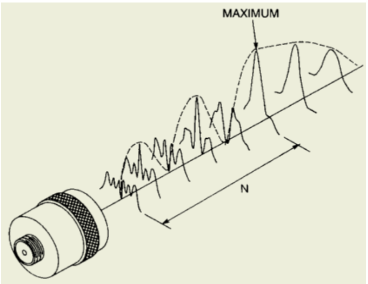
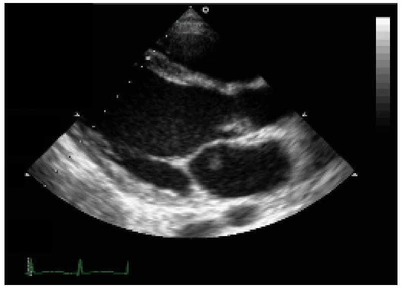
Physics of ultrasonography



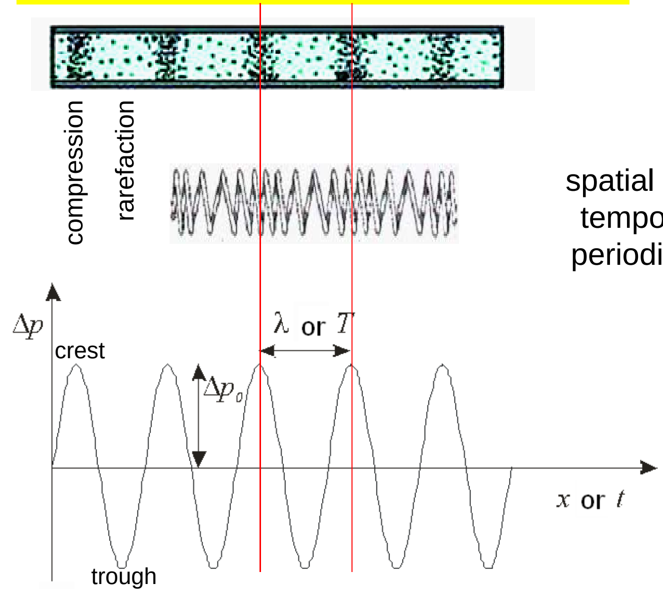


Sound: mechanical wave (model)

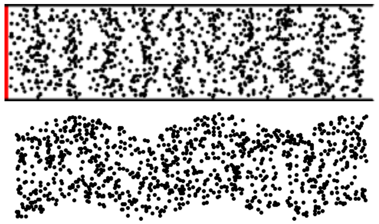
whistle

spring

function



spatial and temporal periodicity



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

transverse wave

hydrostatic pressure

pressure change, sound pressure

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

pressure DC + AC

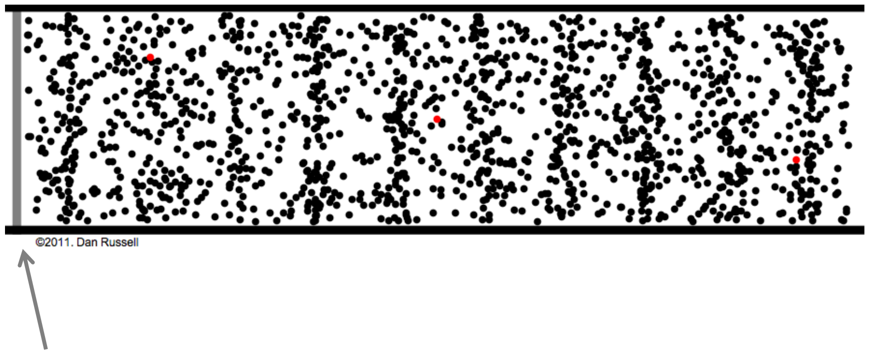
amplitude phase

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

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

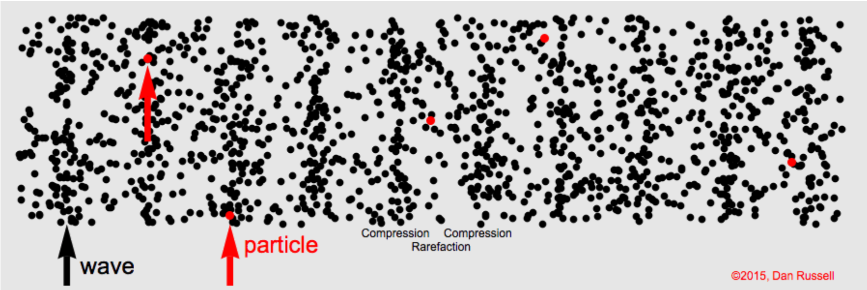
Biophysics textbook, Fig. II.46.

longitudinal wave

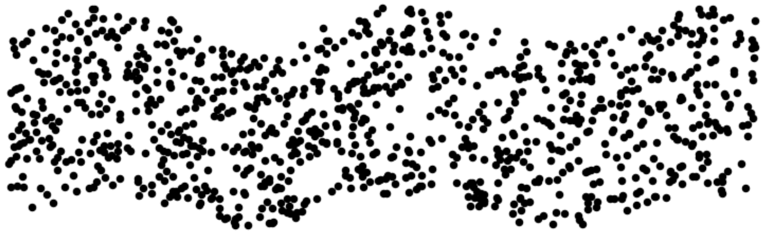


moving surface (source of wave)

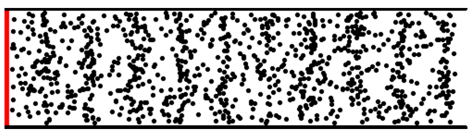
longitudinal wave



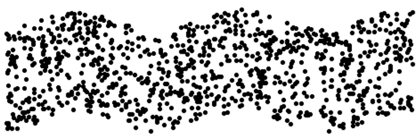
transverse wave



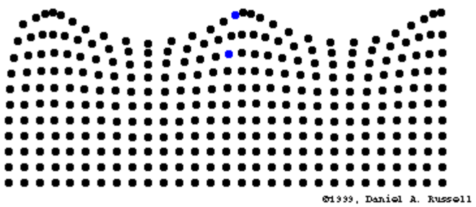
longitudinal wave



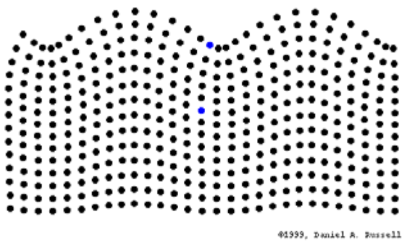
transverse wave

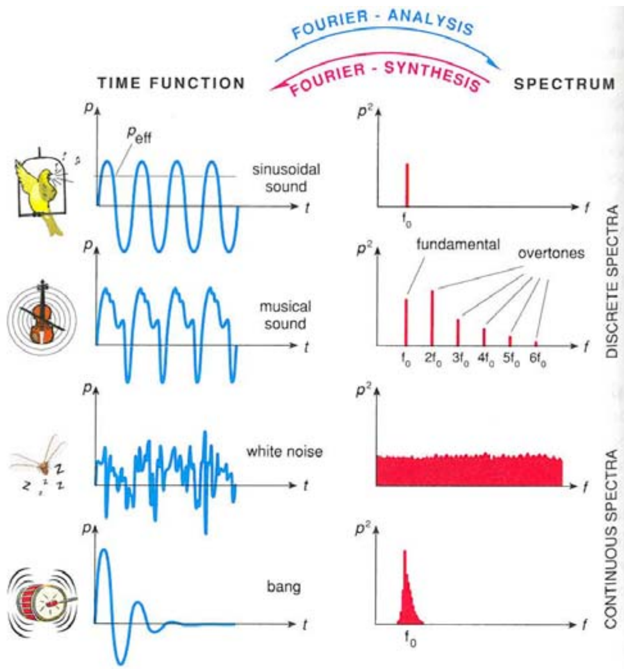


surface wave



Rayleigh wave

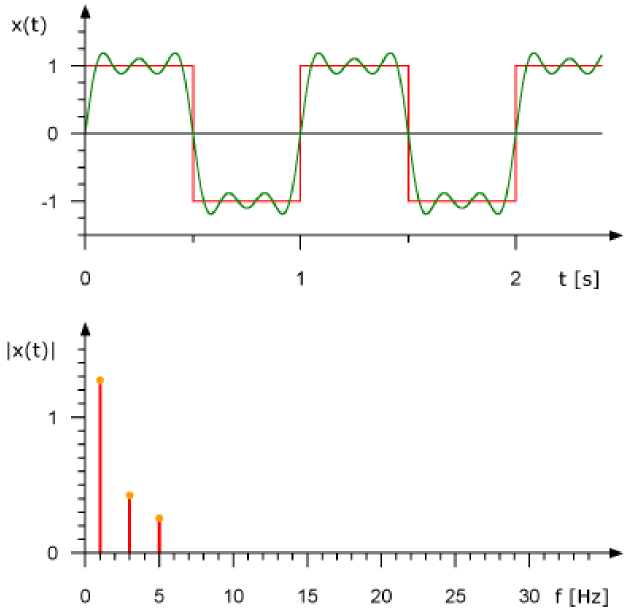




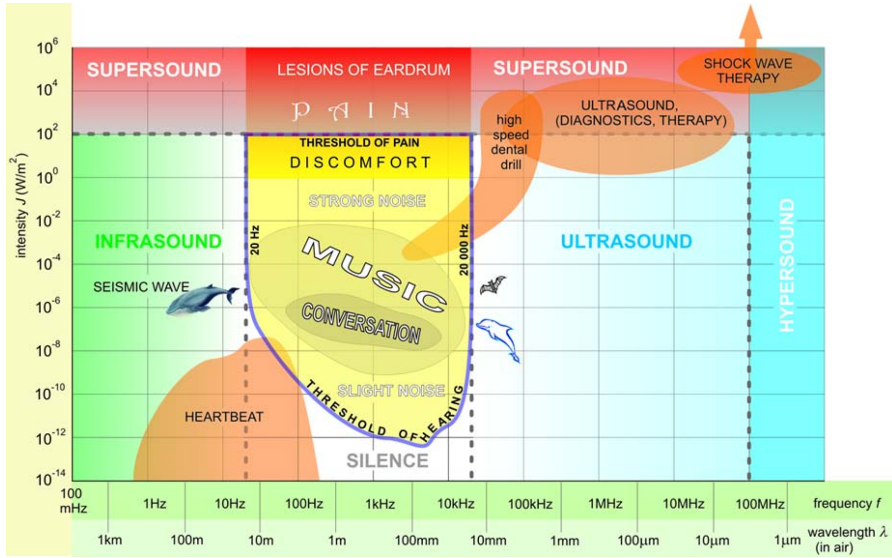
Biophysics textbook, Fig. IV.23.

pitch: frequency of the fundamental

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



Frequency and intensity regions of sounds



Laboratory manual, Audiometry

The role of elastic medium

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

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)

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

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

acoustic **impedance** (useful form)

Supplementary material

Acoustic impedance (way to the useful form)

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

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

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

$$ma = F$$

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

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

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

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

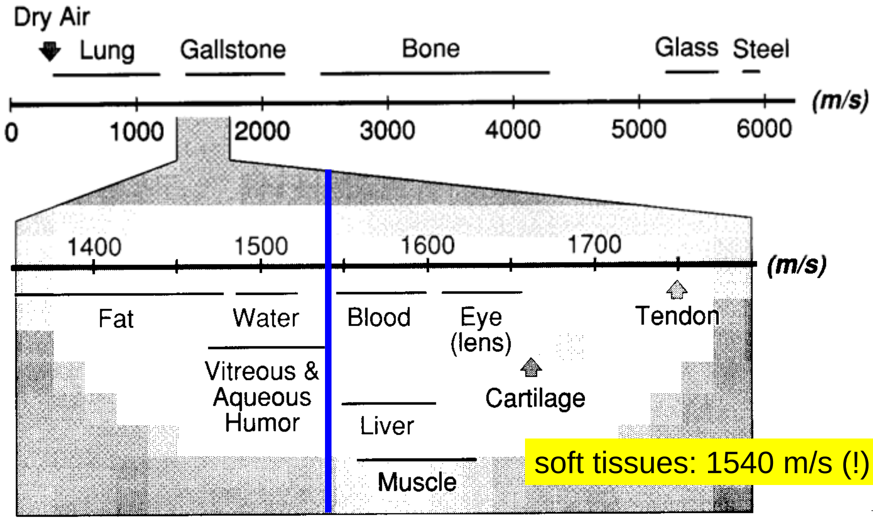
$$\rho y_{\max}\omega^2 \sin\left[\omega(t - \frac{x}{c})\right] = \frac{\Delta p}{\Delta x}$$

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

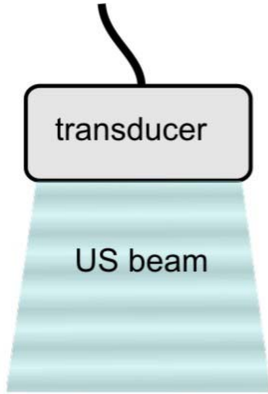
$$p_{\max} = \rho y_{\max}\omega c = \rho v_{\max} c$$

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

Speed of sound/US in different media



soft tissues: 1540 m/s (!)

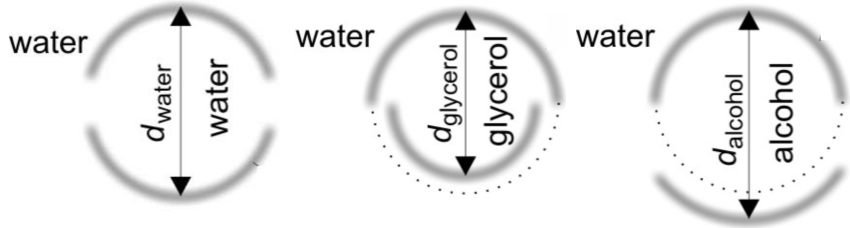


Assuming constant speed of US ➡ Artefacts

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

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

contours of the rubber glove finger on the screen



Laboratory manual, US, Figure 15

Intensity of US

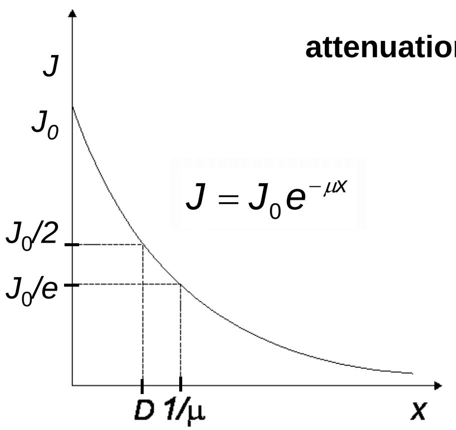
$$J = \frac{1}{Z}\Delta p_{eff}^{\;2}$$

intensity = energy-current density

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

electric analogy

Loss of energy during propagation (absorption)



attenuation: $\alpha = 10 \cdot \lg \dfrac{J_0}{J}$ dB

$\alpha = 10 \cdot \mu \cdot x \cdot \lg e$ dB

μ is proportional to frequency in the diagnostic range

specific attenuation: $\boxed{\dfrac{\alpha}{f \cdot x}}$

μ is proportional to frequency in the diagnostic range

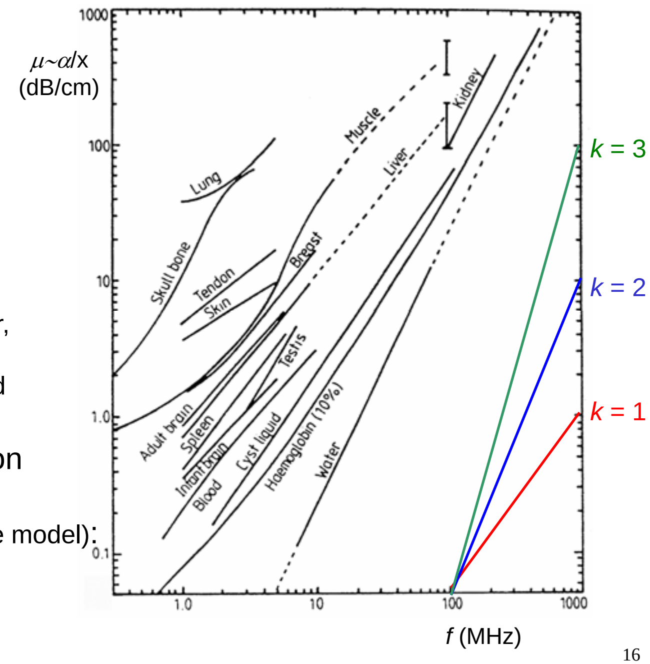
$\mu \sim f^k, \quad k \sim 1(?)$

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

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

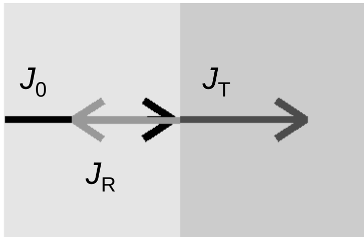
specific attenuation for soft tissues (homogeneous tissue model):

$\boxed{\dfrac{\alpha}{f\,x} \sim 1 \dfrac{\text{dB}}{\text{cm MHz}}}$



Phenomena at the boundary of different media

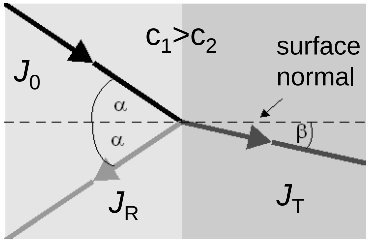
normal/perpendicular incidence



$J_0 = J_R + J_T$

reflection and transmission (penetration)

skew incidence



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

Snellius-Descartes

Biophysics textbook, Fig. II.47.

Reflection (normal incidence)

reflectivity:

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

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

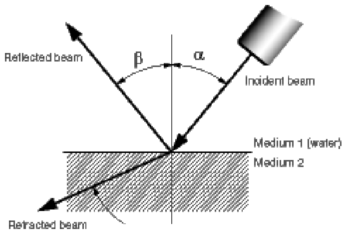
"full" reflection:

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

optimal coupling:

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

Supplementary material



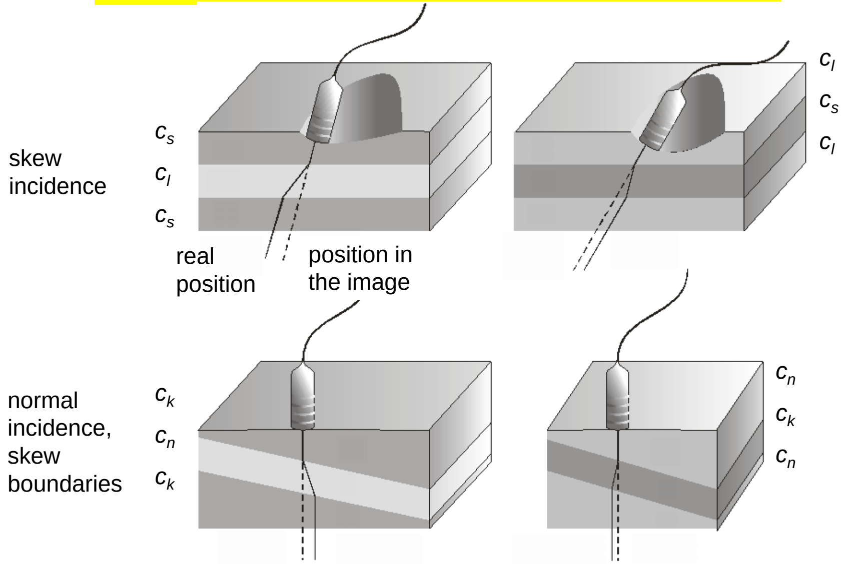
Skew incidence

$$\text{Reflexion coefficient} = R = \left[\frac{z_2\cos\alpha - z_1\cos\gamma}{z_2\cos\alpha + z_1\cos\gamma}\right]^2$$

$$\text{Refraction coefficient} = D = \frac{4 z_1 z_2 \cos^2\alpha}{(z_2\cos\alpha + z_1\cos\gamma)^2}$$

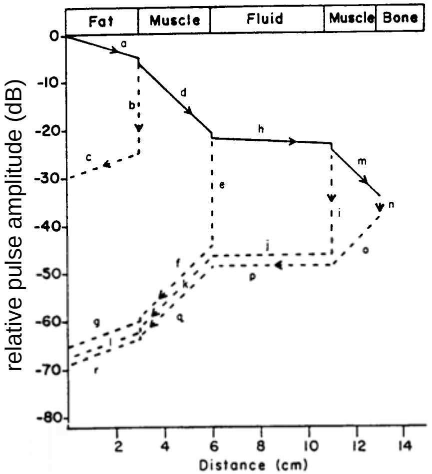
$$\text{Refraction angle} = \gamma = \operatorname{asin}\left(\frac{c_2 \sin\alpha}{c_1}\right)$$

Phenomenon of skew incidence or normal incidence and skew boundaries



Biophysics textbook, Fig. on pg. 153

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*	10lg*R* (dB)	*T*	10lg*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

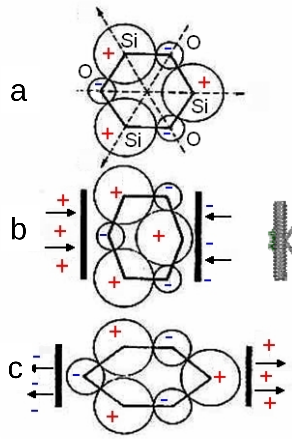
Generation of US. Piezoelectric effect

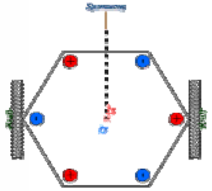
production: inverse ~
detection: direct ~

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 ~).





at home:
gas igniter

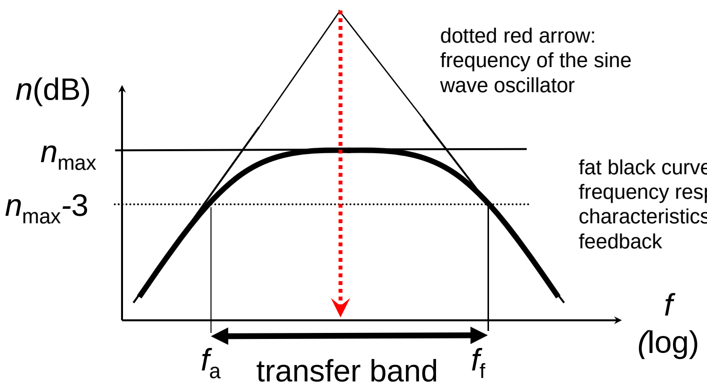
tweeter

Source of electric signal : sine wave oscillator

amplifier with positive feedback

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

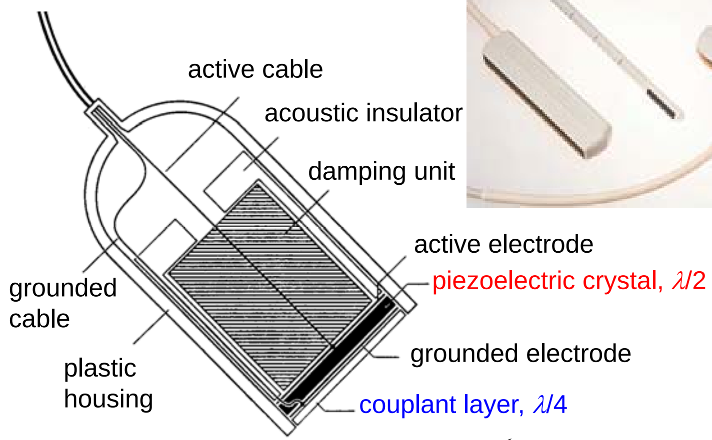
βA_U=1, amplification = „infinity“ ➡ sine wave oscillator
no input signal, output signal: sine voltage



dotted red arrow: frequency of the sine wave oscillator

fat black curve: frequency response characteristics without feedback

Ultrasound transducer

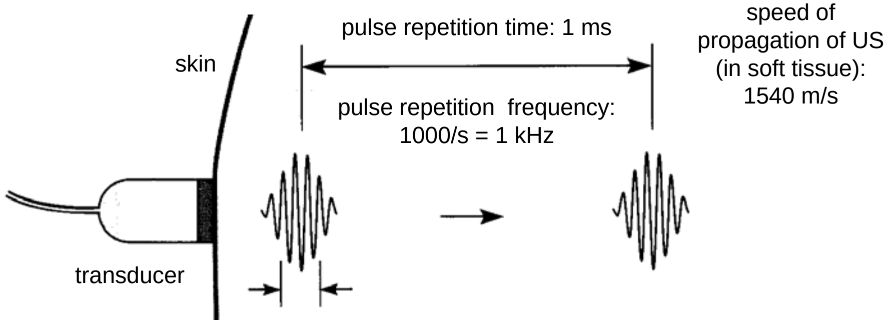


receiver

transmitter

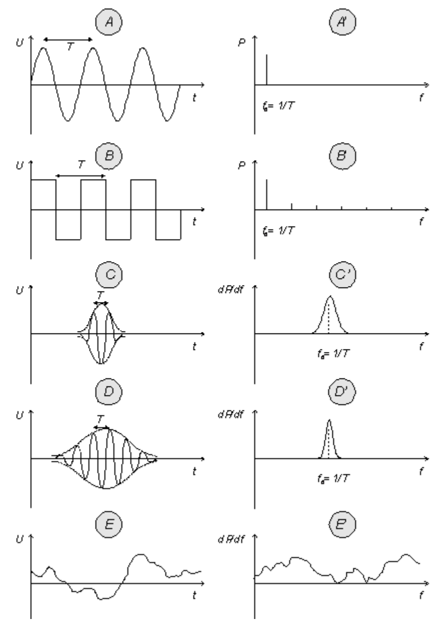
Characteristic of US pulses

transducer: transmitter and receiver is the same unit
time sharing mode: pulses instead of continuous wave US



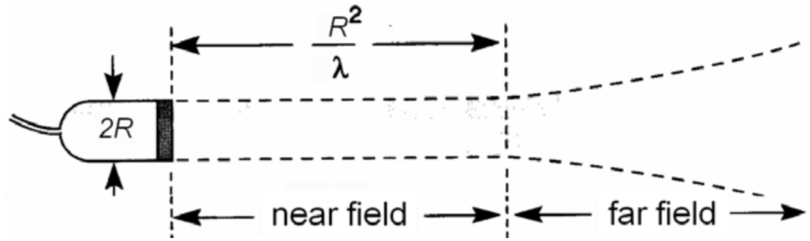
Biophysics textbook, Fig. VIII.32.

Time function **Spectrum**

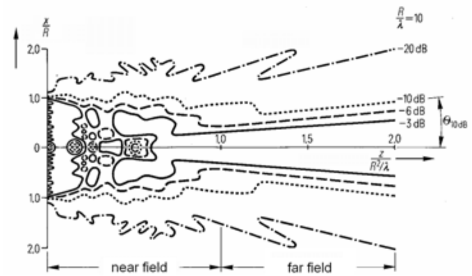


	Time function	Spectrum	
sine function	A	A'	line spectrum (1 line)
square function	B	B'	line spectrum
sine wave pocket (some „periods”)	C	C'	band spectrum
sine wave pocket (several „periods”)	D	D'	**US pulse** band spectrum
aperiodic function	E	E'	continuous spectrum

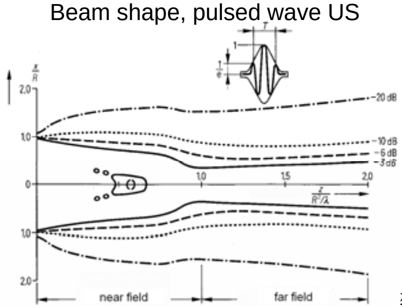
US beam shape (simplified version)



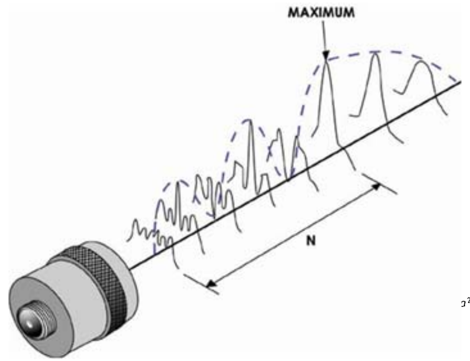
Beam shape, continuous wave US

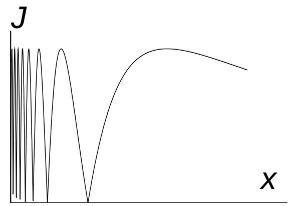


Beam shape, pulsed wave US

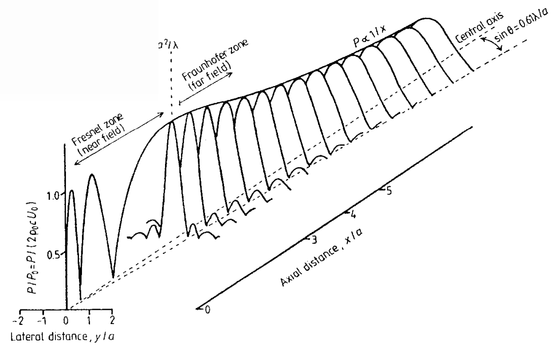


Perspective view of the US beam





change of the intensity in the axial direction



cf. Textbook. Fig. on p.505

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)

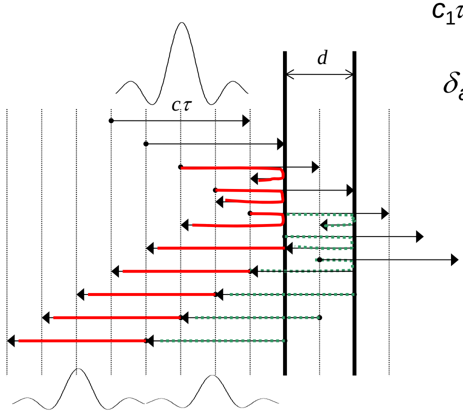
Axial resolving limit depends on the pulse length. Pulse length is inversly proportional to the frequency.

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

Typical values

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

Axial resolving limit



τ : pulse duration

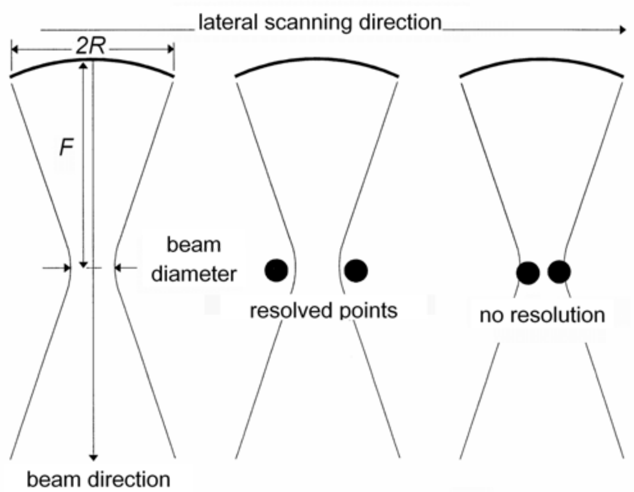
$c_1\tau \cong c_2\tau = c\tau$ pulse length

$\delta_{ax} = d = \dfrac{c\tau}{2}$ 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.

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

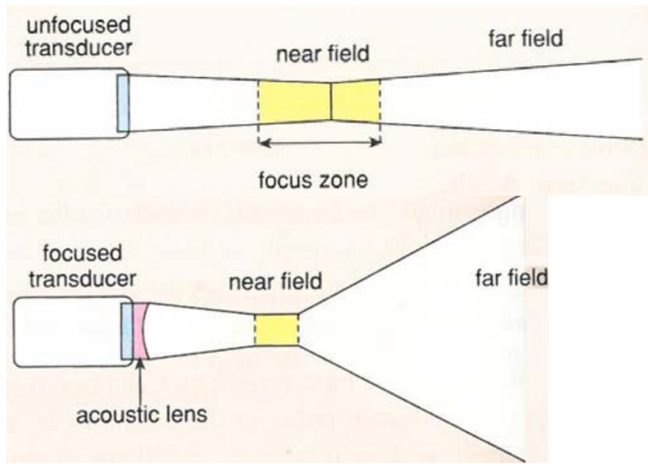
Lateral resolving limit



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

F: focal length
$2R$: diameter of the transducer
λ: wavelength

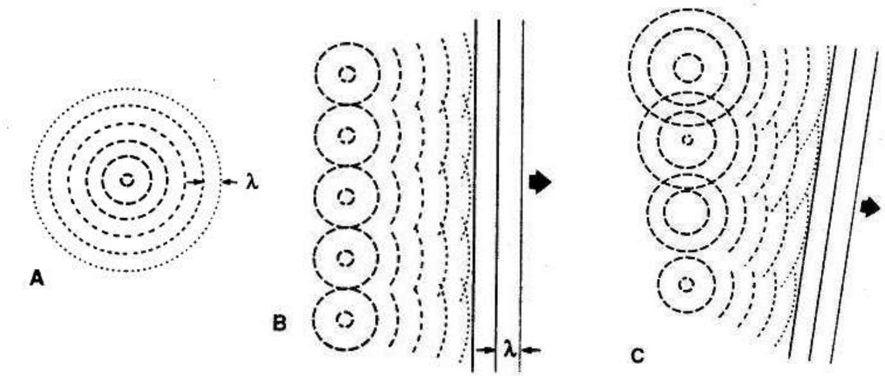
Focusing of the beam



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

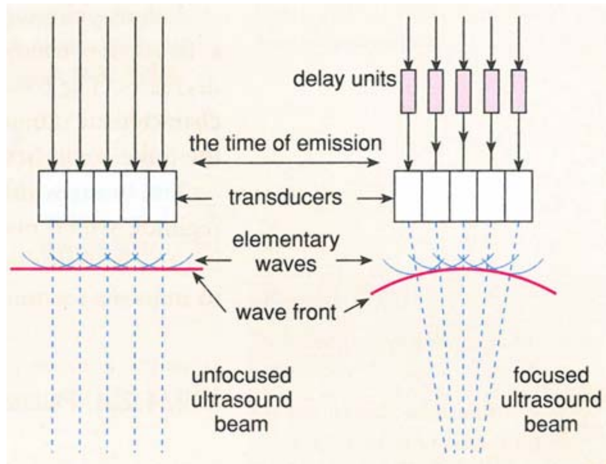
cf. Textbook Fig. on p.506

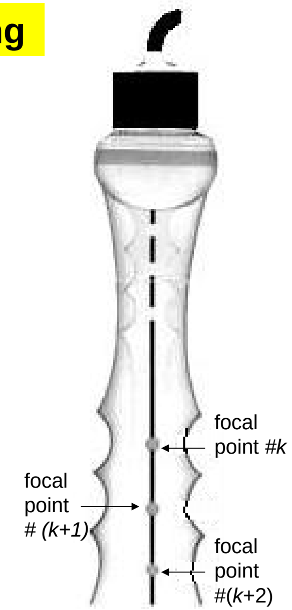
Huygens' principle



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.

Electronic focusing

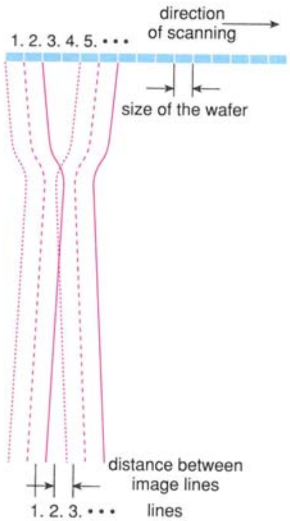




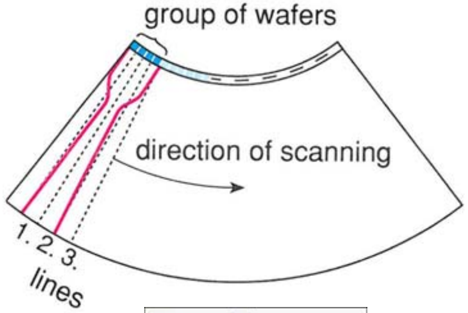
cf. Textbook Fig. on p.507

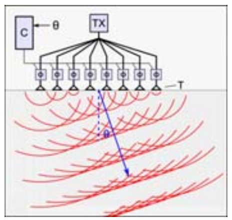
Scanning

multi unit linear array



multi unit curved array



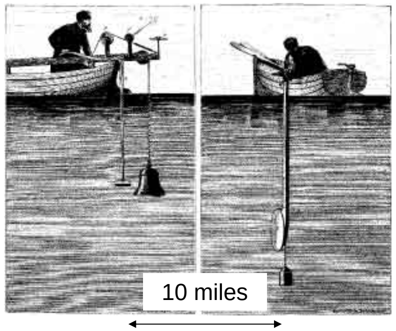


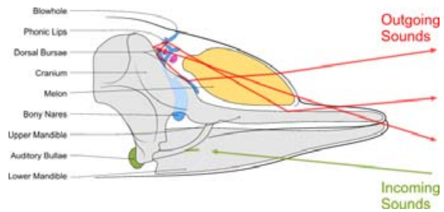
cf. Textbook Fig. VII. 36-37

Echo principle

1794 Spallanzani:
bat's navigation

1822 Colladen
measured the speed of
sound in water

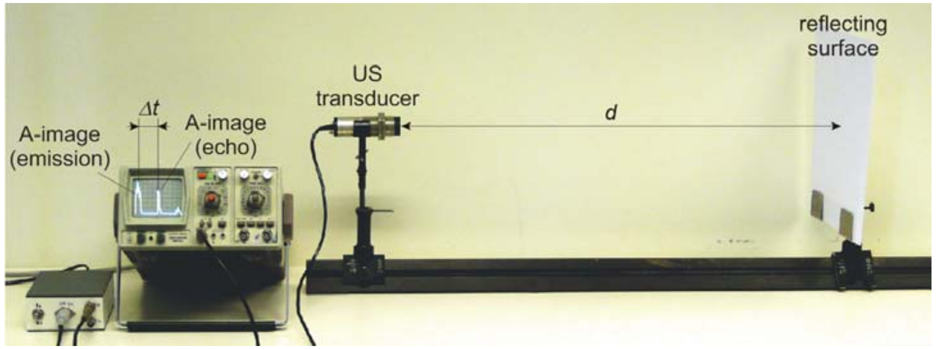




bottlenose dolphin

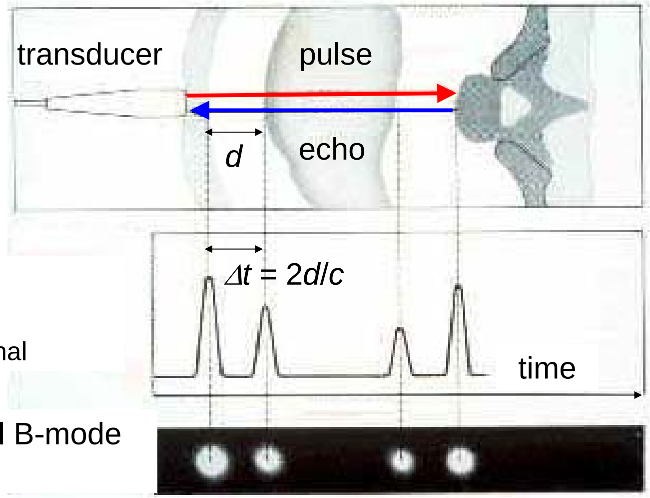
Echo principle

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



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

Receiving the echos



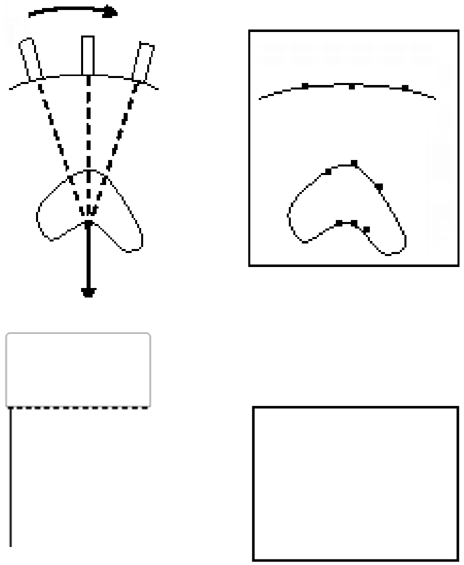
A-mode
(***A***mplitude)
only 1-dimensional

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

cf. Textbook Fig. VIII.33

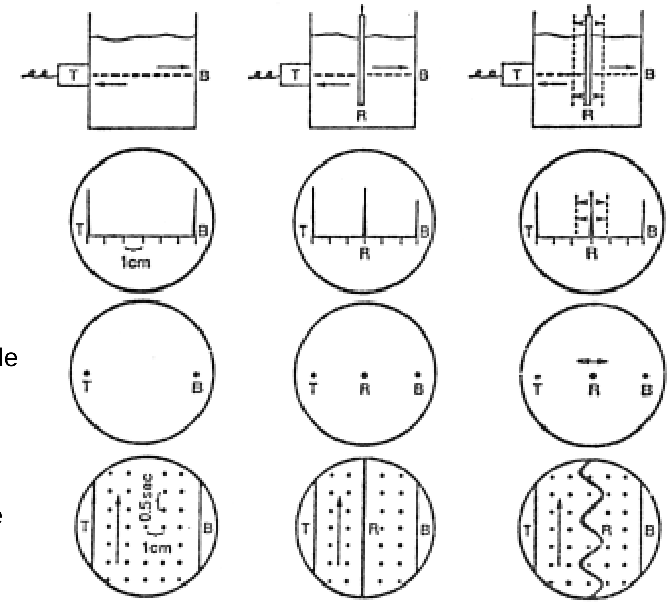
2-dimensional B-mode

moving transducer



B-mode

display

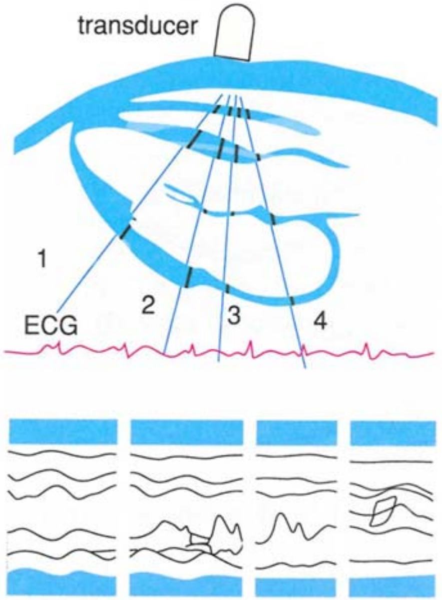


A- mode

1D B- mode

TM- mode

TM-mode



ECG signal
for reference

time

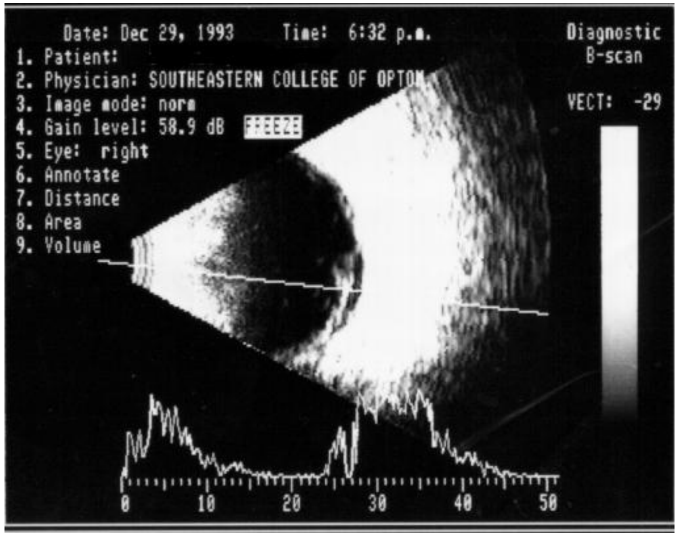
(vertical)
time-dependent
1-dimensional
B-mode

(T)M-mode

Time–
Motion

Textbook Fig. VIII.34

2-dimensional B-mode and A-mode
(used in opthamology)



real speed of propagation for the accurate determination of distances:

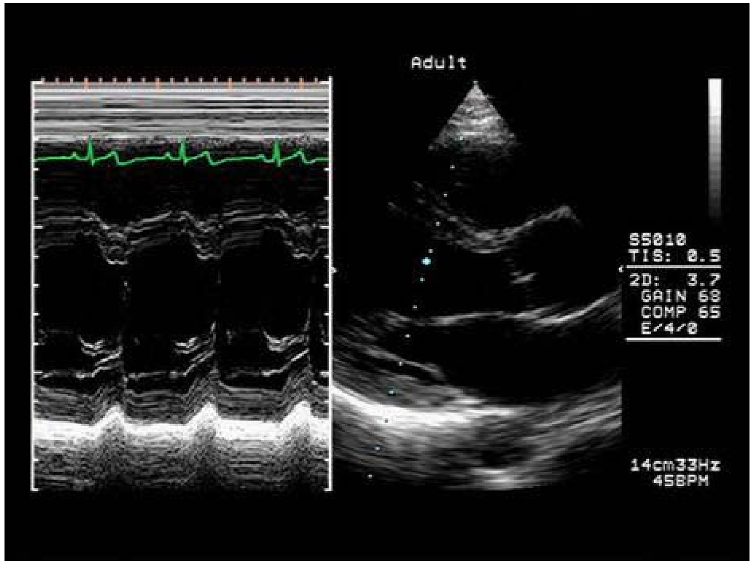
cornea: 1641 m/s

aqueos humour: 1532 m/s

crystalline lens: 1641 m/s

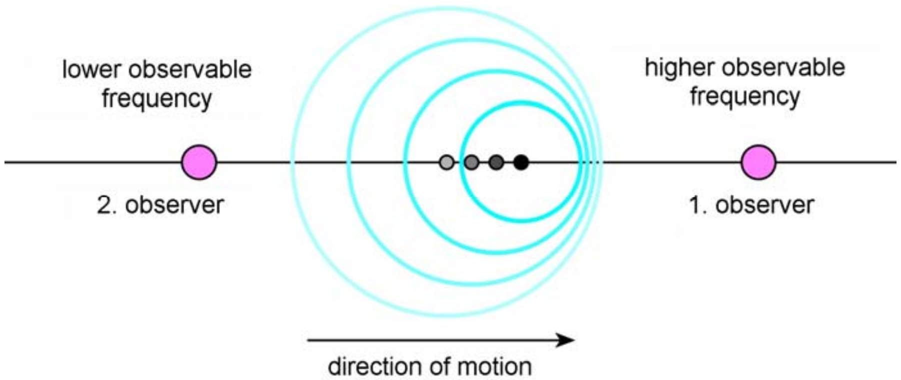
vitreous body: 1532 m/s

TM-mode B-mode



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)



Teextbook Fig. VIII.39

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

(a) standing source and moving observer (v_O)
+: observer approches the source
–: observer moves away from the source

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

(b) moving source and standing observer
(if v_S<<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<<c)

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

Doppler frequency = frequency change = frequency shift

if v_i, v_R<<c (i= S or O)

rearranging equation (a)
moving source or observer:

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

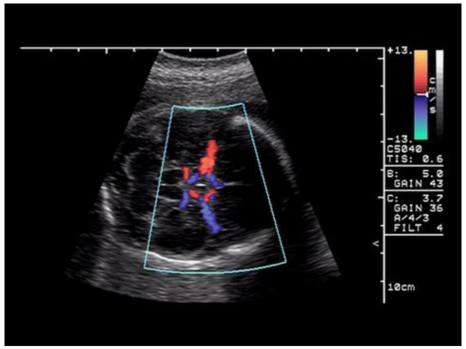
rearranging equation (d)
moving reflecting object or surface:

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

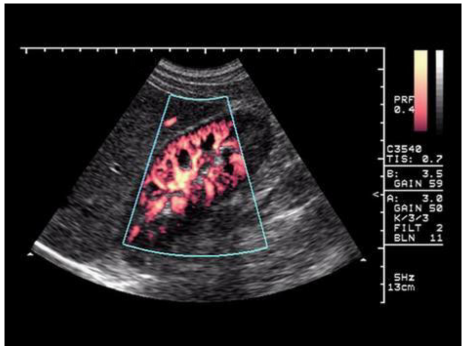
if v and c are not parallel, then $v \cos\Theta$ should be used instead of v (remark: if Θ = 90°, f_D = 0)

Colour coding

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



BART: Blue Away Red Towards



power Doppler

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

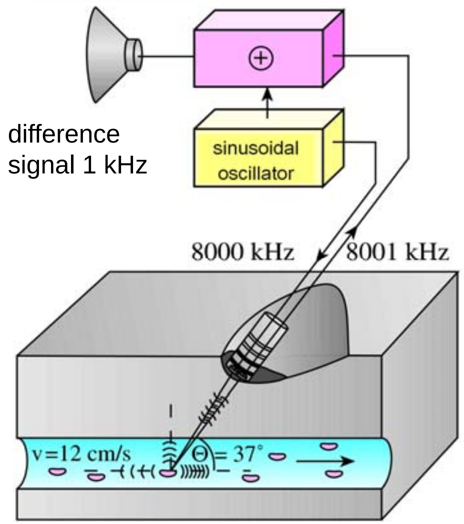
CW: continuous wave

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
Θ = 37º

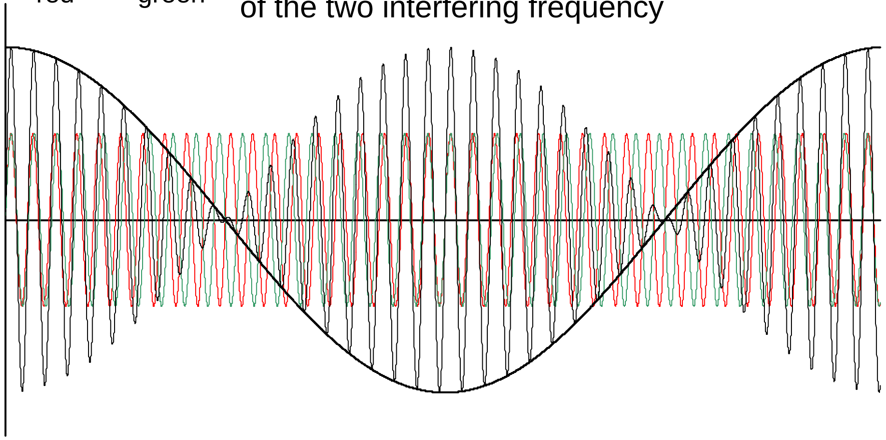
⇨f_D=1 kHz
(beating phenomenon)



Textbook Fig. VIII.41

Beating phenomenon

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

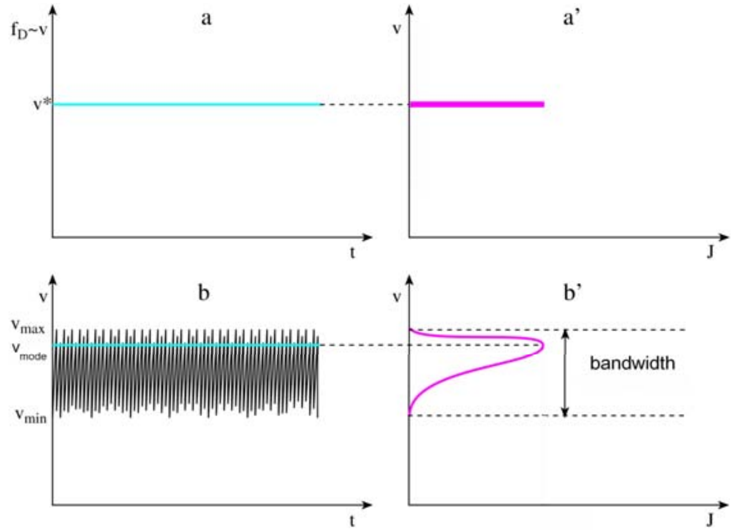


reminder: $\sin\alpha + \sin\beta = 2\sin\frac{\alpha+\beta}{2}\cos\frac{\alpha-\beta}{2}$

Doppler curves

one constant velocity (v*)

frequency distribution (with v_{mode})



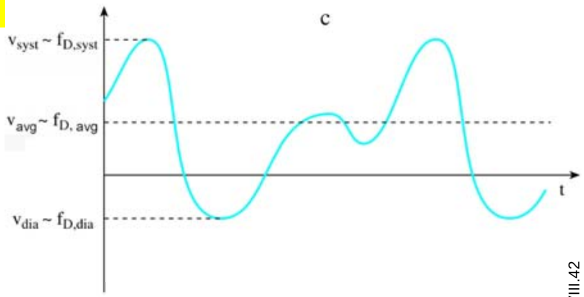
velocity distribution in TM-mode

velocity distribution at a certain time

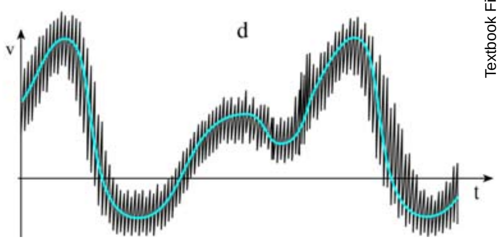
Textbook Fig. VIII.42

Doppler curves

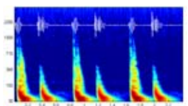
flow can be represented by one velocity in each moment



flow can be represented by a velocity distribution in each moment

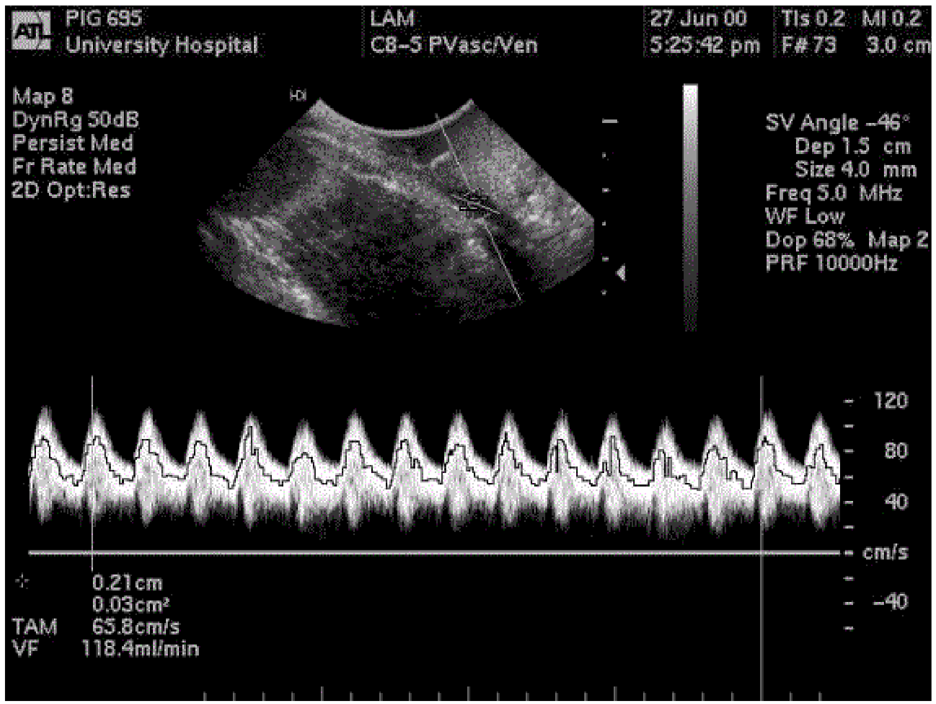


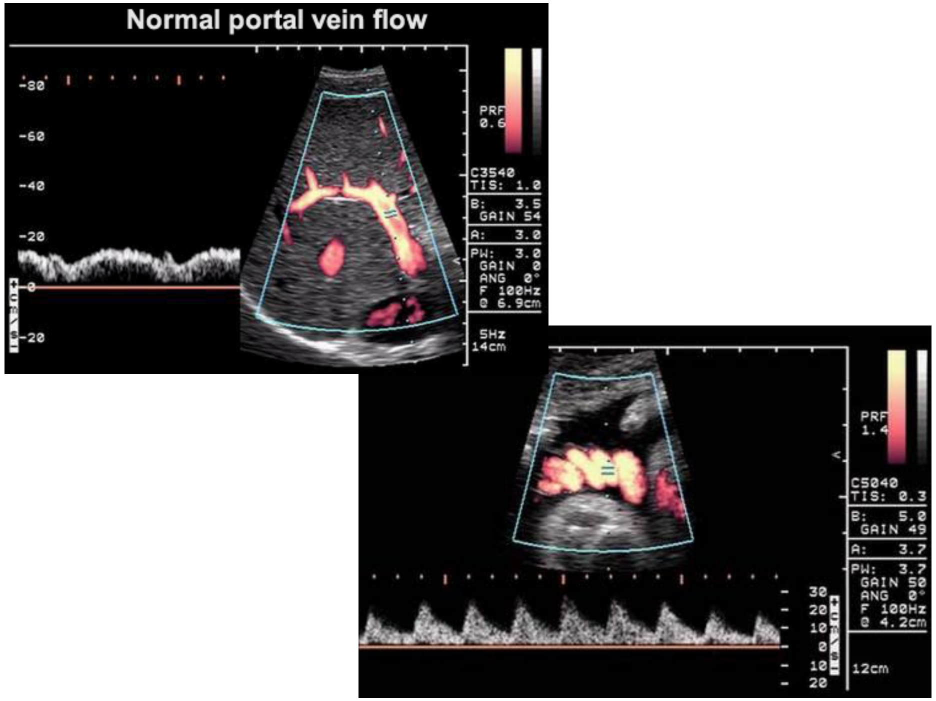
Textbook Fig. VIII.42



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

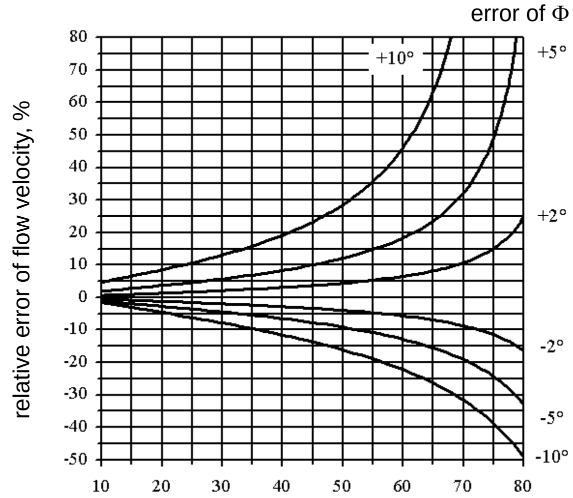
velocity distribution in TM-mode





Supplementary material

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



Φ (= angle between the US-beam and axis of blood vessel)

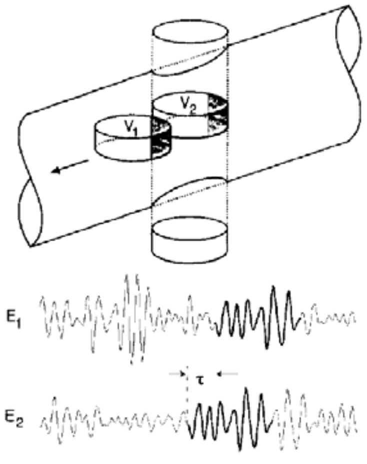
Speckle tracking/Time domain correlation method
(CVI = color velocity imaging)

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

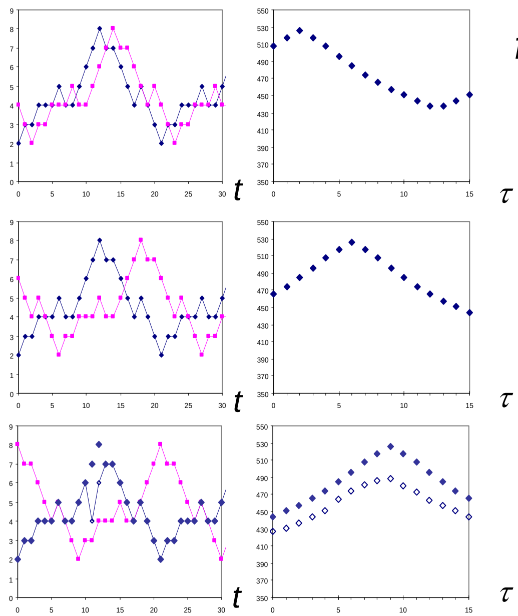
Similar US pattern can be measured at a certain distance from the earlier position (where the reflecting surface/scatterer moved).

How can be compared the similarity of different functions?

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



time domain correlation function



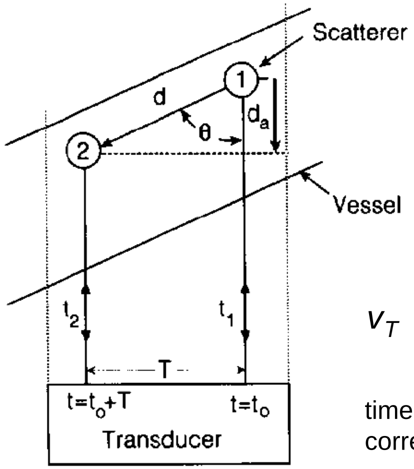
$$f_{\text{blue}}(t) = f_{\text{pink}}(t + \tau^*)$$

$$\tau^* = 2\text{ u}$$

$$\tau^* = 6\text{ u}$$

$$\tau^* = 9\text{ u}$$

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



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

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

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

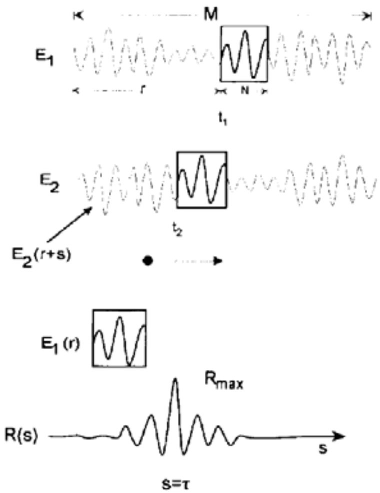
time domain correlation method

cf.: Doppler method

T : pulse repetition time

f : frequency of US

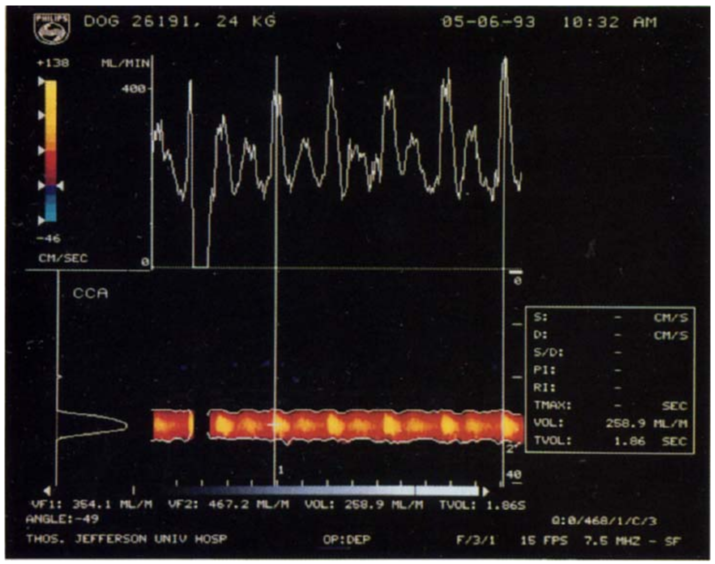
IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUNCY CONTROL, VOL. 40, NO. 6, NOVEMBER 1993



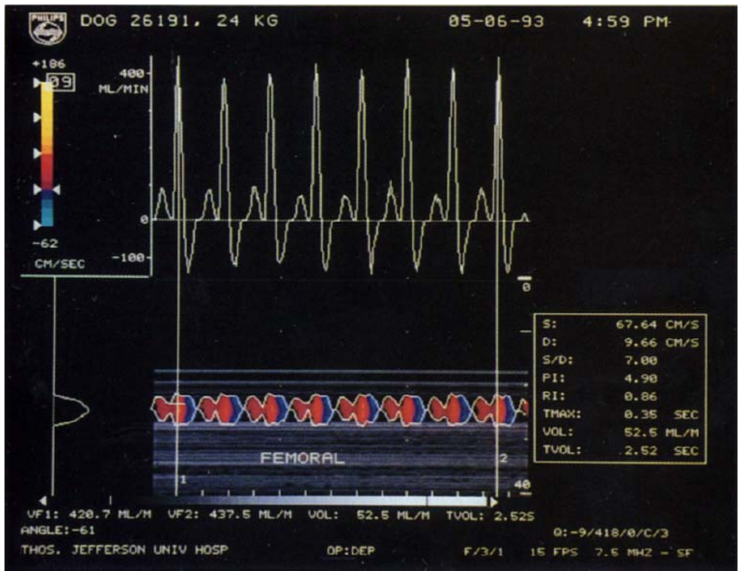
correlation procedure consists of removing a window of width N at desired range from on echo signal E_1

E_1 is correlated at different locations along another echo signal E_2

the value of s producing the maximum corresponds to s = τ



Ultrasound in Med. & Biol., Vol. 21, No. 8, pp. 1037–1045, 1995



Ultrasound in Med. & Biol., Vol. 21, No. 8, pp. 1037–1045, 1995

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

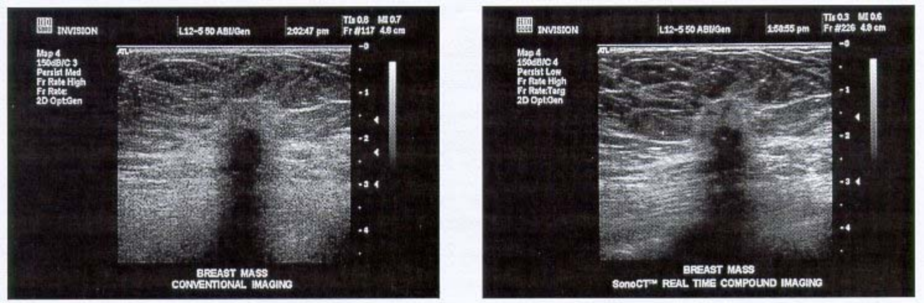
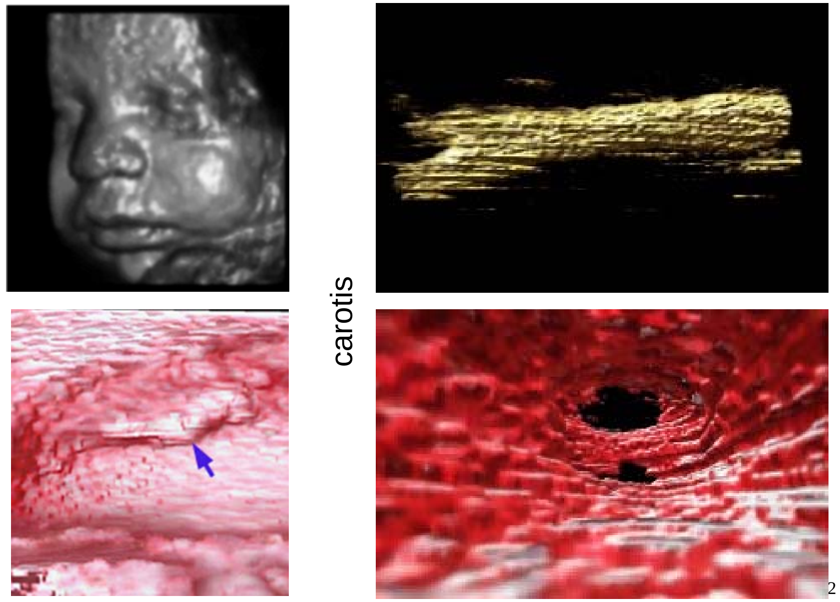


Figure 1. Breast fibroadenoma as shown on conventional ultrasound (left) and SonoCT ultrasound imaging (right).

3D reconstruction



2

palpation:
one of the oldest clinical skills,
tissue elasticity

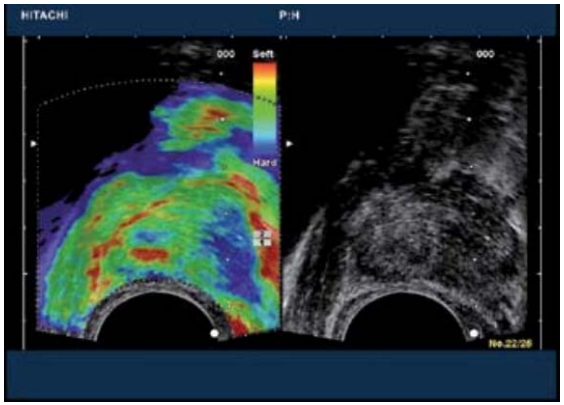
strain:
a region of tissue is compressed and the **degree to which it distorts** is assessed

Hooke's law:

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

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

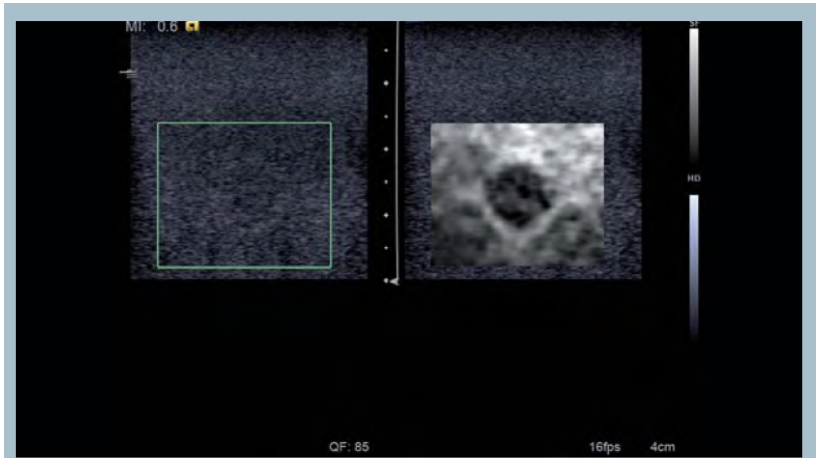
Sonoelastography



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

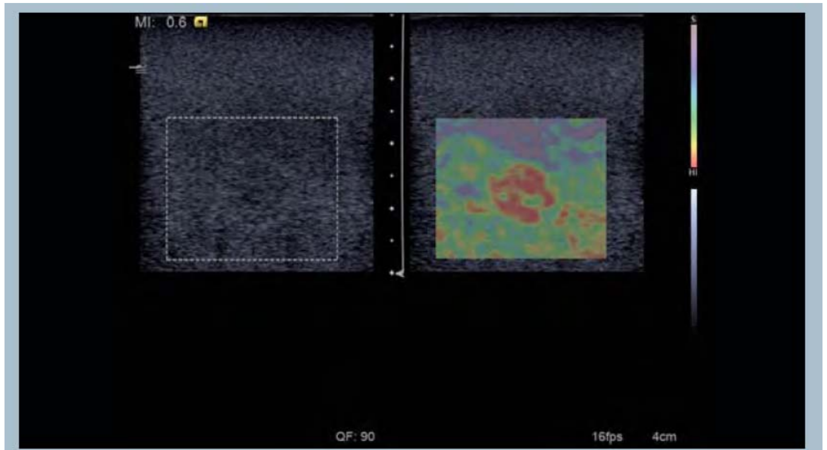
63

Supplementary material



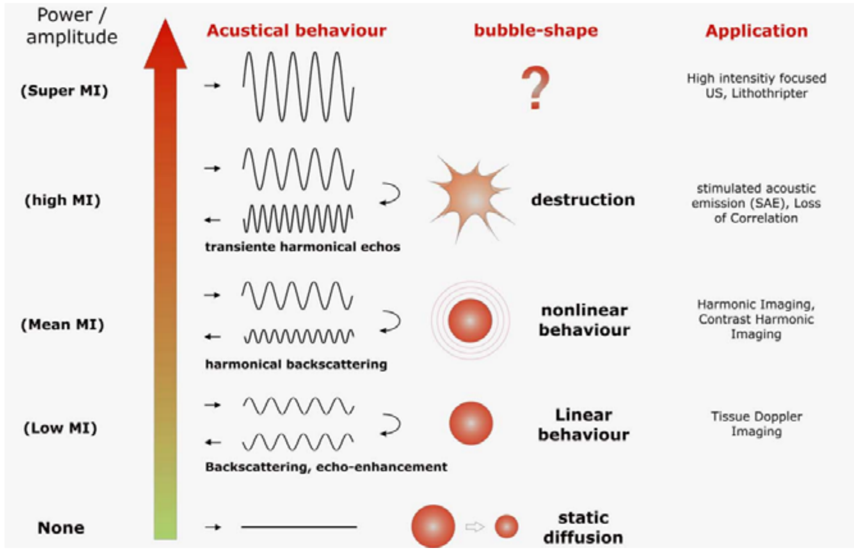
Grayscale eSie Touch Elasticity Imaging demonstrates a lesion which is more stiff (black) than the surrounding tissue. The conventional B-mode ultrasound is the same as displayed in the previous image.

Supplementary material

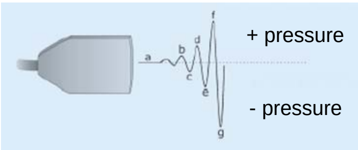


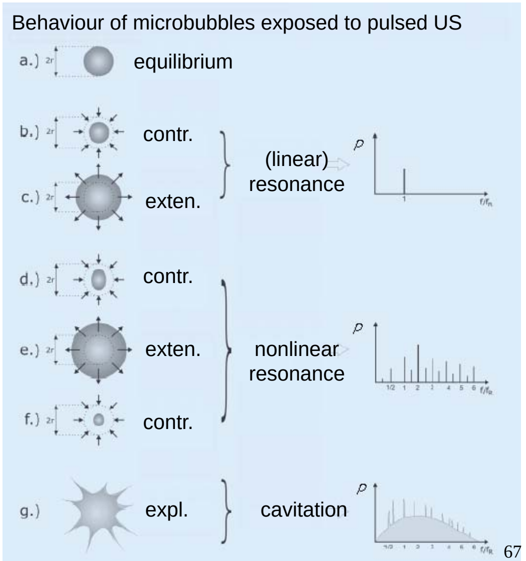
Color scale eSie Touch Elasticity Imaging demonstrates a lesion which is more stiff (red) than the surrounding tissue.

Contrast agents



Contrast harmonic imaging = CHI





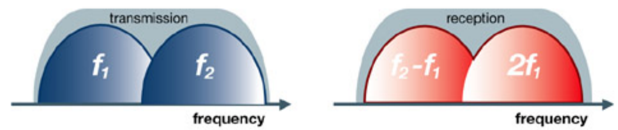
C. Kollmann · M. Putzer
Ultraschallkontrastmittel – physikalische Grundlagen
Radiologe 2005 · 45:503–512

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

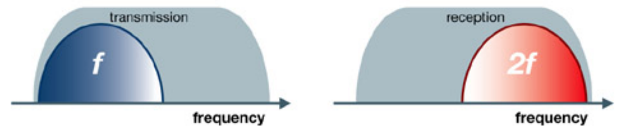
Toshiba

Differential Tissue Harmonic Imaging



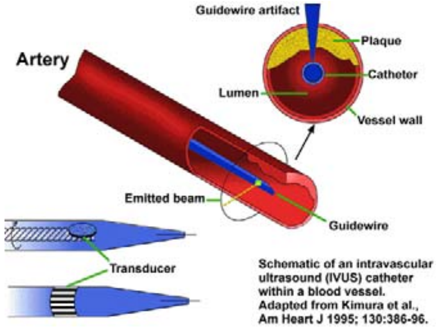
Philips

All Other Tissue Harmonic Imaging Methods

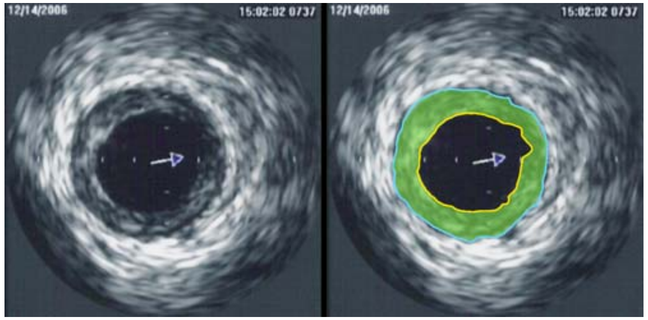


Intravascular ultrasound (IVUS)

20-40 MHz, frame rate: 30 Hz



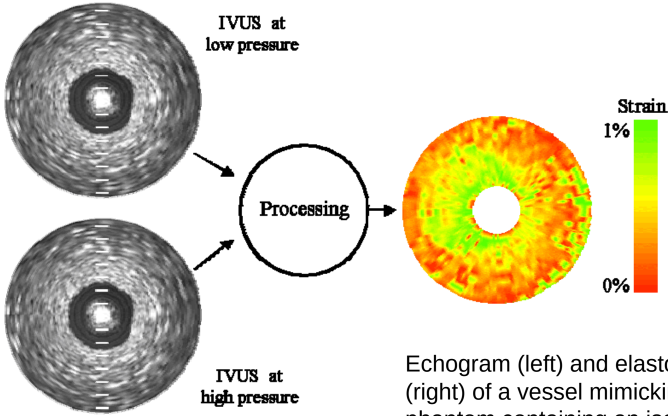
Schematic of an intravascular ultrasound (IVUS) catheter within a blood vessel. Adapted from Kimura et al., Am Heart J 1995; 130:386-96.



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 echogram

Safety

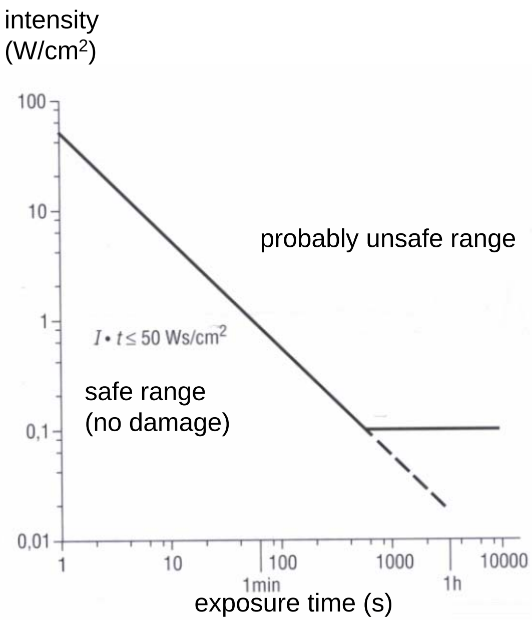
in the diagnostics:

10 mW/cm^2 = 100 W/m^2

cf. pain threshold: 10 W/m^2

in the therapy: 1 W/cm^2

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

in the Skill Center