How to understand ultrasound diagnostics?

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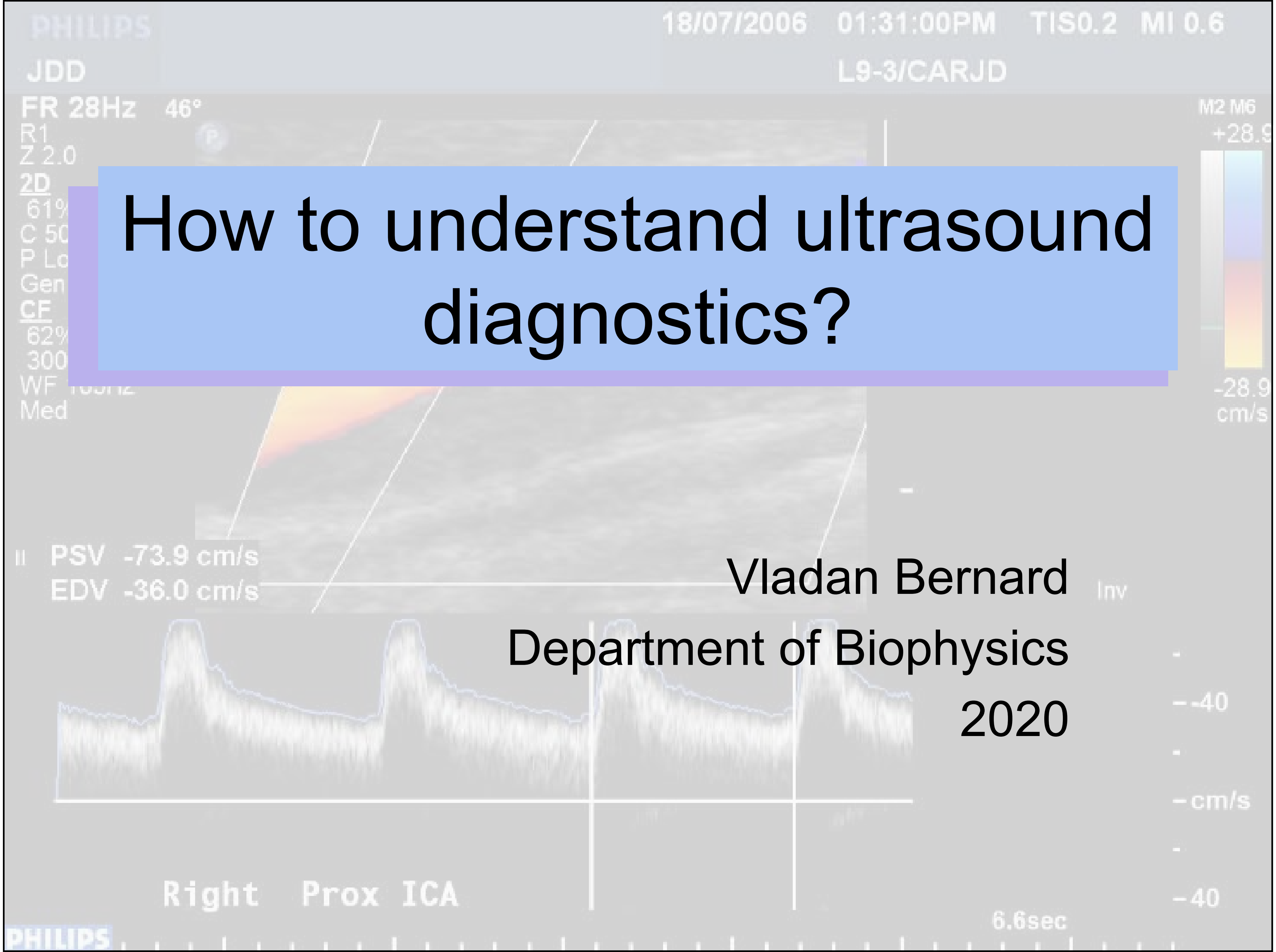


Lecture outline

- introduction to ultrasound
- physical properties of ultrasound and medium
- classification of methods
  - mode A, B and 3D, 4D imaging
  - doppler methods
  - contrast media
- safety, risks

listen to the comment, others are in better quality

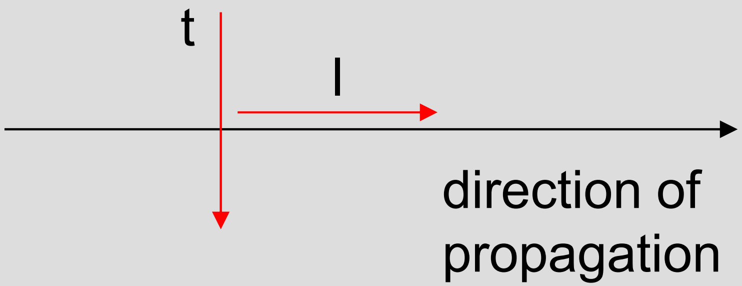
Ultrasound

Ultrasound (US) is *mechanical oscillations* with frequency above 20 kHz which propagate through an elastic medium.

Ultrasound is similar physical phenomenon as the sound; the sound is described by characteristic frequencies from 16 Hz to 16 kHz

In liquids and gases, US propagates as longitudinal waves.

In solids, US propagates also as transversal waves.



Physical properties

Physical properties of ultrasound

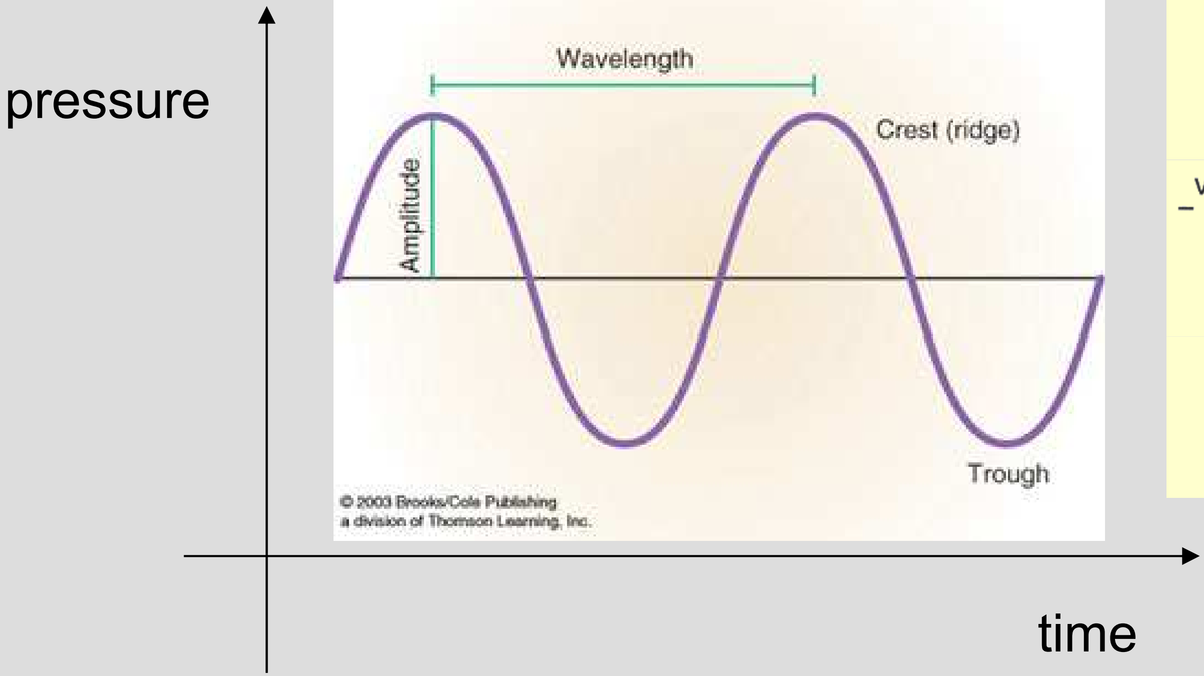
wavelength: λ is usually determined by considering the distance between consecutive corresponding points of the same phase, such as crests, troughs, or zero crossings, and is a characteristic of both traveling waves and standing waves, as well as other spatial wave patterns.

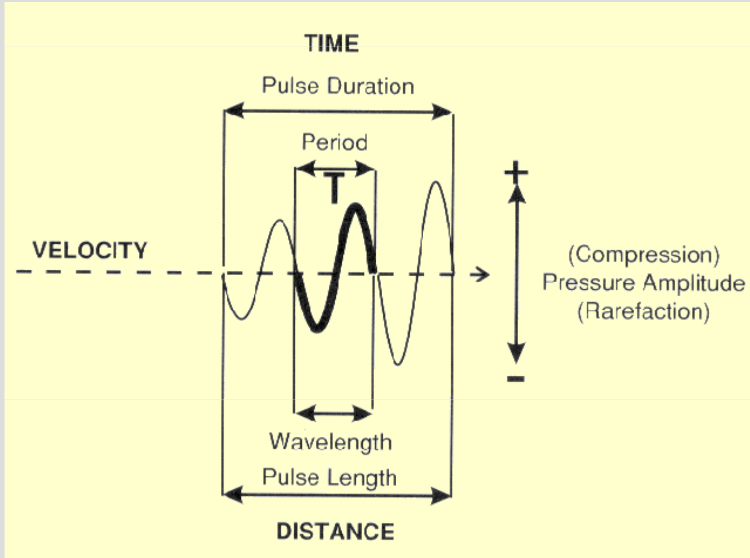
frequency:f is the number of occurrences of a repeating event per unit time

intensity: intensity I of beam US at a point is the amount of energy passing through unit cross-sectional area perpendicularly to the beam per unit time at that point. Intensity is expresed in Joule/second/square centimetre.Intensity can be specified as Watts/square centimetre (W=J/s)

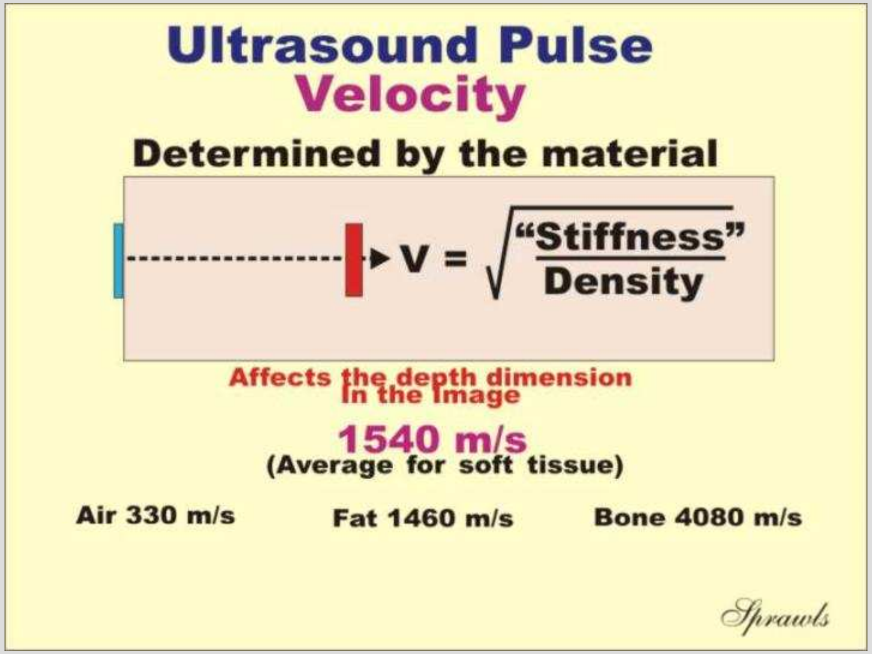
Physical properties

Amplitude may be in the case of ultrasound wave define as a sound pressure level at a given point, for example (or as displacement of mass point in space).





Physical properties



Speed of US c depends on **elasticity** and **density ρ** of the medium:
***K* - modulus of compression**, in water and soft tissues c = 1500 - 1600 m.s^{-1}, in bone about 3600 m.s^{-1}

$$c = \sqrt{\frac{K}{\rho}} \quad [m.s^{-1}]$$

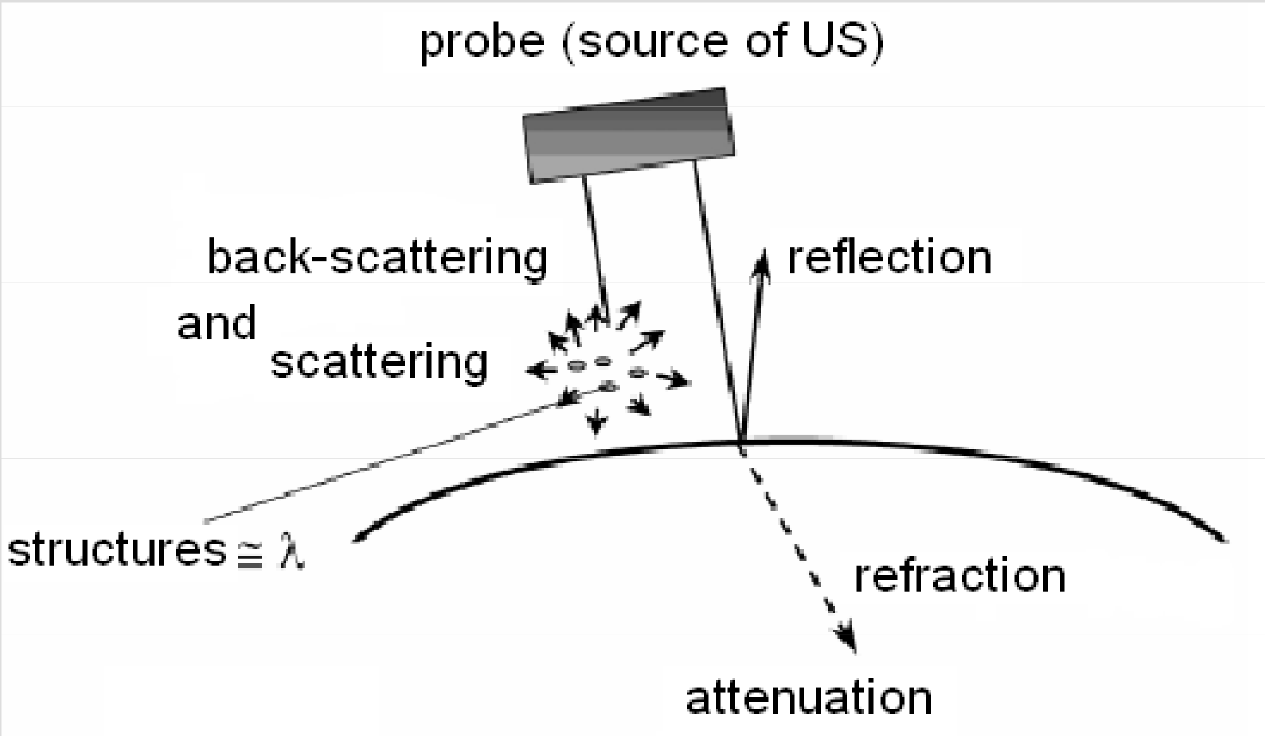
Approximate Velocity of Sound in Various Materials

Material	***Velocity (m/sec)***
Fat	1450
Water	1480
Soft tissue (average)	1540
Bone	4100

Physical properties

Physical properties of medium

Interaction of US with medium – reflection and back-scattering, refraction, attenuation (scattering and absorption)



Physical properties

Physical properties of medium

Attenuation of US expresses decrease of wave amplitude along its trajectory. **It depends on frequency**

$I_x = I_o e^{-2\alpha x}$ $\alpha = \alpha' . f^2$

I_x – final intensity, Io – initial intensity, 2x – medium layer thickness (reflected wave travels „to and from“), α - linear attenuation coefficient (increases with frequency).

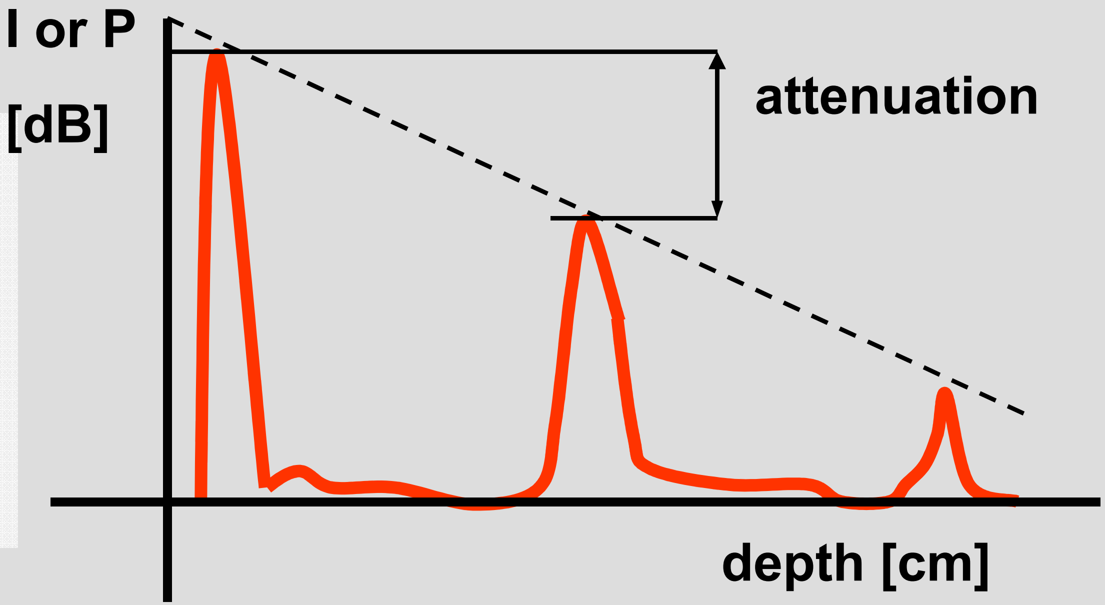
Since

$\alpha = \log_{10}(I_0/I_X)/2x$

we can express α in units dB/cm. At 1 MHz: muscle 1.2, liver 0.5, brain 0.9, connective tissue 2.5, bone 8.0

Physical properties

Physical properties of medium



Attenuation of ultrasound

When expressing intensity of ultrasound in decibels, i.e. as a logarithm of I_x/I_0, we can see the amplitudes of echoes to decrease linearly.

$$\frac{I_x}{I_0} = e^{-2\alpha x} \Rightarrow \ln\frac{I_x}{I_0} = -2\alpha x \Rightarrow \log\frac{I_x}{I_0} = -k' x$$

Physical properties

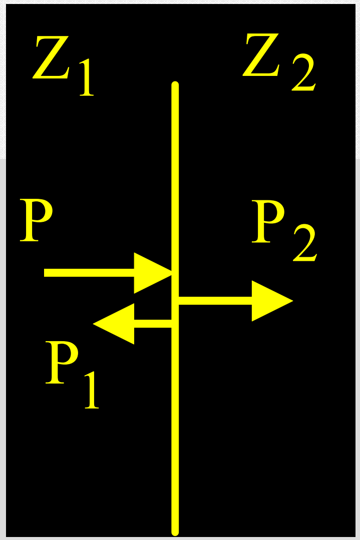
US reflection and transmission on interfaces

We suppose perpendicular incidence of US on an interface between two media with different Z (**Acoustic impedance – following page**) - a portion of waves will pass through and a portion will be reflected (the larger the difference in Z, the higher reflection).

$$R = \frac{P_1}{P} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

P – acoustic pressure

$$D = \frac{P_2}{P} = \frac{2\,Z_1}{Z_2 + Z_1}$$



Coefficient of reflection R – ratio of acoustic pressures of reflected and incident waves

Coefficient of transmission D – ratio of acoustic pressures of transmitted and incident waves

Physical properties

Acoustic parameters of medium

Acoustic impedance: product of US speed *c* and medium density ρ

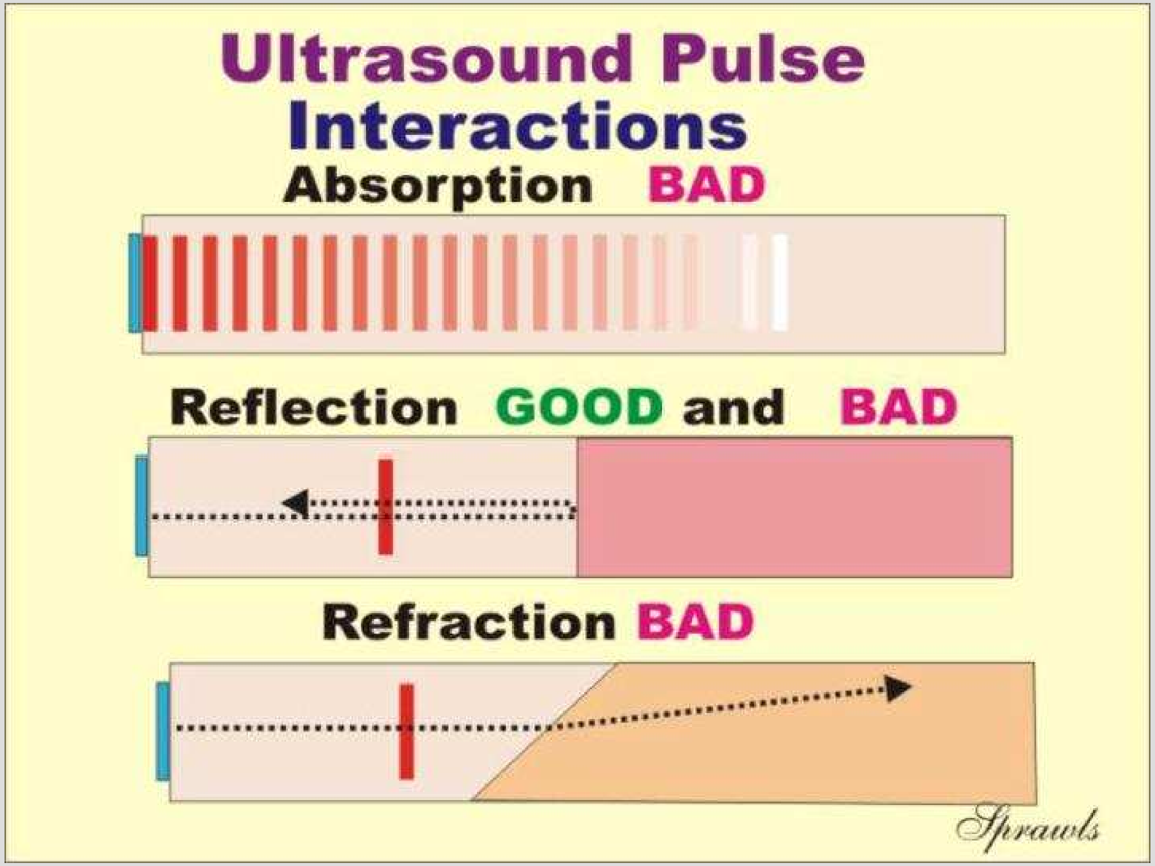
Z = ρ . c (Pa. m/s)

Acoustic impedance Z: muscles 1.7, liver 1.65 brain 1.56, bone 6.1, water 1.48 (x 10^{-6})

Physical quantity describing the „willingness“ of tissue to transmit ultrasound. How to easy propagate ...

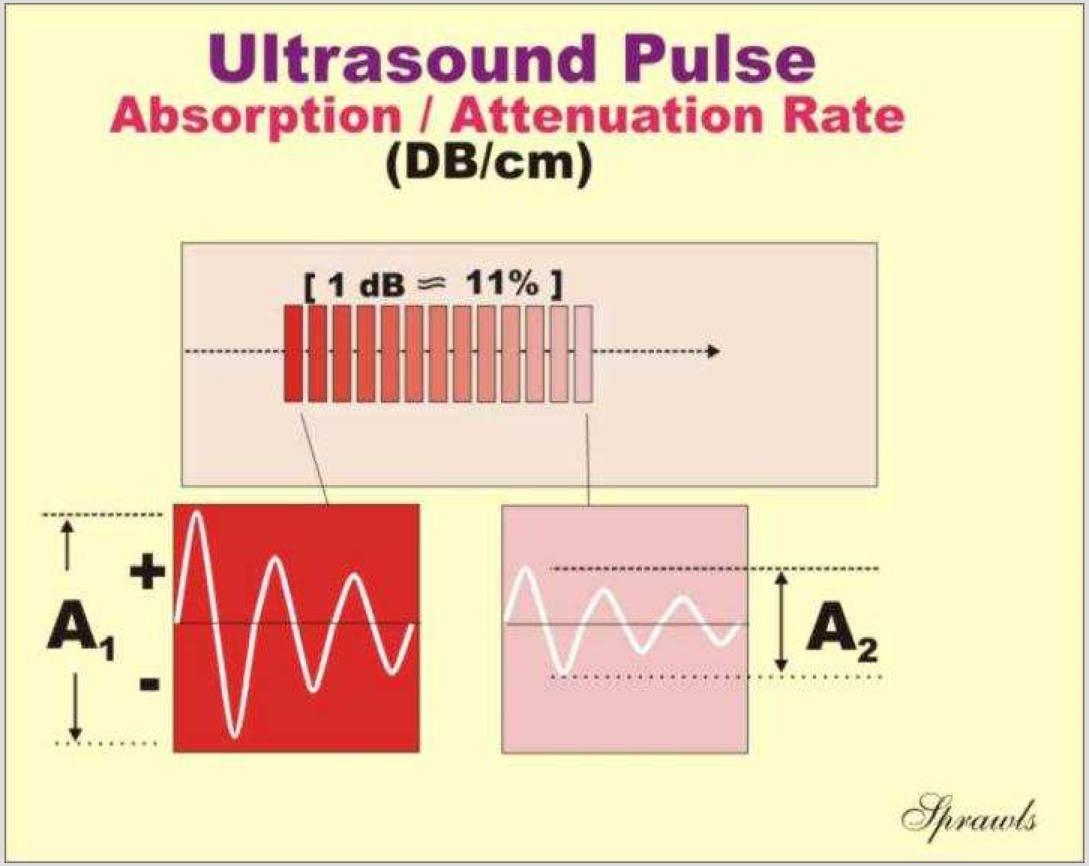
Types of Ultrasound Pulse Interactions

As an ultrasound pulse passes through matter, such as human tissue, it interacts in several different ways. Some of these interactions are necessary to form an ultrasound image, whereas others absorb much of the ultrasound energy or produce artifacts and are generally undesirable in diagnostic examinations. The ability to conduct and interpret the results of an ultrasound examination depends on a thorough understanding of these ultrasound interactions.



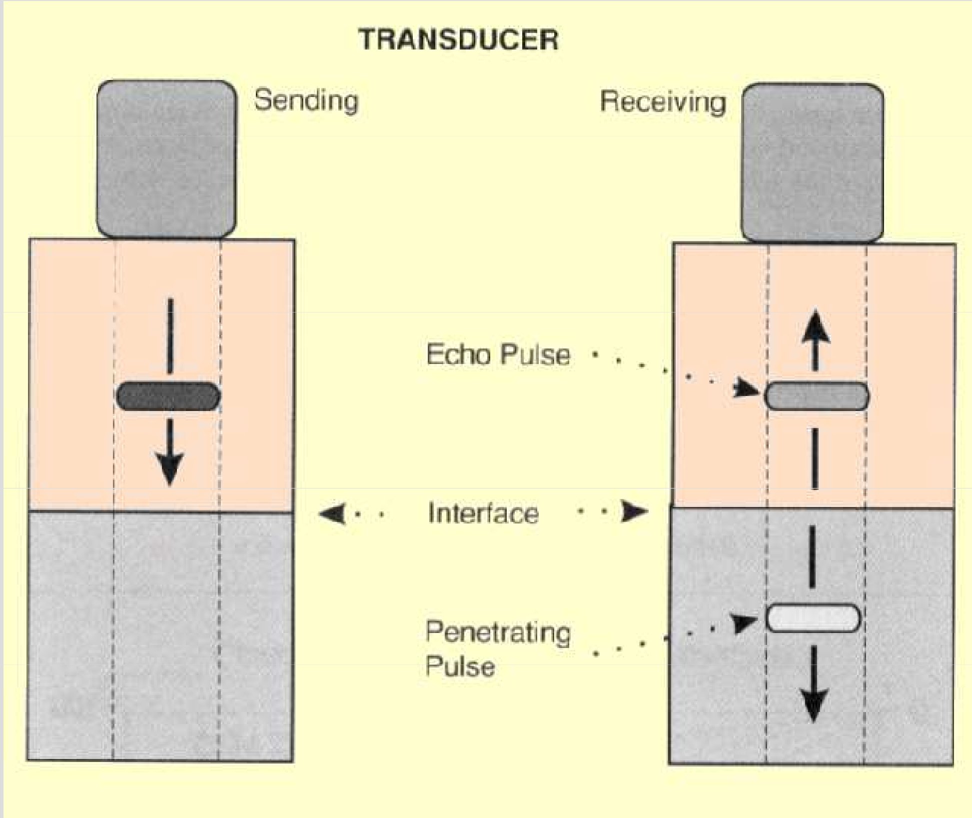
Absorption

- As the ultrasound pulse moves through matter, it continuously loses energy. This is generally referred to as attenuation. Several factors contribute to this reduction in energy. One of the most significant is the absorption of the ultrasound energy by the material and its **conversion into heat**. Ultrasound pulses **lose energy continuously** as they move through matter. This is unlike x-ray photons, which lose energy in "one-shot" photoelectric or Compton interactions. Scattering and refraction interactions also remove some of the energy from the pulse and contribute to its overall attenuation, but absorption is the most significant.



Reflection

- At most interfaces within the body, only a portion of the ultrasound pulse is reflected. The pulse is divided into two pulses, and one pulse, the echo, is reflected back toward the transducer and the other penetrates into the other material, as shown in the figure. The brightness of a structure in an ultrasound image depends on the strength of the reflection, or echo. This in turn depends on how much the two materials differ in terms of acoustic impedance Z.



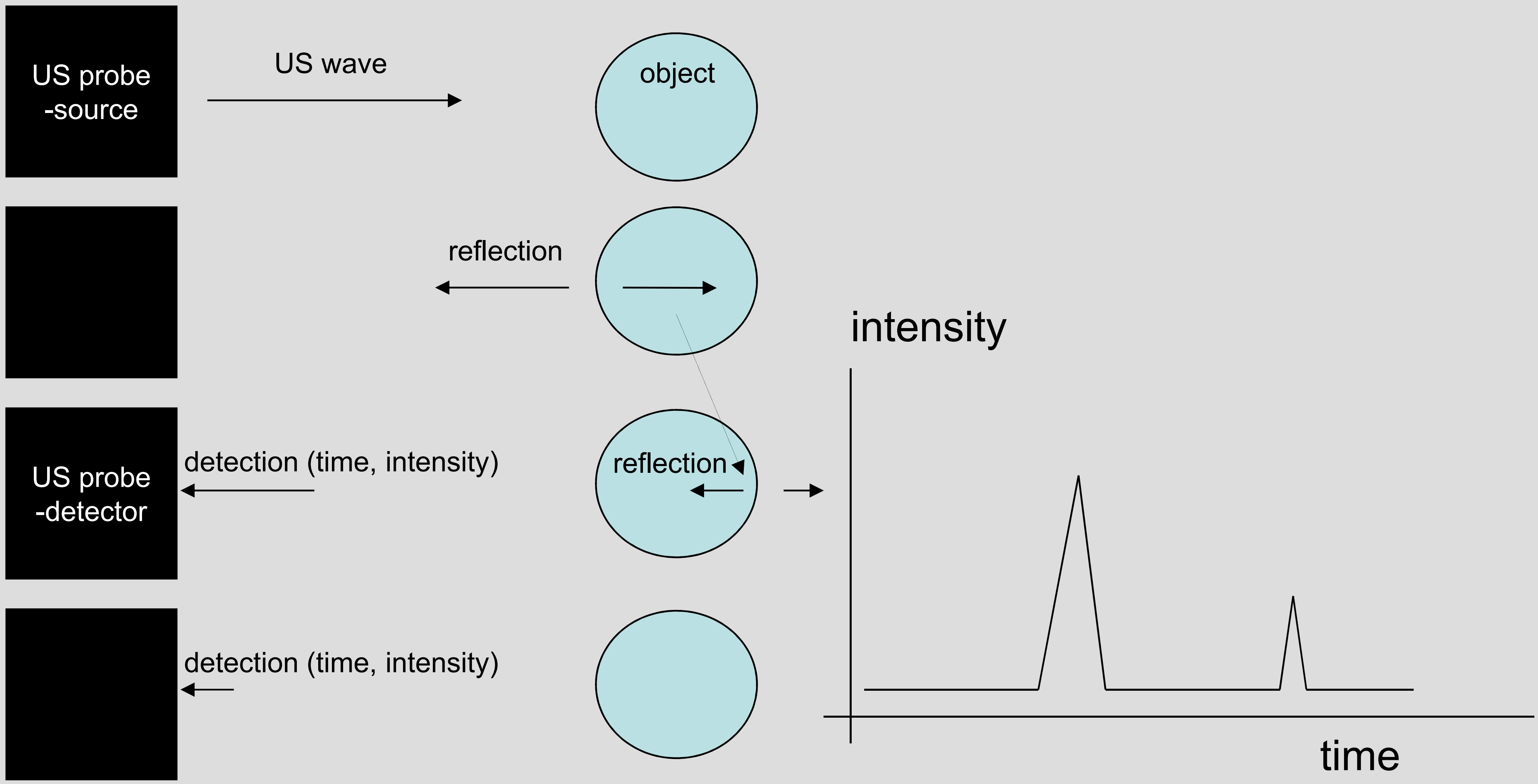
Ultrasonography X Ultrasound

Ultrasonography – diagnostic method, used reflection of ultrasound

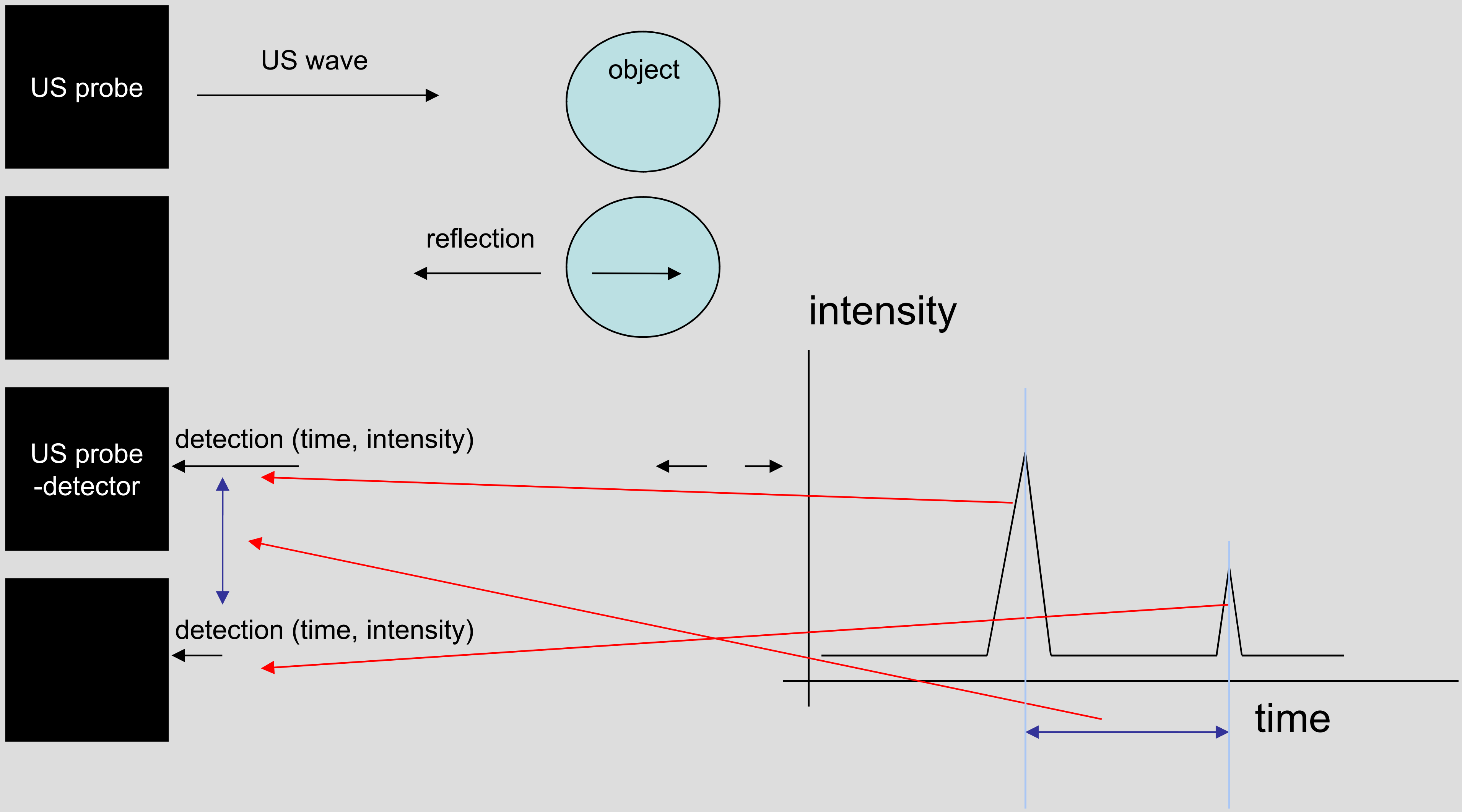
Characteristic:

- Passive US – low intensity waves which **cannot** cause substantial changes of medium.
- In US diagnostics **(ultrasonography = sonography = echography) -** used frequencies are 2 - 40 MHz with (temporal average, spatial peak) intensity of about 1 kW/m^2
- **Impulse reflection method:** a probe with one transducer which is *source as well as detector* of US impulses. A portion of emitted US energy is *reflected* on the acoustic interfaces and the same probe then receives reflected signal. After processing, the signal is displayed on a screen.

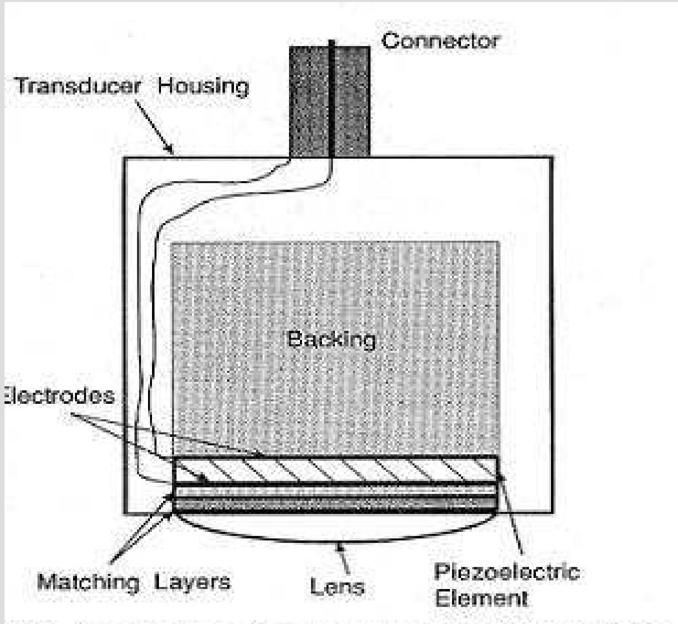
Ultrasonography



Ultrasonography



Supplement - piezo element



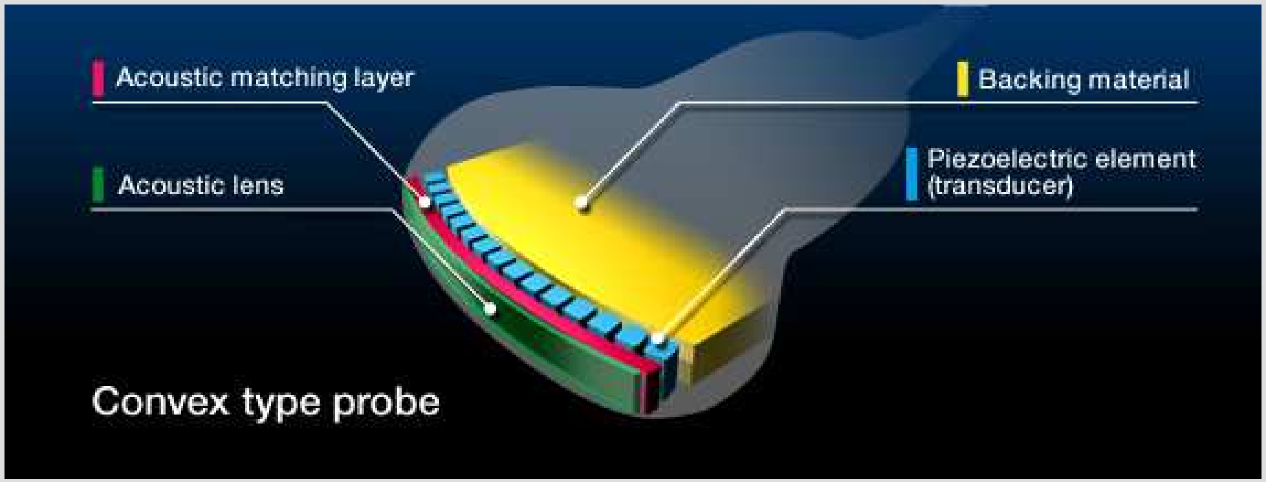
5.8 Construction of a single-element ultrasonic trans-

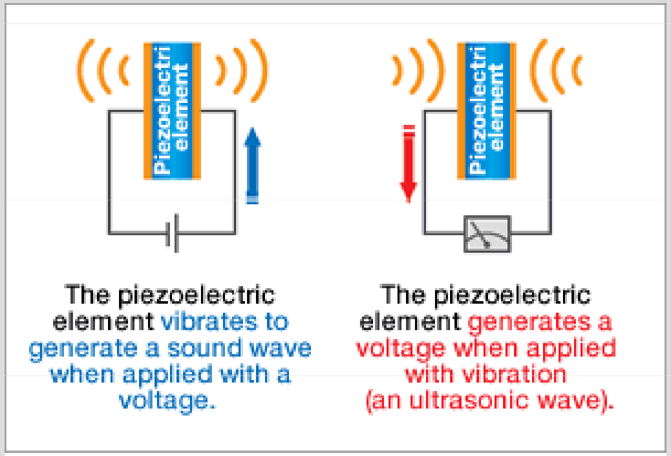
Material that changes its conformation when an electric pulse is present. Attached AC causes vibration of the material and following mechanic vibration of tissue.

Supplement – ultrasound probe 1

The piezoelectric element is an essential part of the probe to generate ultrasonic waves. On both sides of the piezoelectric element electrodes are affixed and a voltage is applied. The element then oscillates by repeatedly expanding and contracting, generating a sound wave. When the element is externally applied with viblation (or an ultrasonic wave) in turn, it generates a voltage.

Among the several types of piezoelectric elements, piezoelectric ceramic (PZT: lead zirconate titanate) is most commonly used because of its high conversion efficiency.

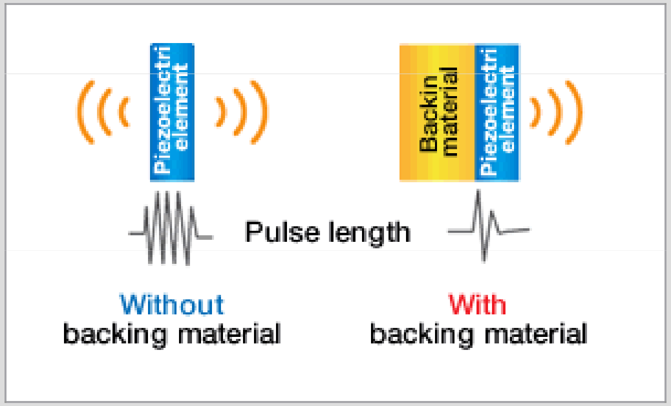




http://www.ndk.com

Supplement – ultrasound probe 2

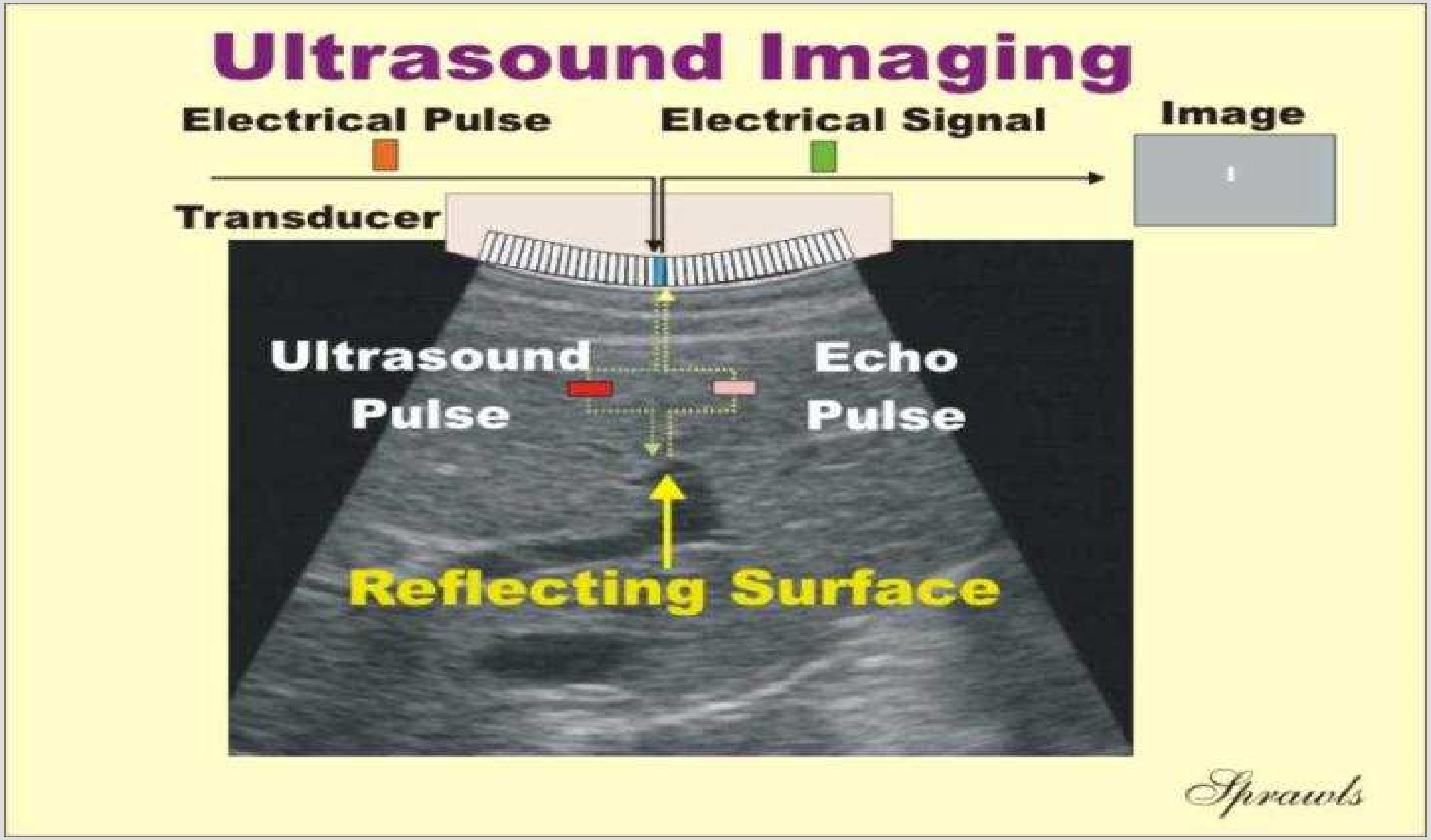
The backing material is located behind the piezoelectric element to prevent excessive vibration.
Reducing excessive vibration will cause the element to generate ultrasonic waves with a shorter pulse length, improving axial resolution in images.



http://www.ndk.com

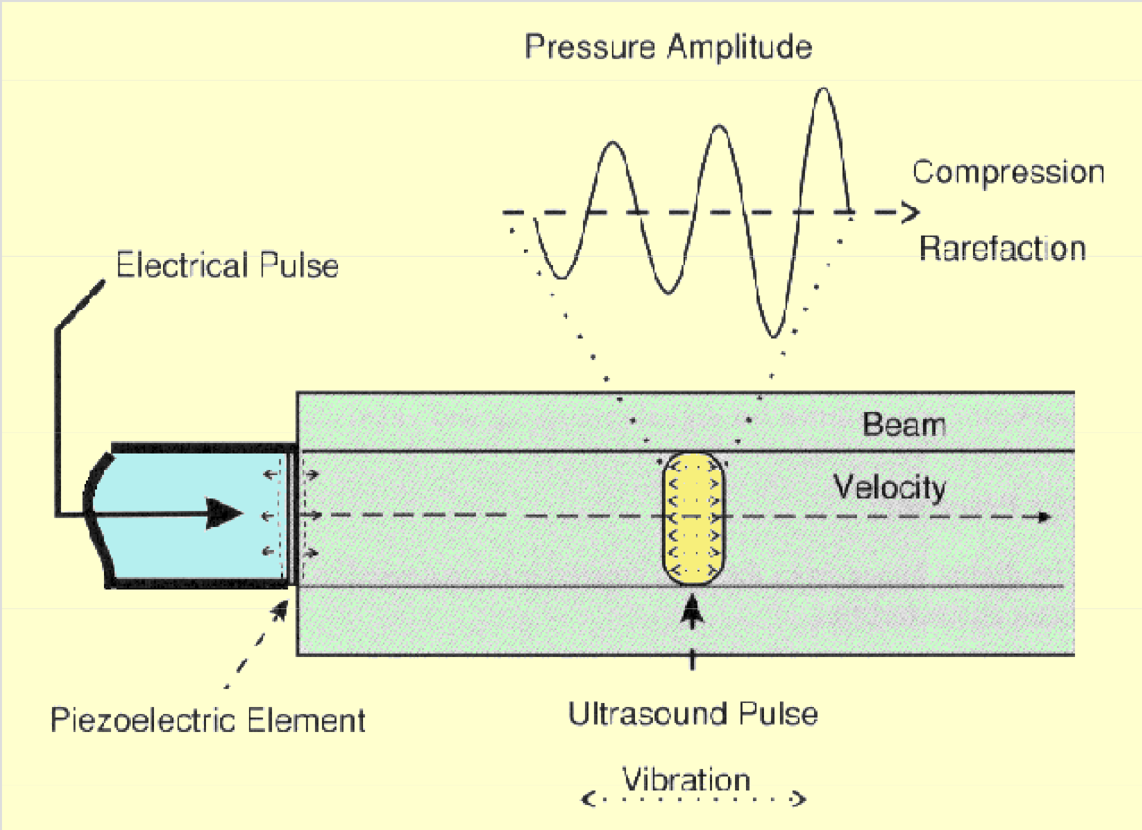
The Basic Ultrasound Imaging Process

The **transducer** is the component of the ultrasound imaging equipment that is placed in direct contact with the patient's body. It performs several functions. It's first function is to produce the ultrasound pulses when electrical pulses are applied to it. A short time later, when echo pulses return to the body surface they are picked up by the transducer and converted back into electrical pulses that are then processed by the system and formed into an image.



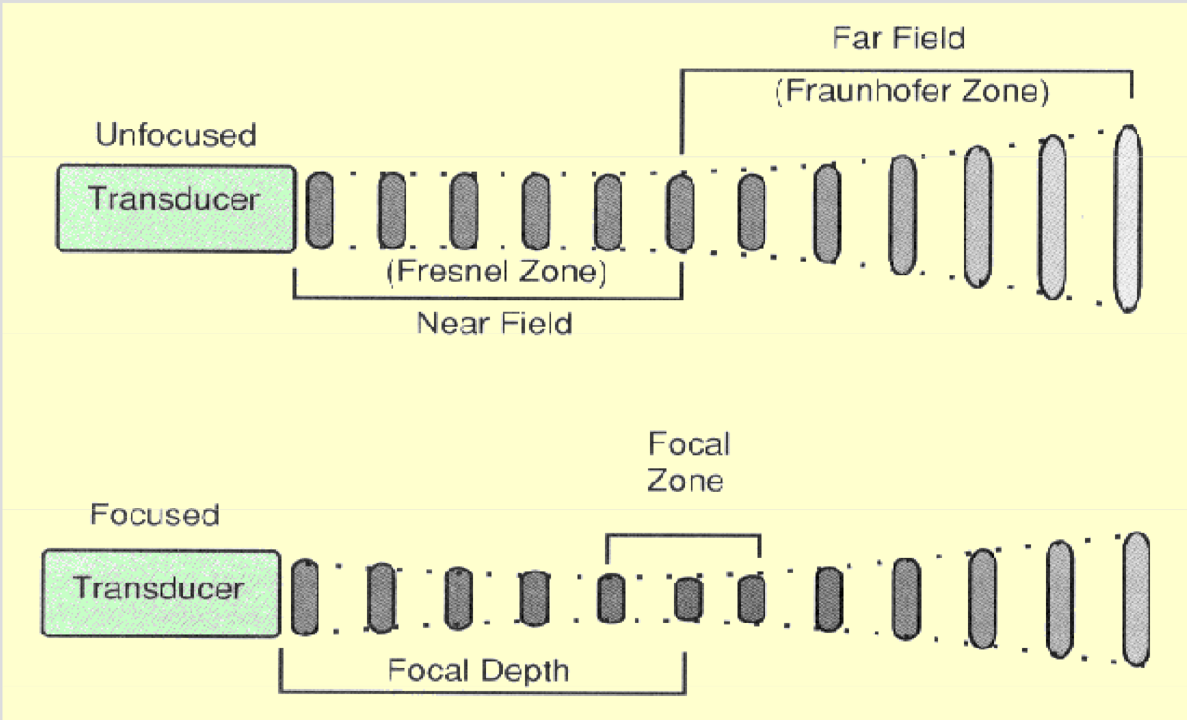
Principles of generation of ultrasound pulse

The source of sound is a vibrating object, the piezoelectric transducer element. Since the vibrating source is in contact with the tissue, it is caused to vibrate. The vibrations in the region of tissue next to the transducer are passed on to the adjacent tissue. This process continues, and the vibrations, or sound, is passed along from one region of tissue to another. The rate at which the tissue structures vibrate back and forth is the frequency of the sound. The rate at which the vibrations move through the tissue is the velocity of the sound.



Transducer Focusing

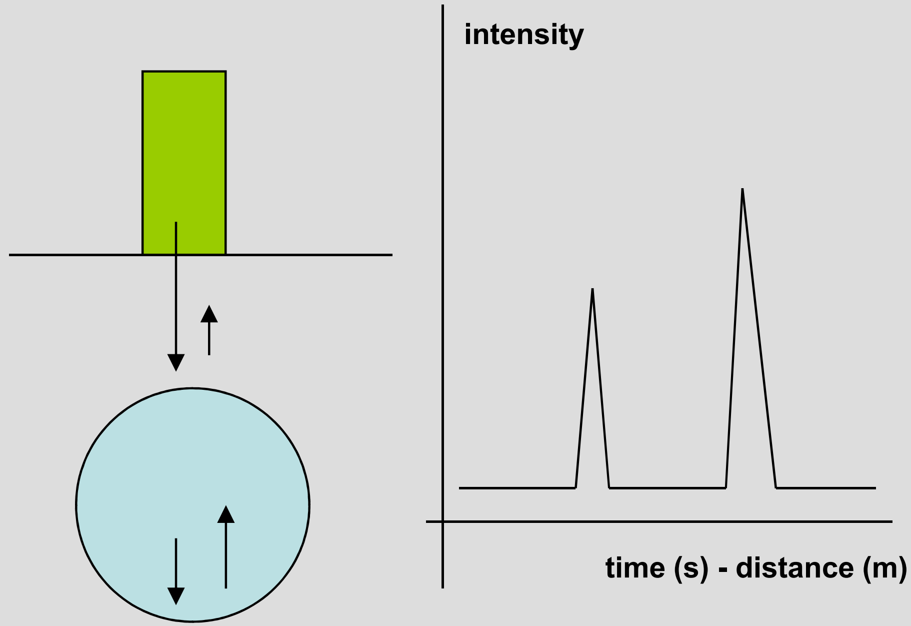
- Transducers can be designed to produce either a focused or non-focused beam, as shown in the following figure. A focused beam is desirable for most imaging applications because it produces pulses with a small diameter which in turn gives better visibility of detail in the image. The best detail will be obtained for structures within the focal zone. The distance between the transducer and the focal zone is the focal depth.



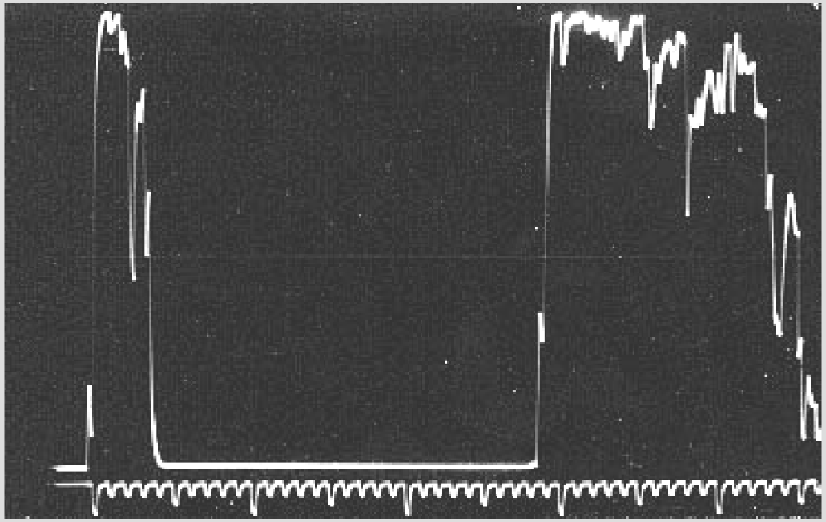
A-mode – one-dimensional

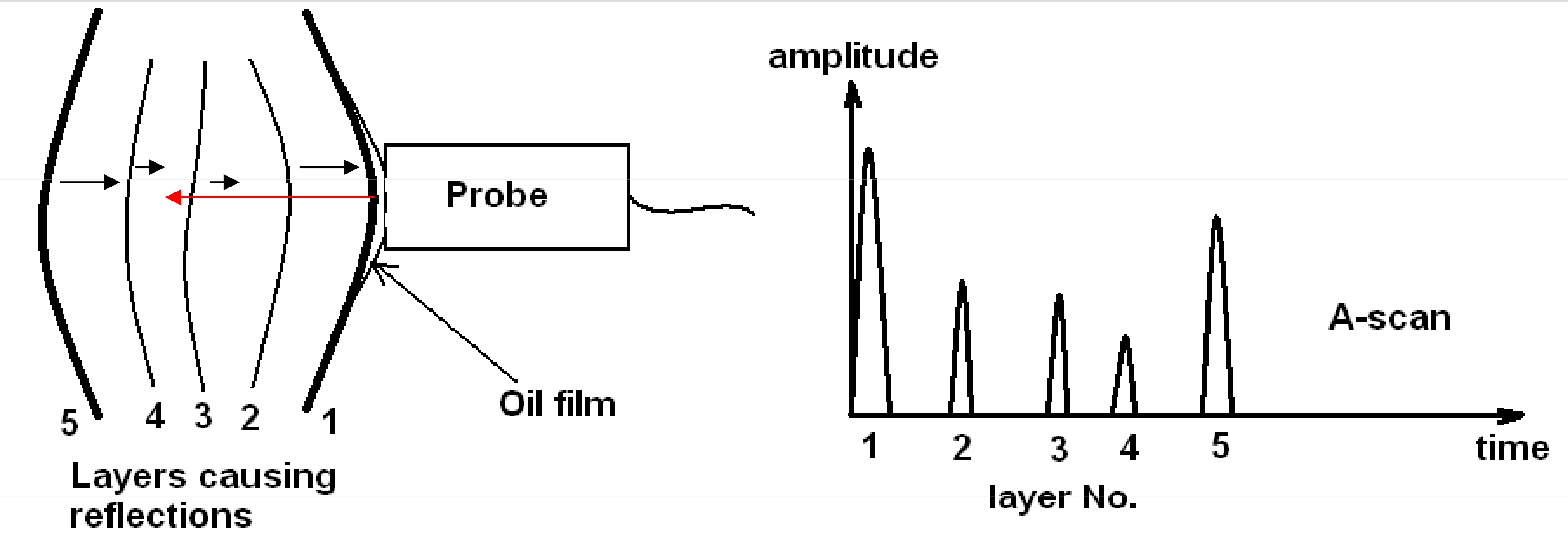
- Distances between reflecting interfaces and the probe are shown.
- Reflections from individual interfaces (boundaries of media with different acoustic impedances) are represented by *vertical deflections* of base line, i.e. the echoes.
- Echo amplitude is proportional to the *intensity of reflected waves* (Amplitude modulation)
- Distance between echoes shown on the screen is approx. proportional to real distance between tissue interfaces.
- Today used mainly in ophthalmology.

- A-mode shows reflections of ultrasound in the axis of US wave



A-mode – one-dimensional



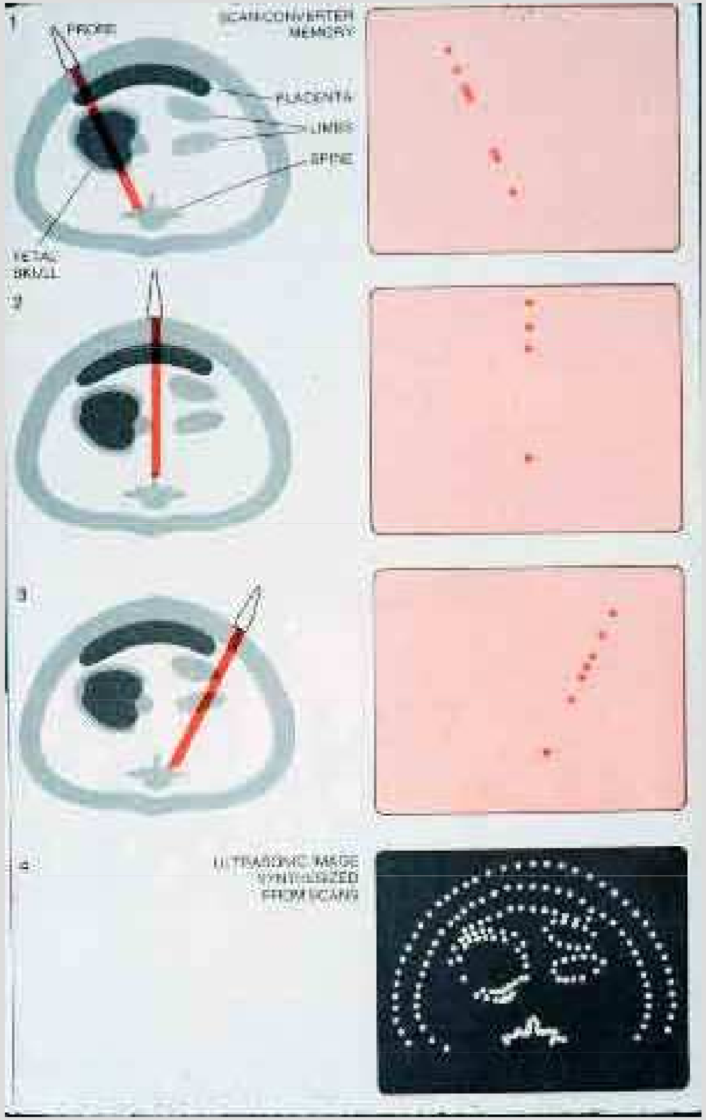


PRINCIPLE OF A-MODE SCAN

B-mode – two-dimensional

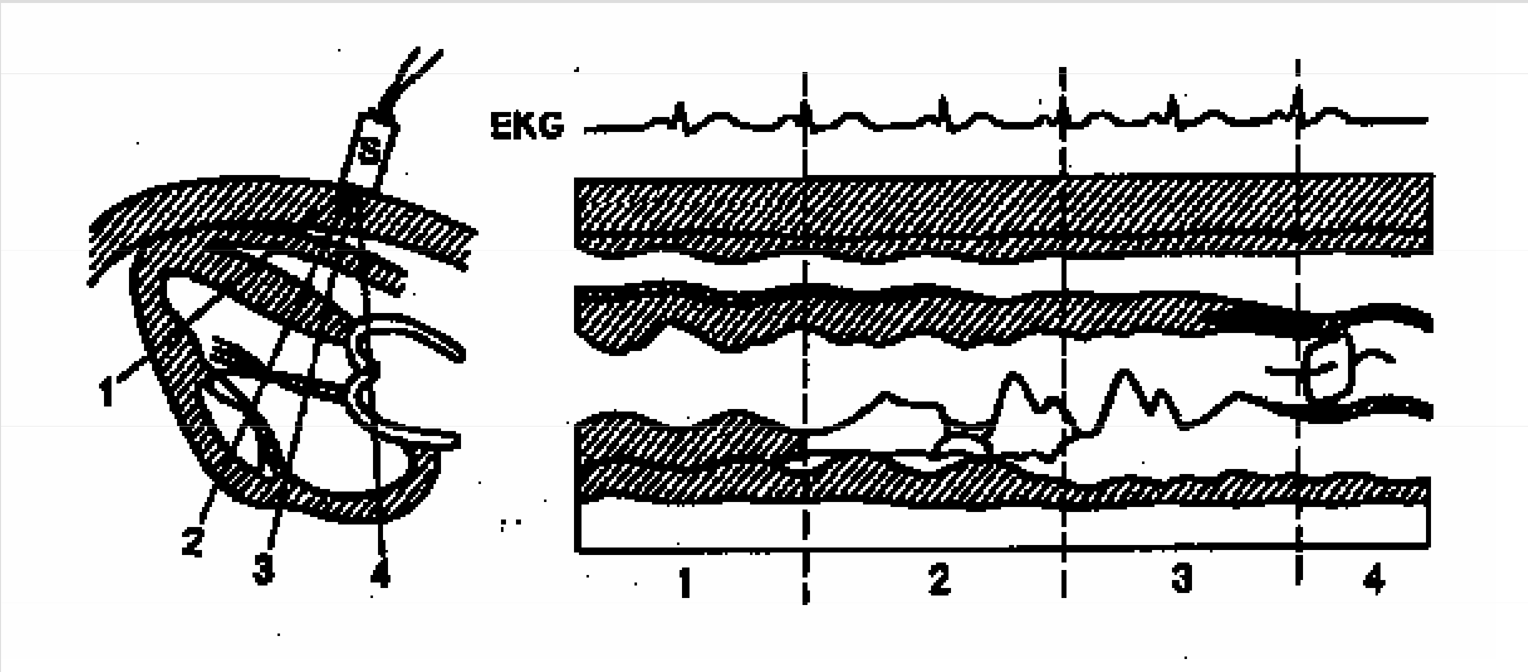
- A tomogram is depicted.
- Brightness of points on the screen represents intensity of reflected US waves (Brightness modulation).

- Static B-scan: a cross-section image of examined area in the plane given by the beam axis and direction of *manual* movement of the probe on body surface. The method was used in 50‘ and 60‘ of 20th century

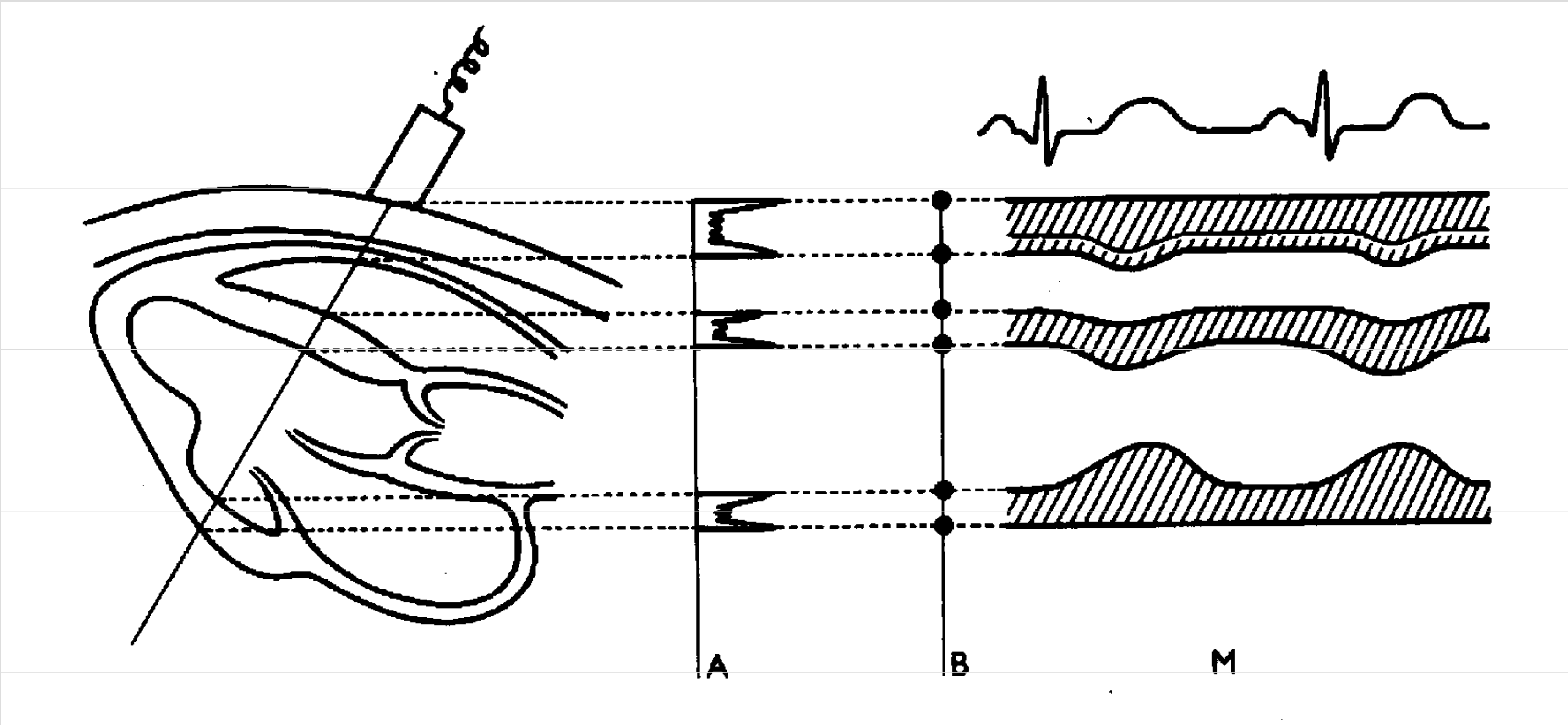


M-mode

- One-dimensional static B-scan shows movement of reflecting tissues. The second dimension is time in this method.
- Static probe detects *reflections* from moving structures. The bright *points* move *vertically* on the screen, *horizontal shifting* of the record is given by slow time-base.
- Displayed curves represent *movement* of tissue structures

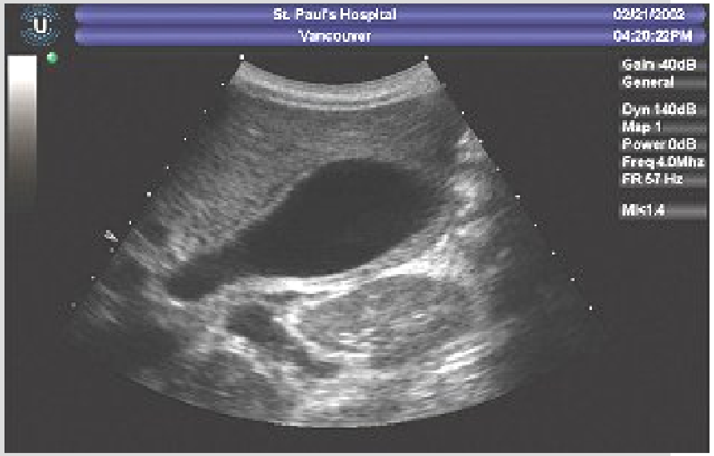


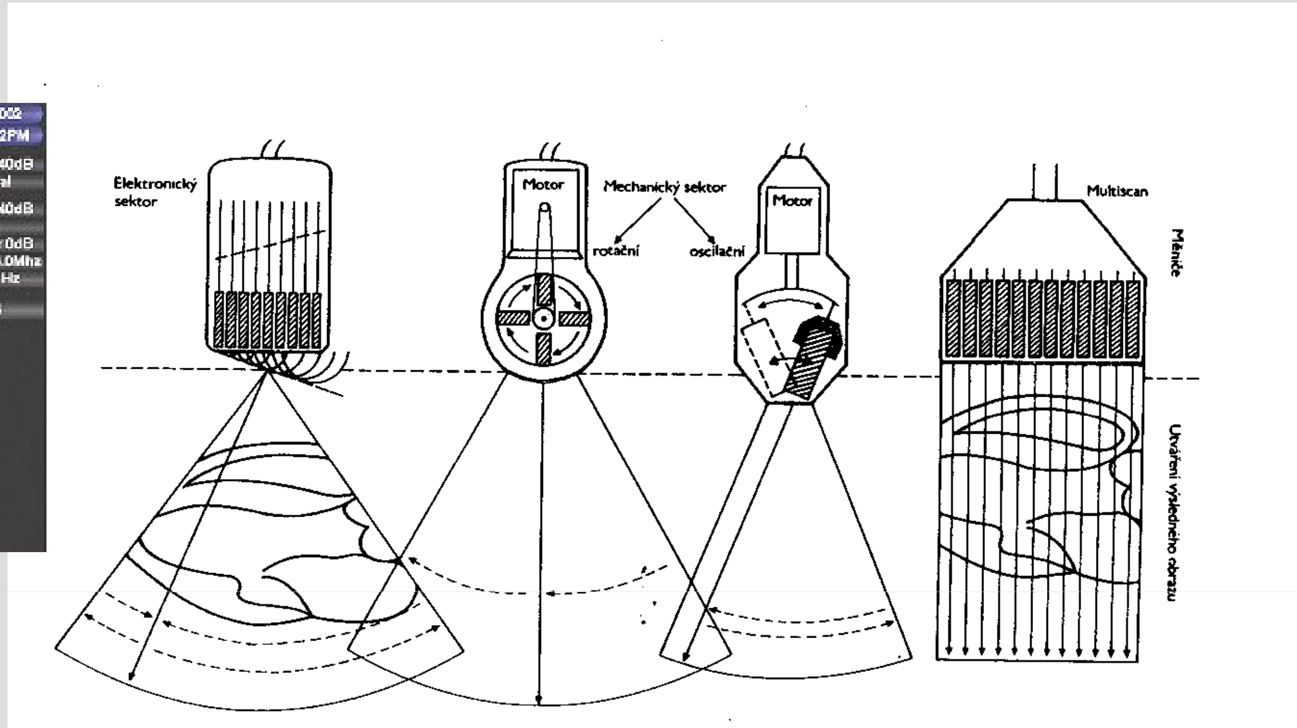
Comparison of A-, B- and M-mode principle



B-mode - dynamic

- Repetitive formation of B-mode images of examined area by **fast deflection of US beam** mechanically (in the past) or electronically „in real time“ today.
- Electronic probes consist of many piezoelectric transducers which are gradually activated.



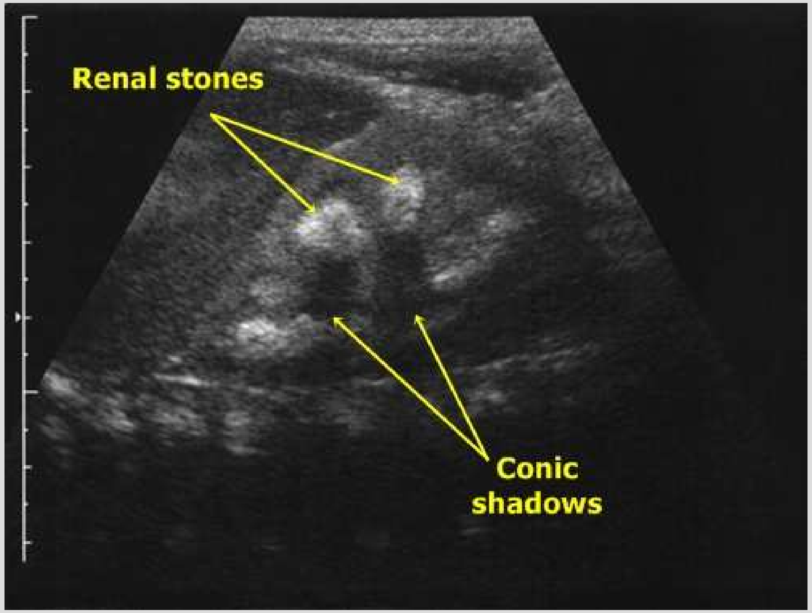


Basic characteristics of US images

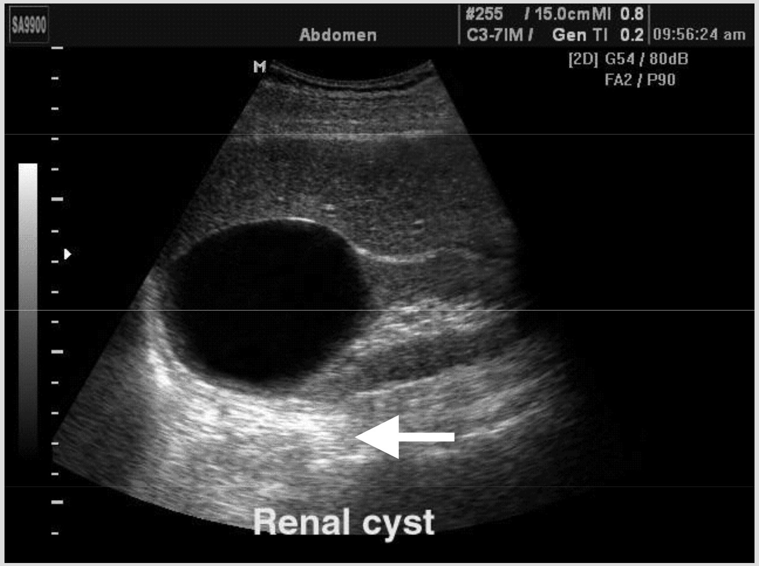
Degree of reflectivity – echogenity. The images of cystic (liquid-filled) and solid structures are different. According to the intensity of reflection *in the tissue bulk* we can distinguish structures:

- **hyperechogenic, izoechogenic, hypoechogenic, anechogenic.**
- **Solid structures – acoustic shadow** (caused by absorption and reflection of US)

Air bubbles and other strongly reflecting interfaces cause repeating reflections (reverberation, „comet tail“).



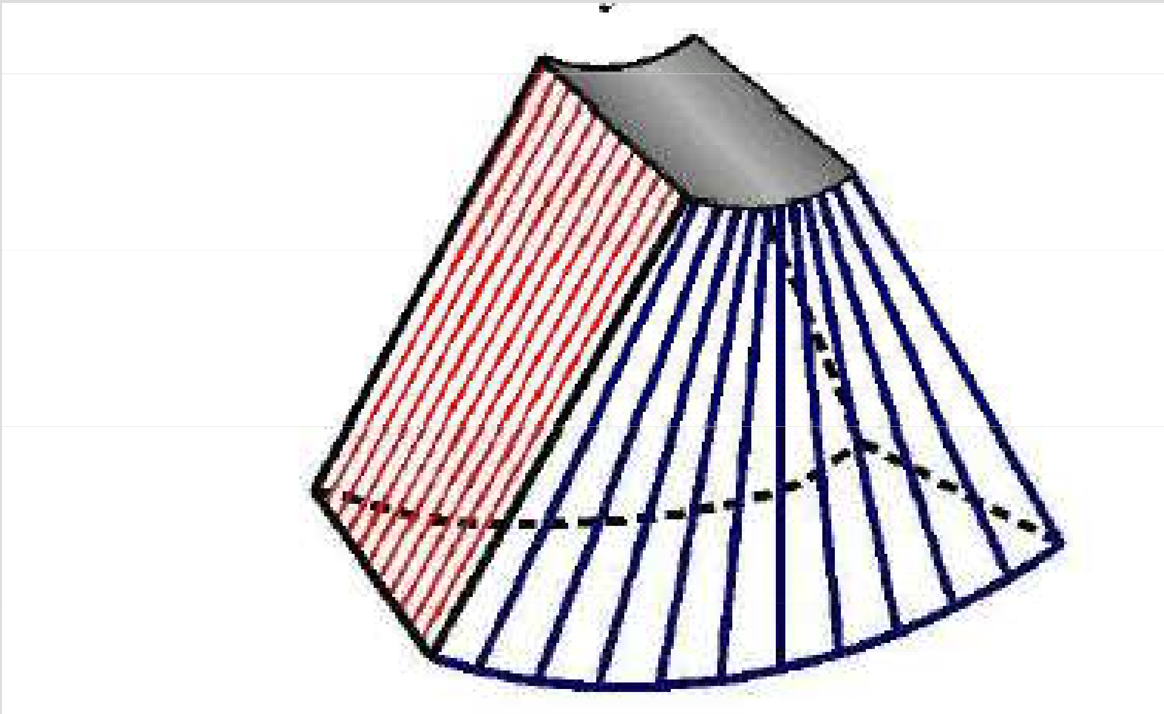
Acoustic shadow caused by absorption and reflection of US by a kidney stone (arrow)



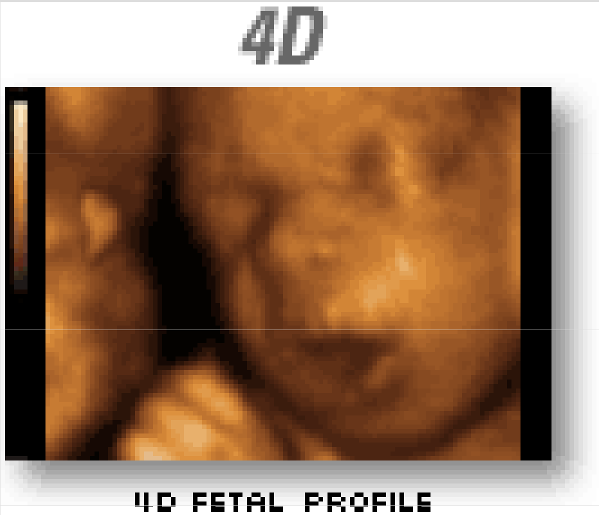
Hyperechogenic area below a cyst (low attenuation of US during passage through the cyst compared with the surrounding tissues – arrow)

Three-dimensional (3D) imaging

- The probe is linearly shifted, tilted or rotated.
The data of reflected signals in individual planes are stored in memory of a powerful PC which consequently performs **mathematical** reconstruction of the image.
Disadvantages of some 3D imaging systems: relatively **long time** is needed for mathematical processing, **price.**



Four-dimensional (4D) image



The fourth dimension is time (x,y,z,t)

http://www.youtube.com/watch?v=NNHk3GJwN7o&feature=related

Doppler flow measurement

Christian. A. Doppler (1803-1853), Austrian physicist and mathematician, formulated his theory in 1842 during his stay in Prague.

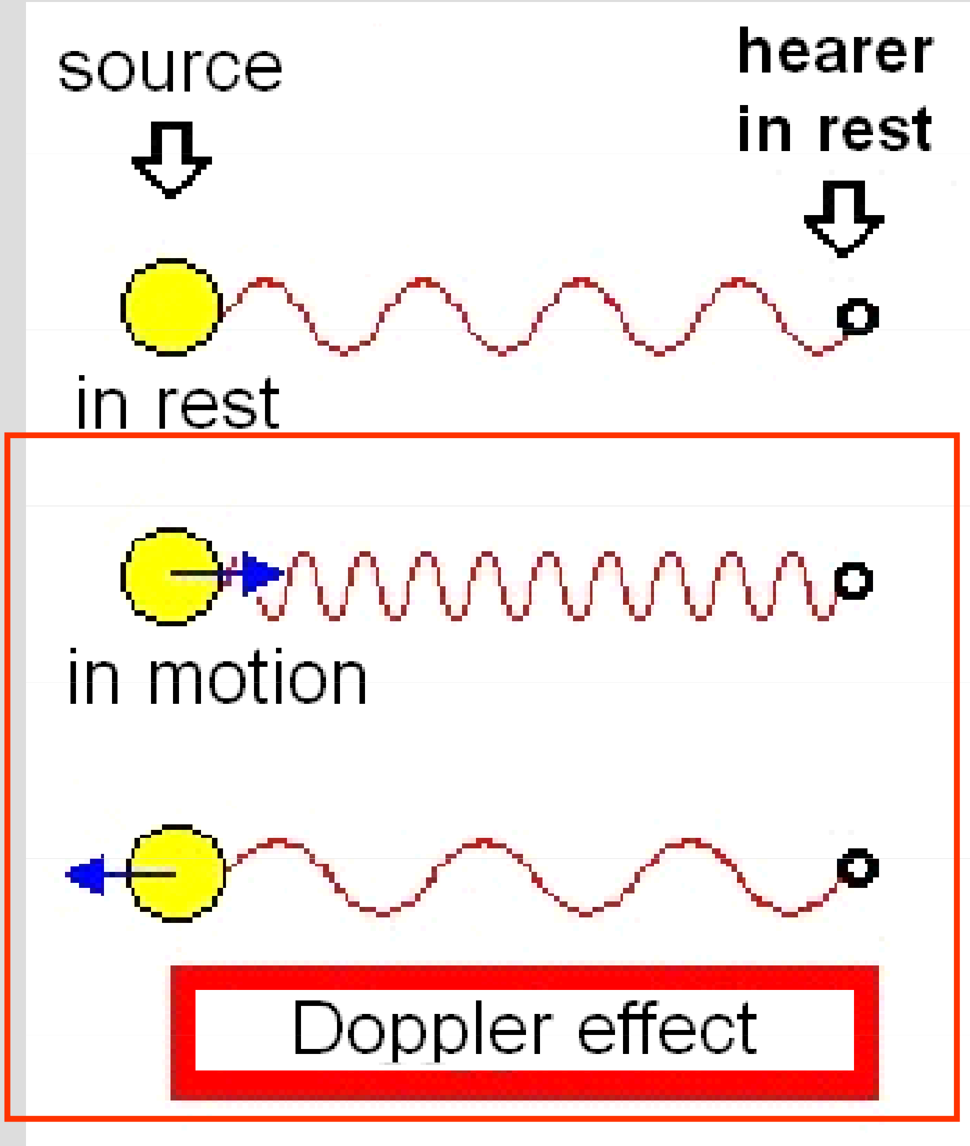
The Doppler effect (frequency shift of waves formed or reflected at a moving object) can be used for detection and measurement of blood flow, as well as, for detection and measurement of movements of some acoustical interfaces inside the body (foetal heart, blood vessel walls)

Principle of Doppler effect

perceived (detected) frequency corresponds with frequency of source in rest

perceived (sense) frequency is higher when source is in motion to the object

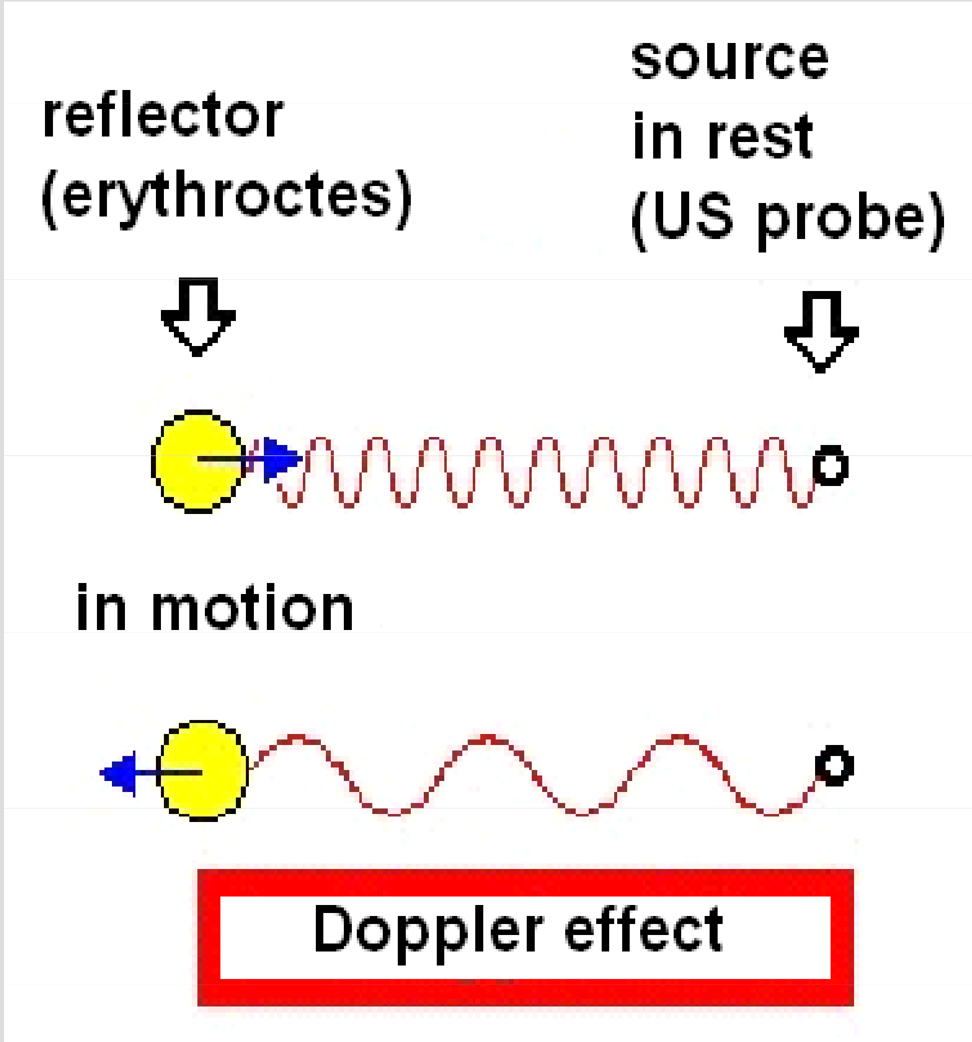
perceived frequency is lower when source is moving away



Principle of Doppler effect

Application of Doppler effect in blood flow velocity measurement

Moving reflector (back scatterer) = erythrocytes

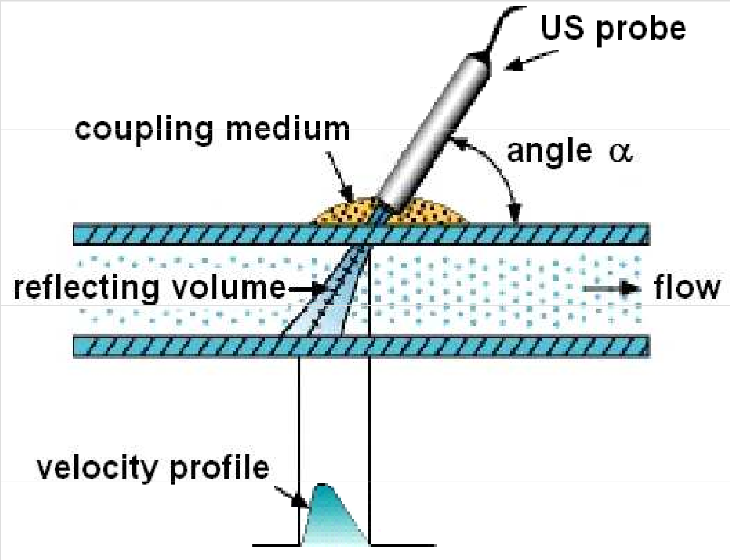


Doppler flow measurement

1) Calculation of Doppler frequency change f_d
2) Calculation of „reflector“ (erythrocytes) velocity v

1) $$f_d = \frac{2 f_v \times v \times \cos\alpha}{c}$$

2) $$v = \frac{f_d \times c}{2 f_v \times \cos\alpha}$$



f_v - frequency of emitted US waves
α - angle made by axis of emitted US beam and the velocity vector of the reflector
c – US speed in the given medium (about 1540 m/s in blood)

DUPLEX doppler method

is a combination **of dynamic B-mode imaging** (the morphology of examined area with blood vessels is depicted) **and the PW Doppler system** (measurement of velocity spectrum of blood flow).

It allows to examine blood flow inside heart or in deep blood vessels (flow velocity, direction and character)

Scheme: sector image with sampling volume

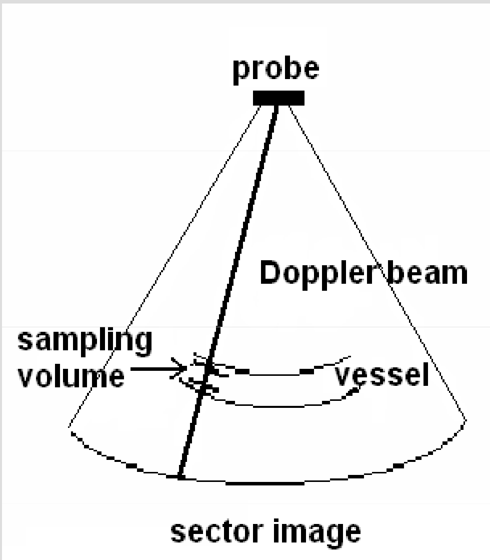
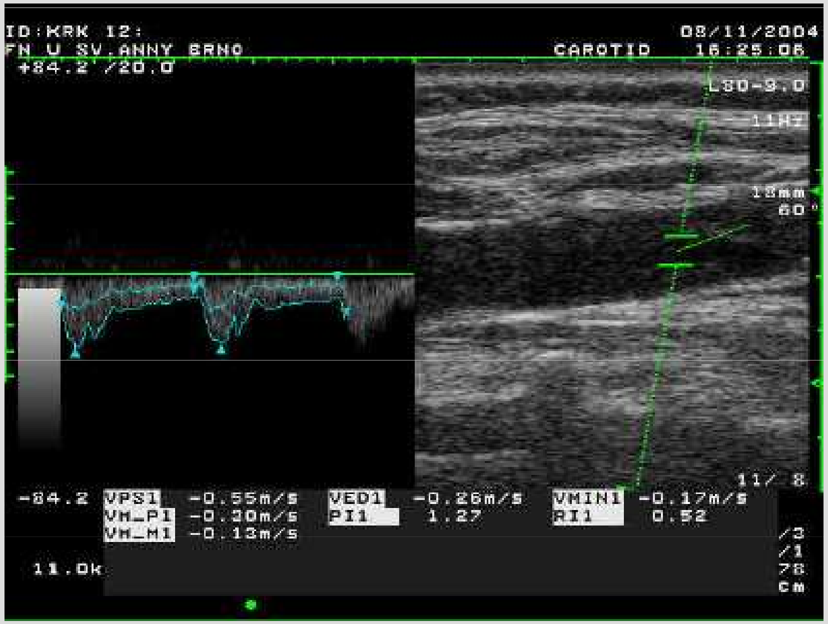


Image of carotid with spectral analysis of blood flow velocity



Colour Doppler imaging

The image consists of black-white and colour part.

The black-white part contains information about **reflectivity and structure** of tissues.

The colour part informs about **movements** in the examined section. (The colour is derived from average velocity of flow.)

The apparatus depicts distribution and direction of flowing blood as a two-dimensional image.

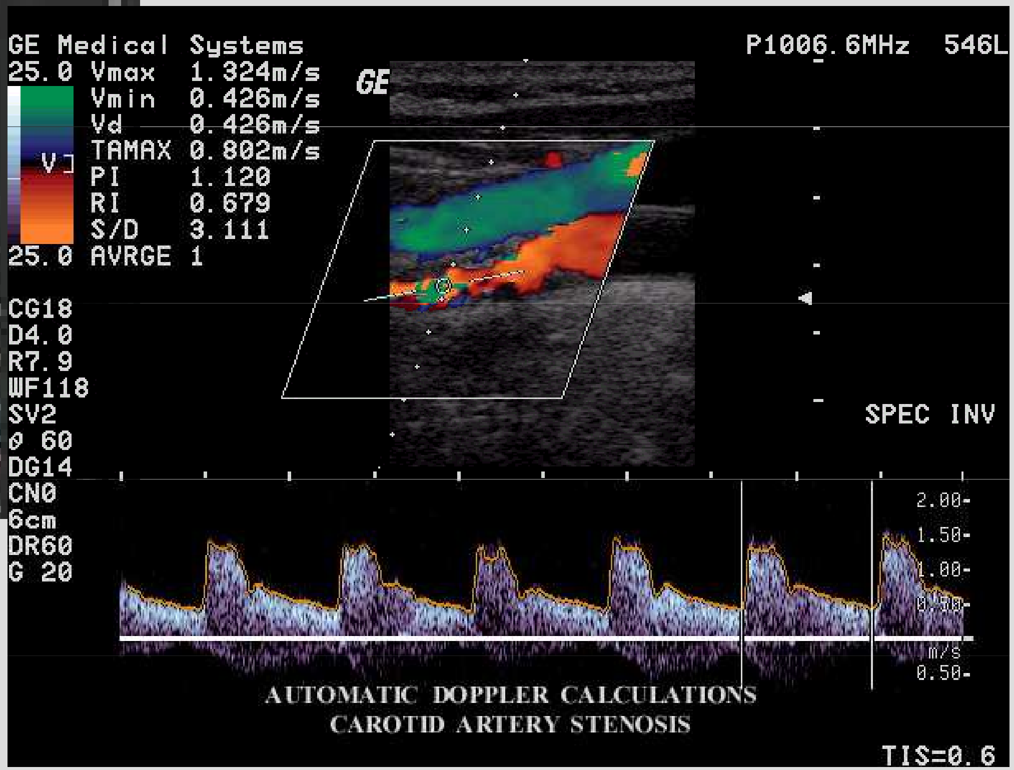
BART rule – blue away, red towards. The flow away from the probe is coded by blue colour, the flow towards the probe is coded by red colour. The brightness is proportional to the velocity, turbulences are depicted by green patterns.

Carotid bifurcation

TRIPLEX doppler method

- A combination of duplex method (B-mode imaging with PW Doppler) and colour flow mapping

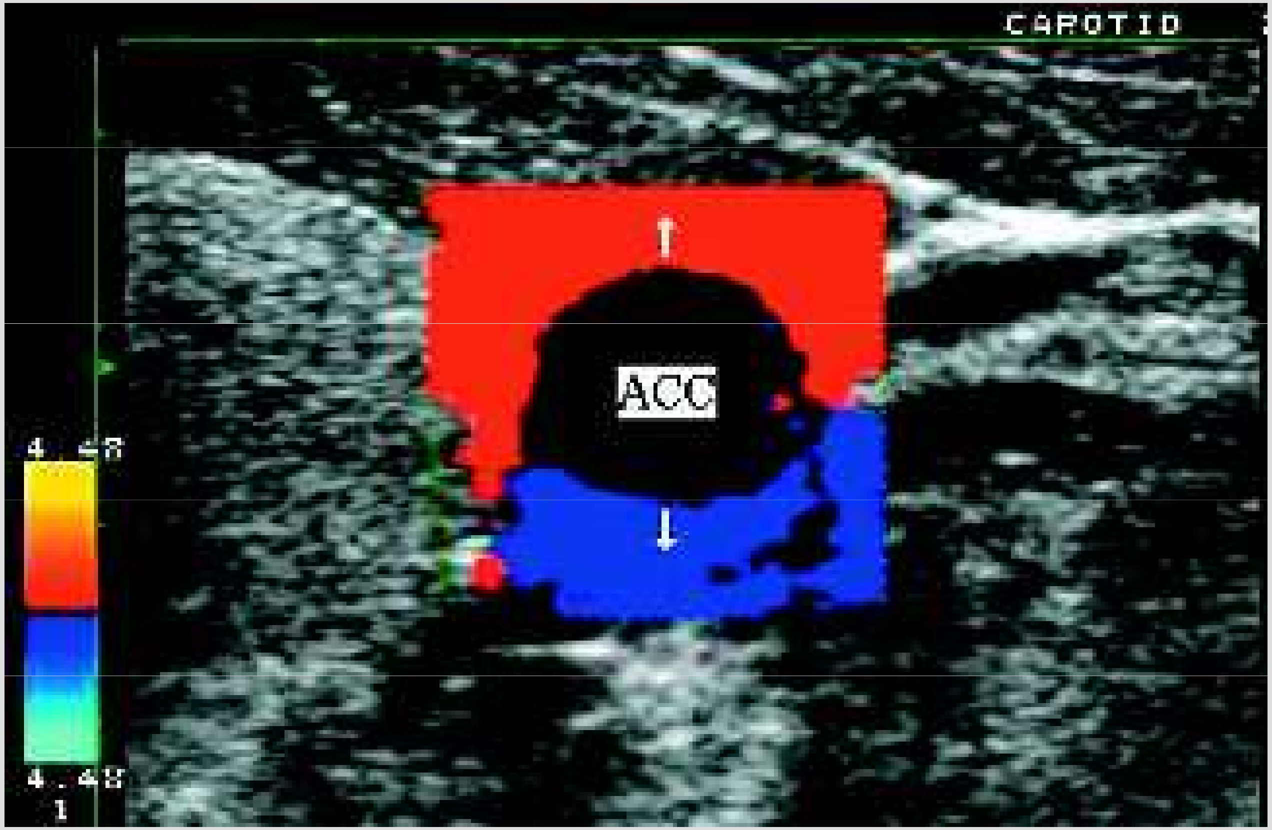
Normal finding of blood flow in *a. carotis communis*



Tissue Doppler Imaging (TDI)

- Colour coding of information about velocity and direction of movements of tissues

- Velocities 1-10 mm/s
- are depicted.

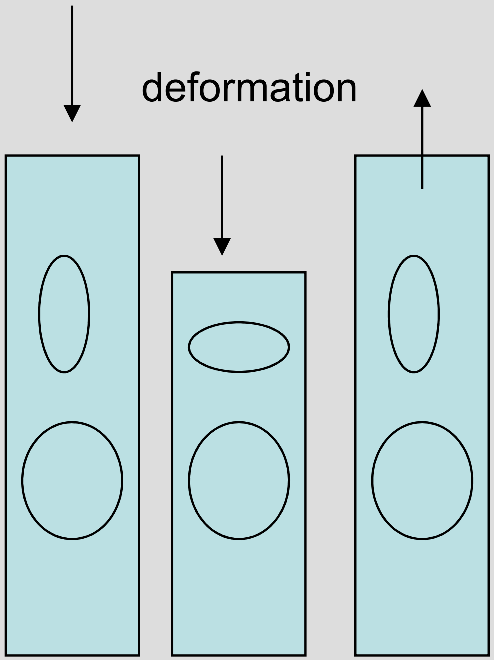


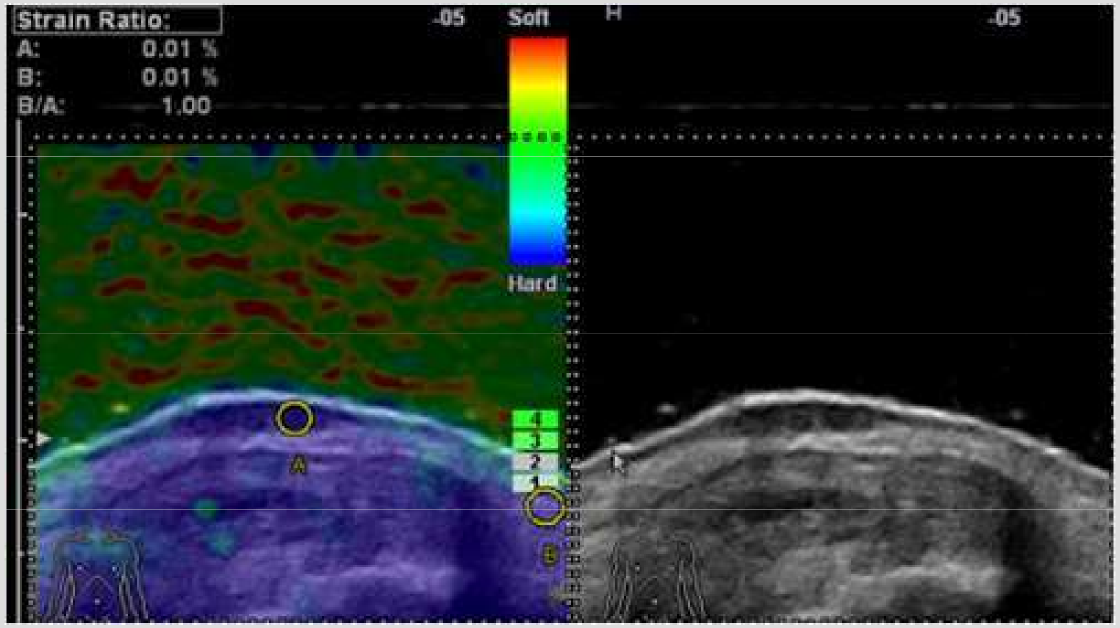
TDI of *a. carotis communis* during systole

Ultrasound elastography

US elastography tracks tissue movement during compression by dynamic B-mode.

Finding the deformation of objects – measurement of value of eleasticity



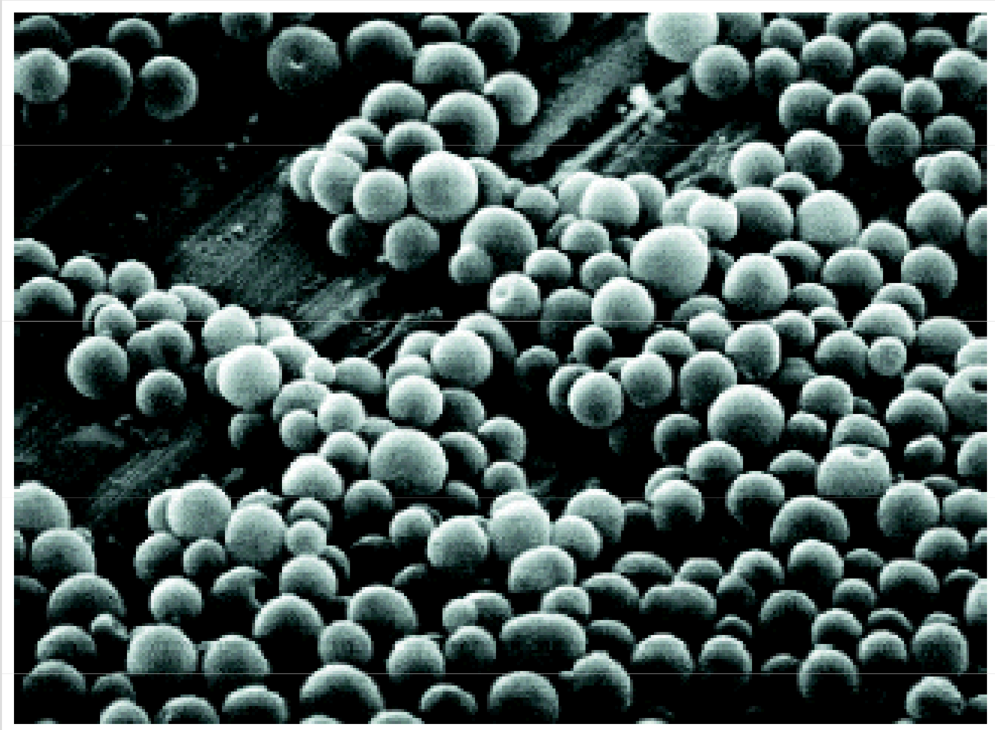


Skin cancer is shown in an elastogram, with elasticity strain ratio on the left, and in an ultrasound image on the right.

Echocontrast agents

- **increase echogenity** of streaming blood
- Gas microbubbles (mainly air or volatile hydrocarbons)

- free
- enclosed in biopolymer envelope



A SEM micrograph of encapsulated echocontrast agent

Echocontrast agents

Enhanced demarcation of heart ventricle after application of the echocontrast agent

Patient Safety

Reducing Ultrasound ‘Doses’

US is non-ionising BUT since many bioeffects of ultrasound have not yet been studied fully, ‘prudent’ use is recommended

ALARA – as low as reasonably achievable (exposure)

In practice ‘prudent’ = justification + optimisation

Sources:

- **Lecture of prof. Mornstein**
- **Ultrasound Production and Interactions**
  Perry Sprawls, Ph.D.

Thank you for your attention