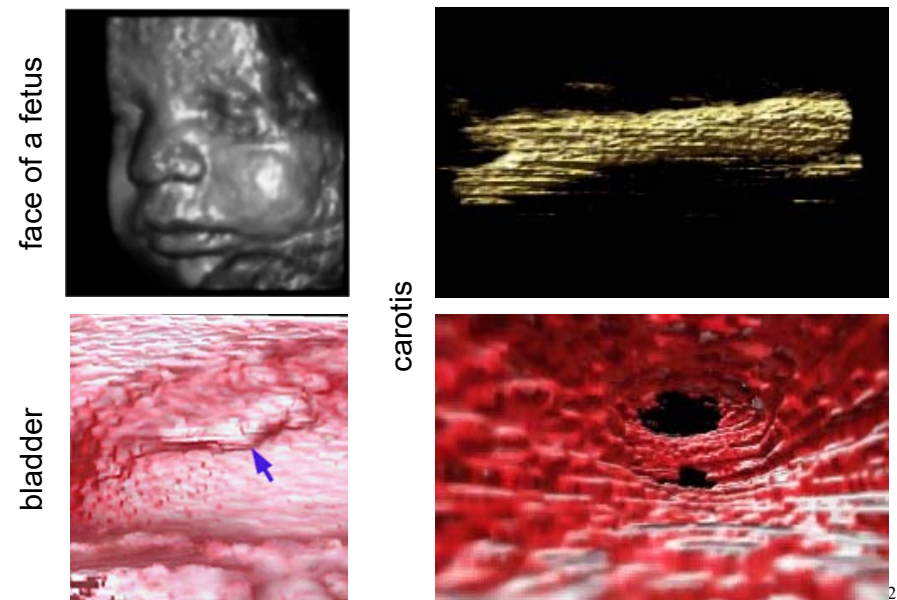


Figure 1. Breast fibroadenoma as shown on conventional ultrasound (left) and SonoCT ultrasound imaging (right).

## 3D reconstruction



**palpation:**  
one of the oldest  
clinical skills,  
**tissue elasticity**

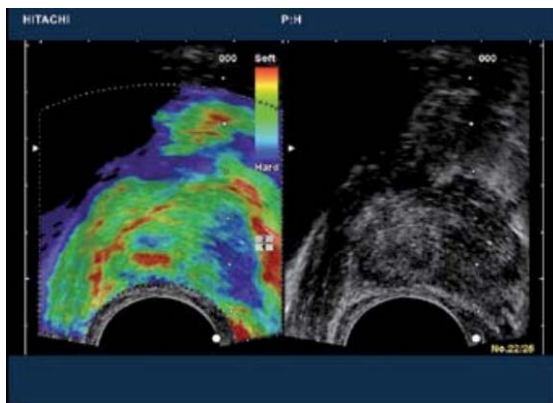
**strain:**  
a region of tissue is  
compressed and the  
**degree to which it  
distorts** is assessed

Hooke's law:

$$\frac{F}{A} = E \frac{\Delta L}{L}$$

F: force  
A: cross-sectional area  
L: resting length  
 $\Delta L$ : extension  
F/A: stress  
E: Young modulus  
 $\Delta L/L$ : relative extension  
(strain)

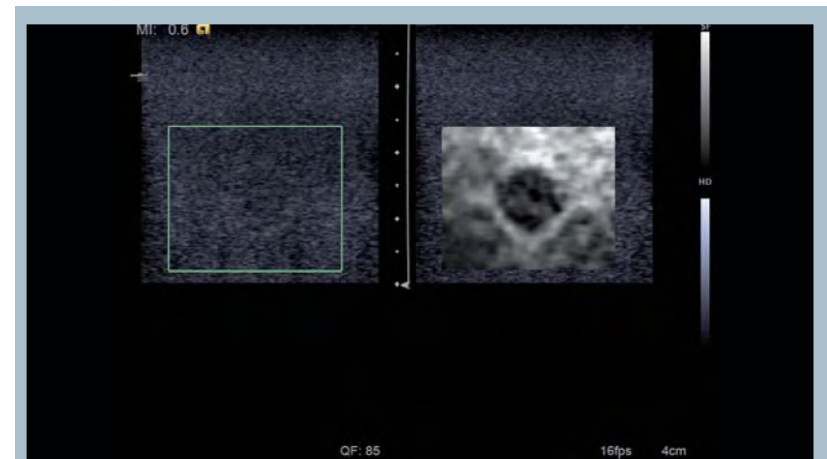
## Sonoelastography



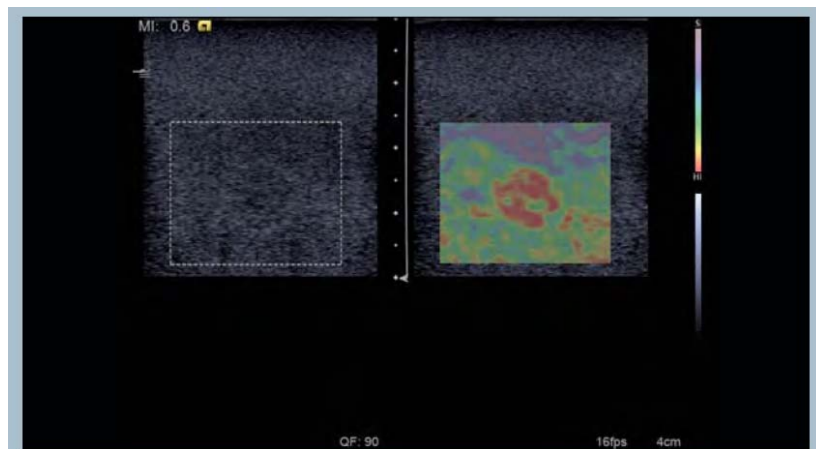
Prostate cancer. The right panel shows the B-mode frame of a prostate ultrasound scan with the corresponding elastography frame on the left. The colour codes (here) blue for hard and red for soft. This hard lesion, which is not apparent on the B-mode, was a carcinoma on biopsy

63

## Supplementary material

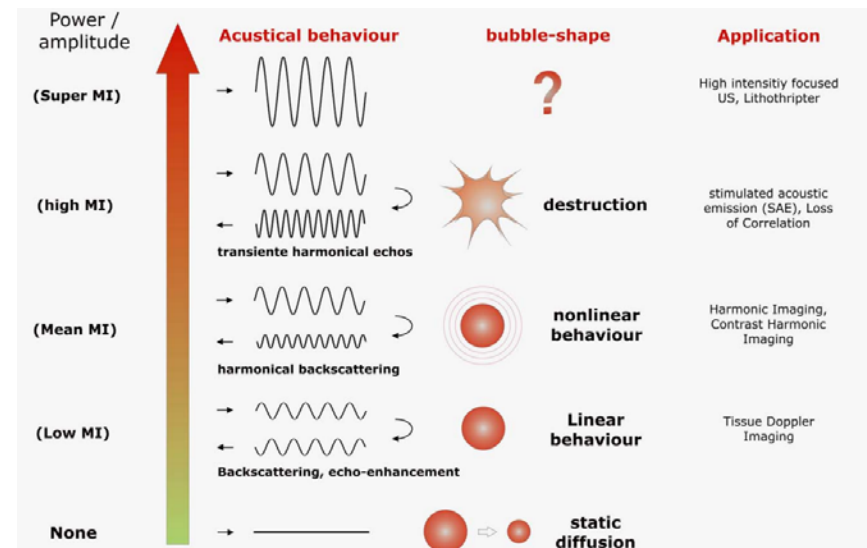


Grayscale eSie Touch Elasticity Imaging demonstrates a lesion which is more stiff (black) than the surrounding tissue. The conventional B-mode ultrasound is the same as displayed in the previous image.



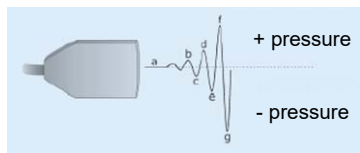
Color scale eSie Touch Elasticity Imaging demonstrates a lesion which is more stiff (red) than the surrounding tissue.

## Contrast agents

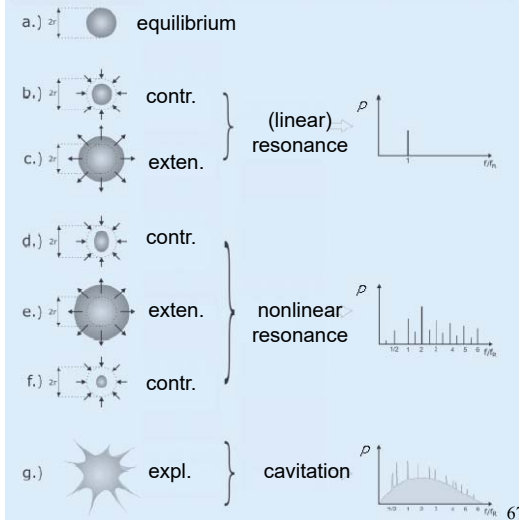


66

## Contrast harmonic imaging = CHI



Behaviour of microbubbles exposed to pulsed US



C. Kollmann · M. Putzer  
**Ultraschallkontrastmittel –  
physikalische Grundlagen**  
Radiologie 2005 · 45:503–  
512

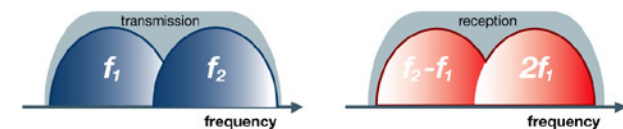
## Tissue harmonic imaging = THI

Principle:

- Simultaneous transmission of 2 pulses at different frequencies
- Reception of signals at harmonic and differential frequencies
- Cancellation of fundamental signals using Pulse Subtraction

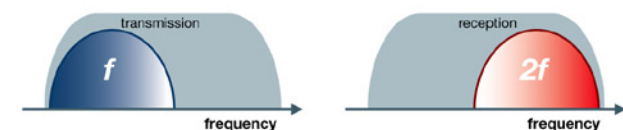
Toshiba

Differential Tissue Harmonic Imaging



Philips

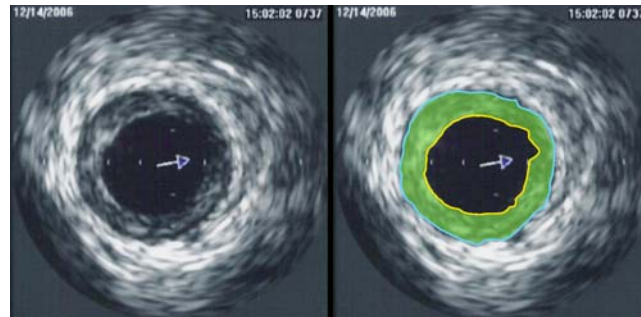
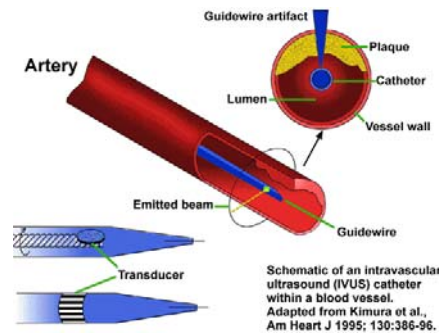
All Other Tissue Harmonic Imaging Methods



68

## Intravascular ultrasound (IVUS)

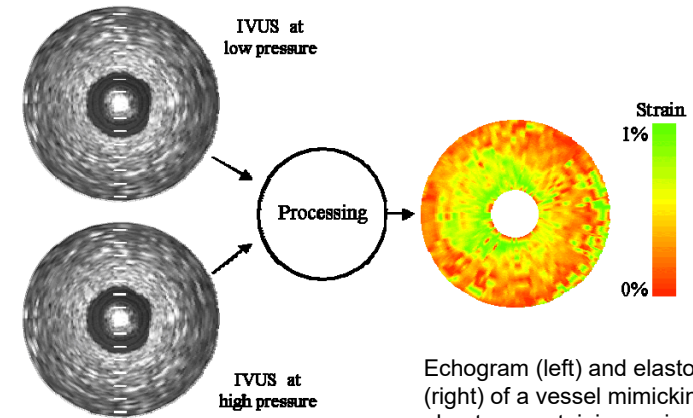
20-40 MHz, frame rate: 30 Hz



lumen of the coronary artery: yellow

outer elastic membrane: blue

## Intravascular sonoelastography



Echogram (left) and elastogram (right) of a vessel mimicking phantom containing an isoechoic soft lesion between 7 and 11 o'clock. The lesion is invisible in the echogram, while it is clearly depicted in the elastogram

## Safety

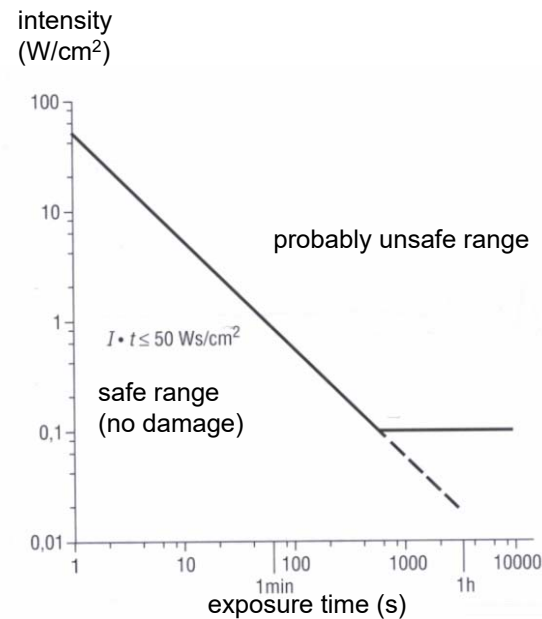
in the diagnostics:

10 mW/cm<sup>2</sup> = 100 W/m<sup>2</sup>

cf. pain threshold: 10 W/m<sup>2</sup>

in the therapy: 1 W/cm<sup>2</sup>

spatial average temporal average (SATA) intensity;  
spatial peak temporal peak (SPTP) intensity;  
spatial peak temporal average (SPTA) intensity;  
spatial peak pulse average (SPPA) intensity  
spatial average pulse average (SAPA) intensity



more:

practices

in our practical laboratories

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