Basic principles of ultrasound

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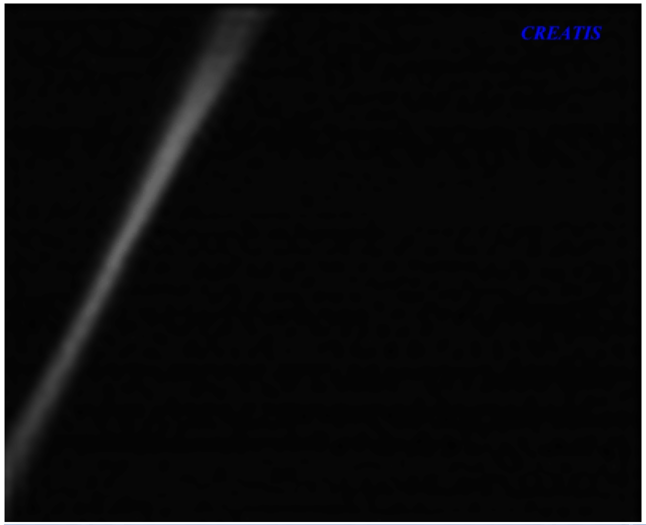
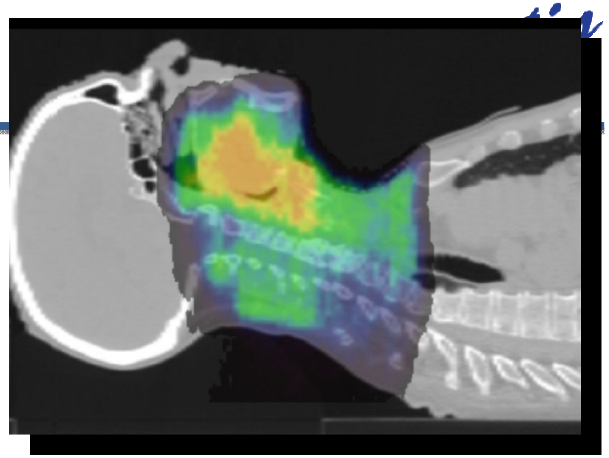
Université Lyon 1

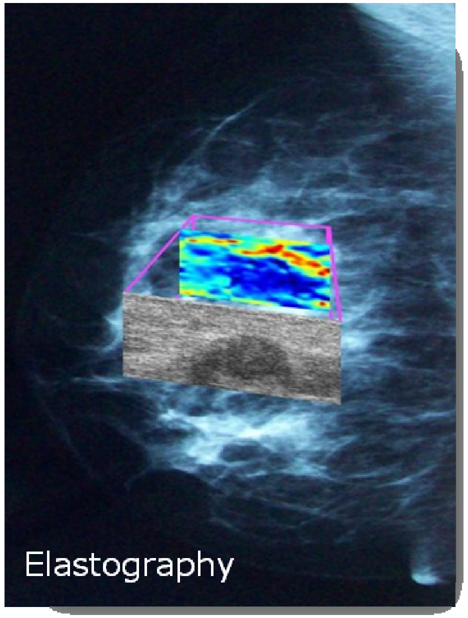


Université de Lyon

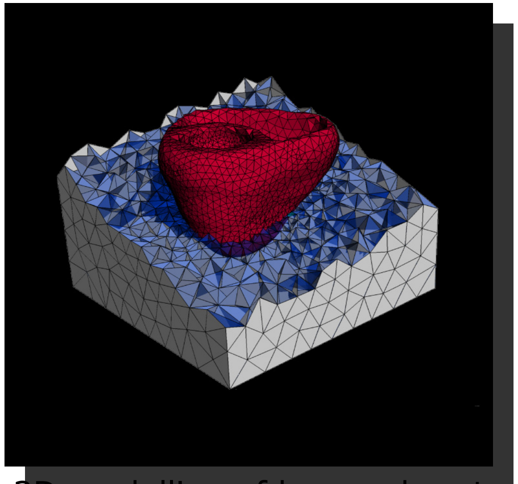
CREATIS is a key european laboratory for biological and medical imaging



Simulation of dose distribution for radiotherapy



at the interface between **engineering**, **computer sciences** and **living sciences**



3D modelling of human heart based on MRI

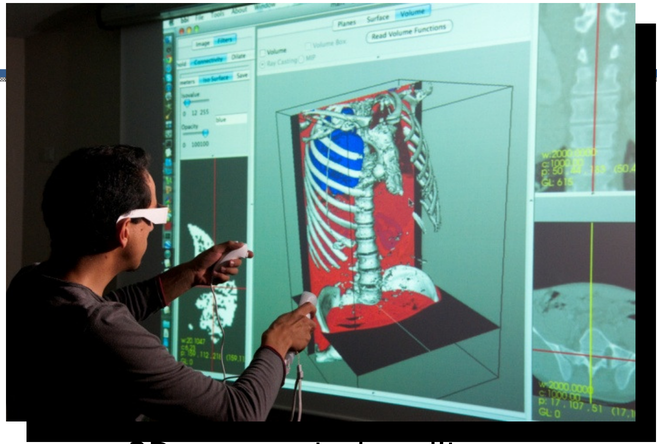
About 200 persons

Development of

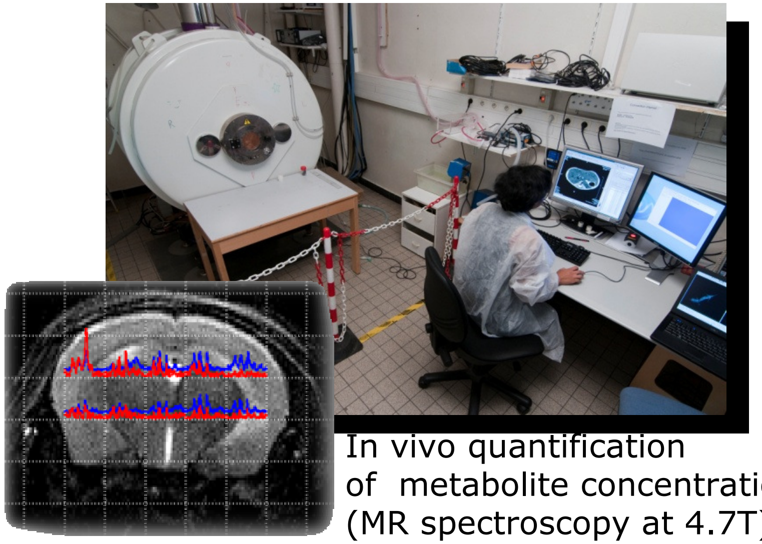
imaging methods,

new algorithms,

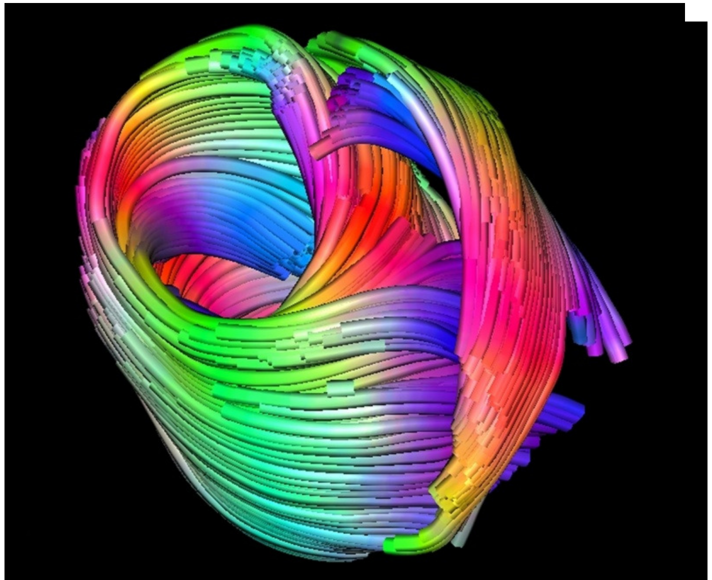
and **instrumental systems** to answer medical questions



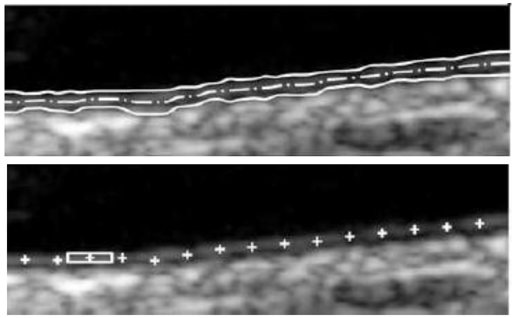
3D augmented reality



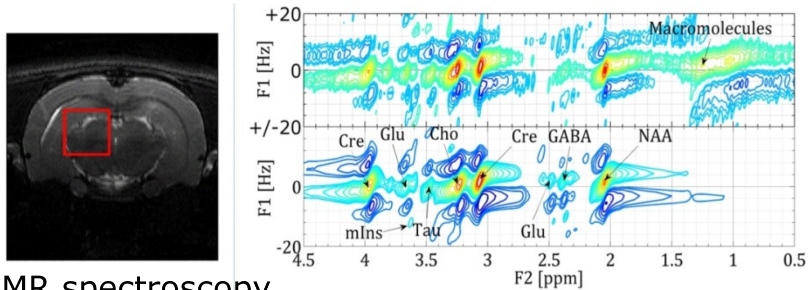
In vivo quantification
of metabolite concentration
(MR spectroscopy at 4.7T)



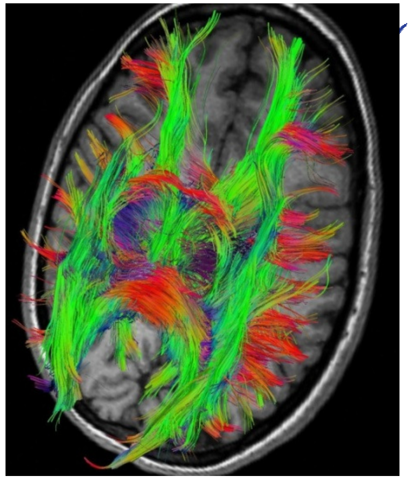
3D imaging of cardiac muscular fibers



Segmentation and tracking
of carotid artery wall in US



MR spectroscopy



Diffusion Tensor Imaging
of the brain

6 research teams

1 - Imaging of the Heart-Vessels-Lungs

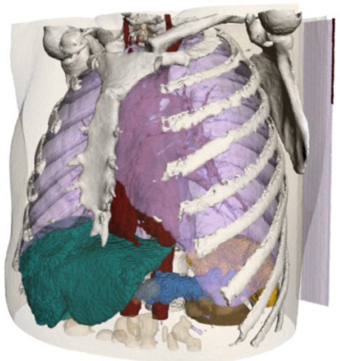
2 - Images et models

3 – Ultrasound Imaging

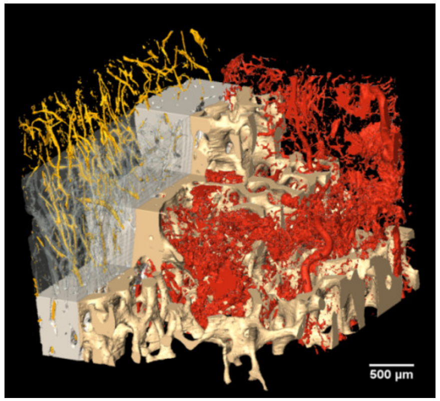
4 - Tomographic imaging and therapy with radiation

5 - MRI and Optics : Methods and Systems

6 – Brain imaging



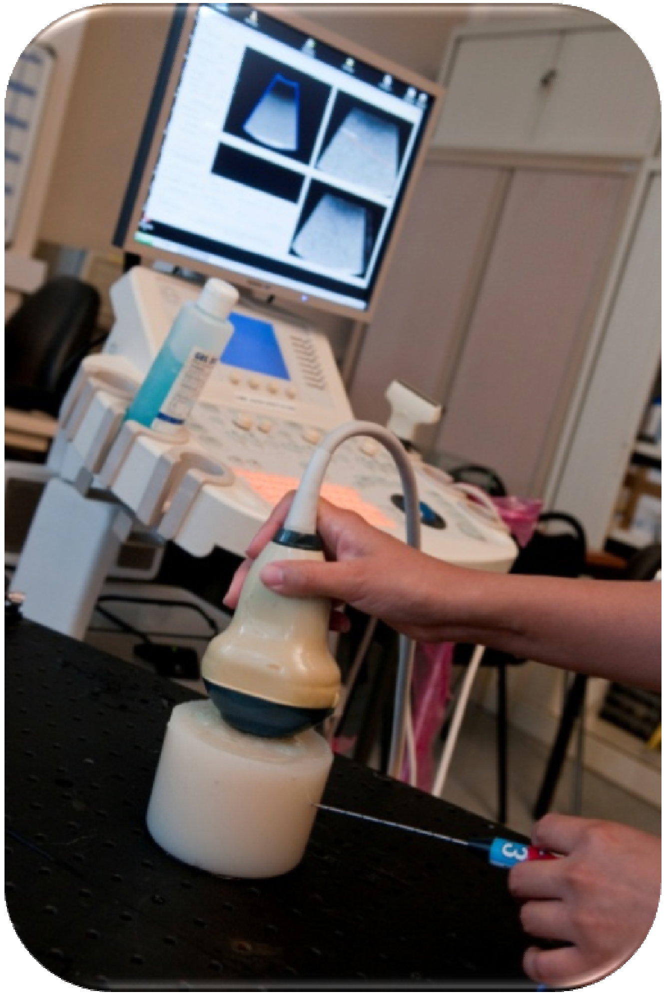
Multi-organs segmentation



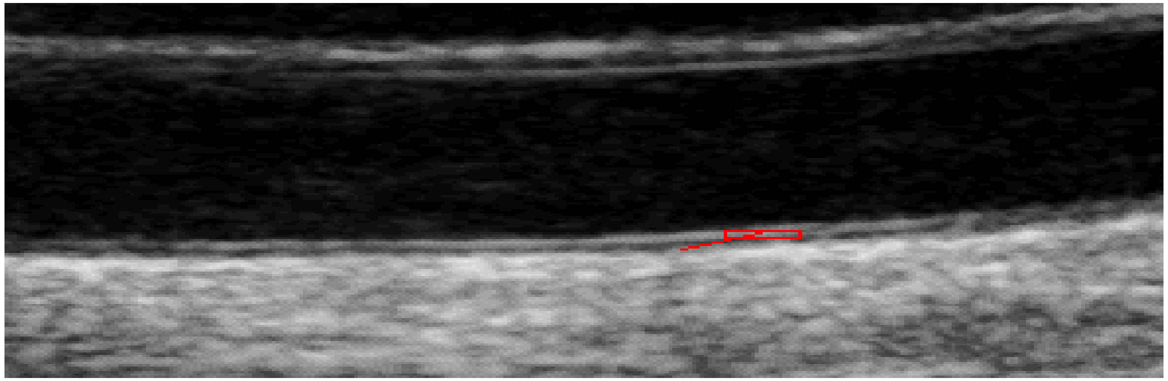
Microarchitecture and micro-vasculature
of trabecular bone(1 voxel=1,4µm)

Dynamic model of the heart

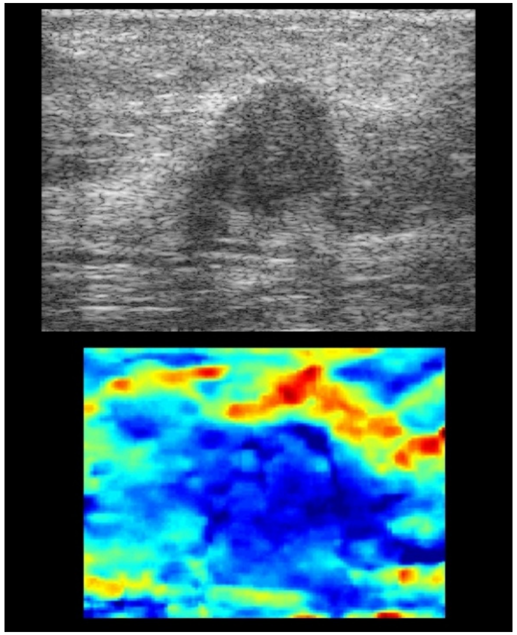
Ultrasound imaging platform



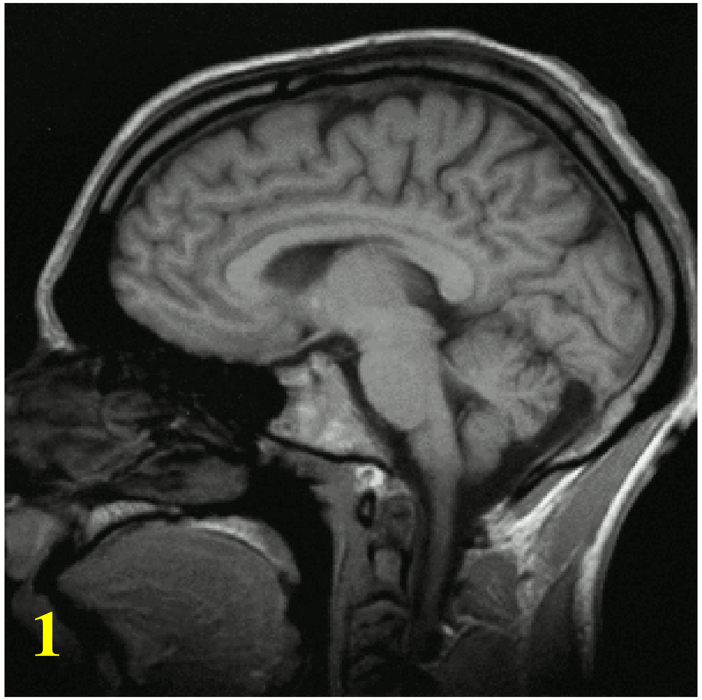
4 research ultrasound scanners, motorized and automated acquisition system

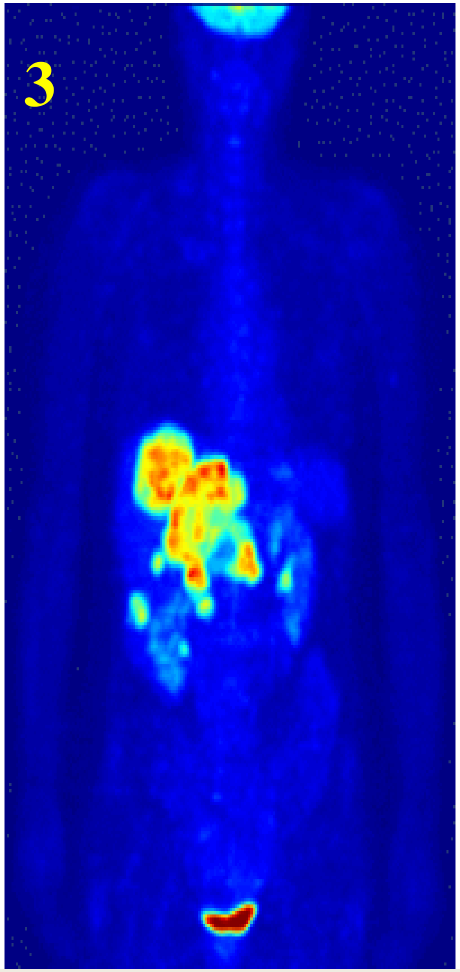


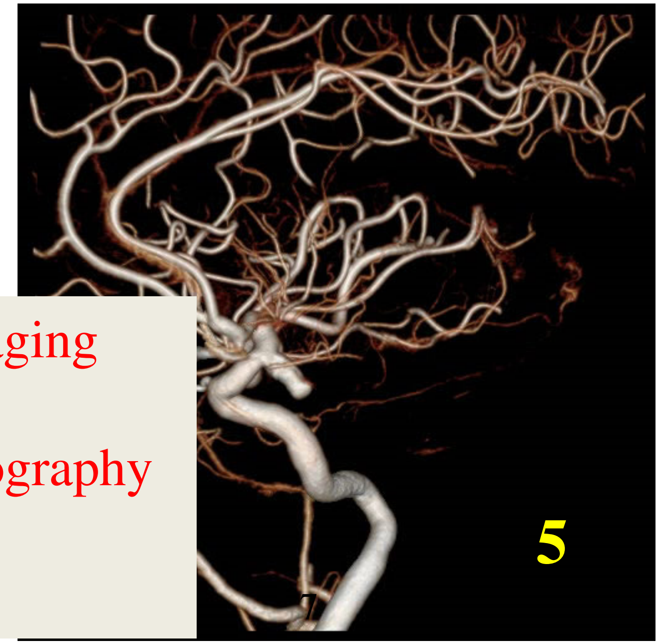
Longitudinal motion of the carotid artery wall as a new marker of cardiovascular risk



2D ultrasound **elastography**



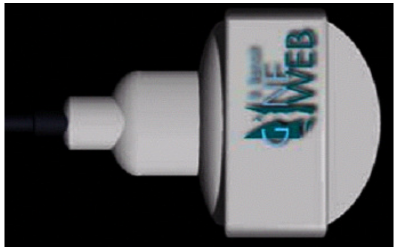




1 –Magnetic Resonance Imaging
2 – Ultrasound
3 – Positron Emission Tomography
4 – X ray
5 – Angiography

Ultrasound scanning

Scanner



Probe

Ultrasound imaging is Non Destructive Testing

The place of ultrasound in medical imaging

Public Hospitals in Lyon (2012) – 2 million inhabitants

- 9 MRI
- 11 scanners
- 8 gamma (scintillation) cameras
- 1 PET (Positron Emission Tomographie)
- **More than 100 ultrasound scanners**

Specific rooms

Real time imaging

IN LIVE

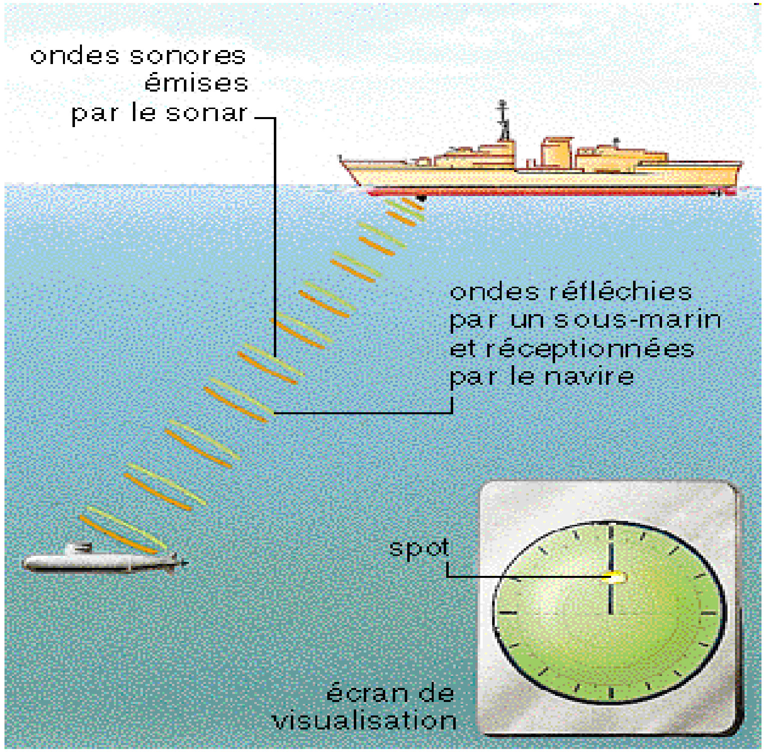
- **10 to 60 frames/s**

The place of ultrasound in medical imaging

- **Ultrasound has the last ten years been the fastest growing imaging modality for non-invasive medical diagnosis.**
- **Of all the various kinds of diagnostic produced in the world, one of four is an ultrasound scan.**
- **Reasons for this are the ability to image soft tissue and blood flow**
  - the **real time imaging** capabilities,
  - the **harmlessness** for the patient and the physician (no radiation)
  - the **low cost** of the equipment.
  - **no special building** requirements as for X-ray, Nuclear, and Magnetic Resonance imaging.
- **Limitations are that ultrasound imaging cannot be done through bone or air (limitations on chest imaging).**

Ultrasound scanner and sonar

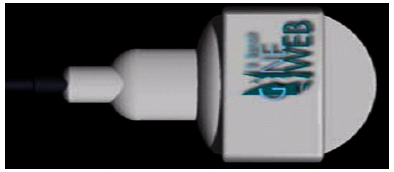
- Ultrasound scanner works as sonar

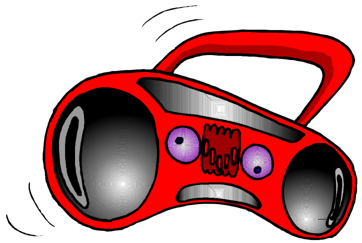


The probe: transmitter and receiver

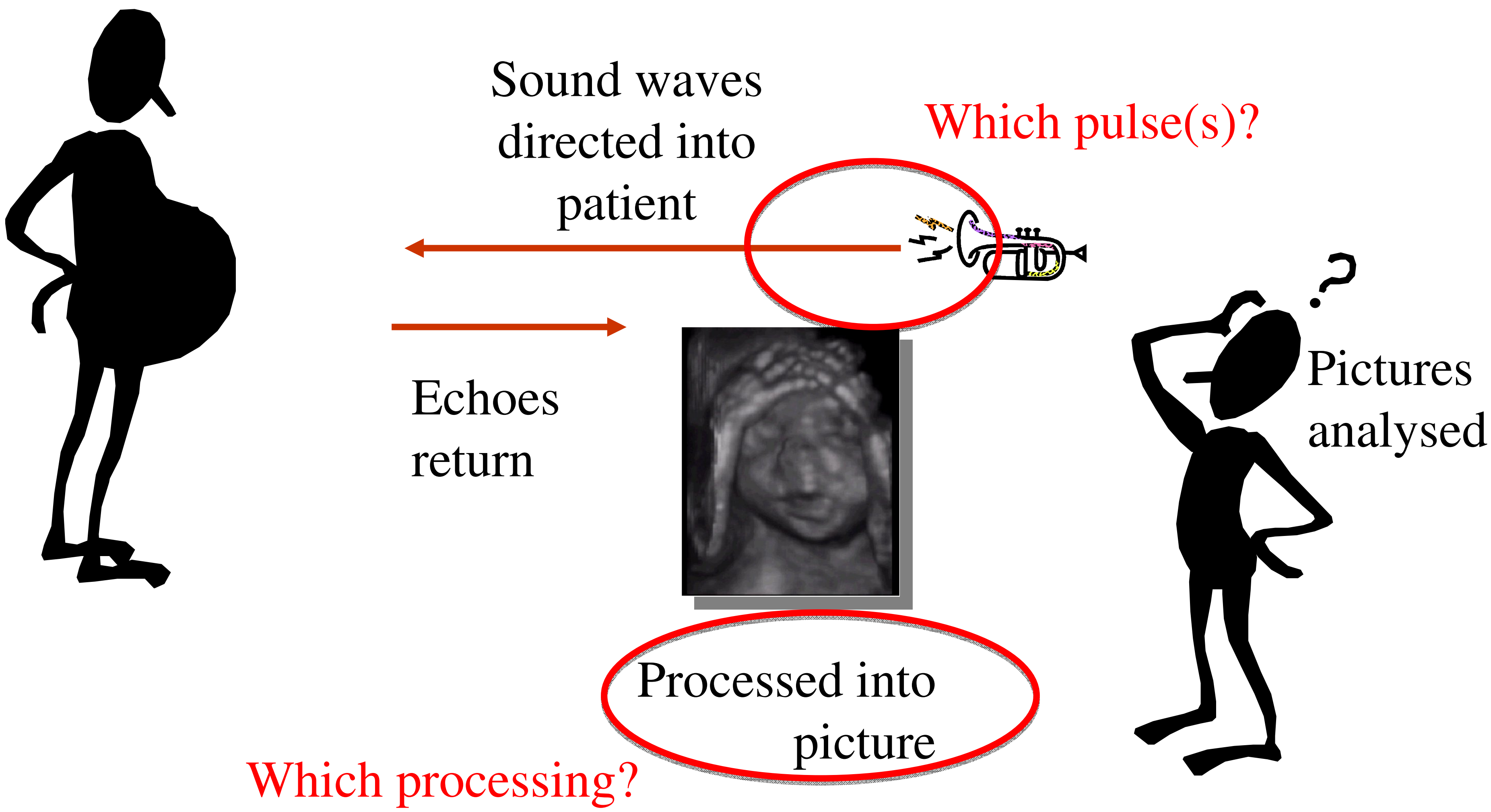
- The same probe is used **first as transmitter**, **second as receiver**

- Probe ⇔ Loudspeaker + Microphone





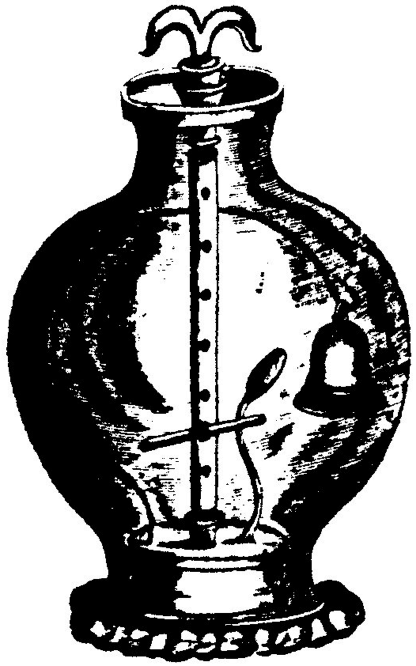
Diagnostic Ultrasound



Mechanical wave

Sound is a mechanical wave

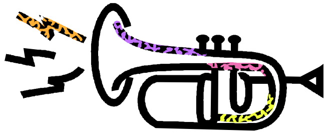
- Created by a vibrating object
- Propagated through a medium



Vacuum chamber

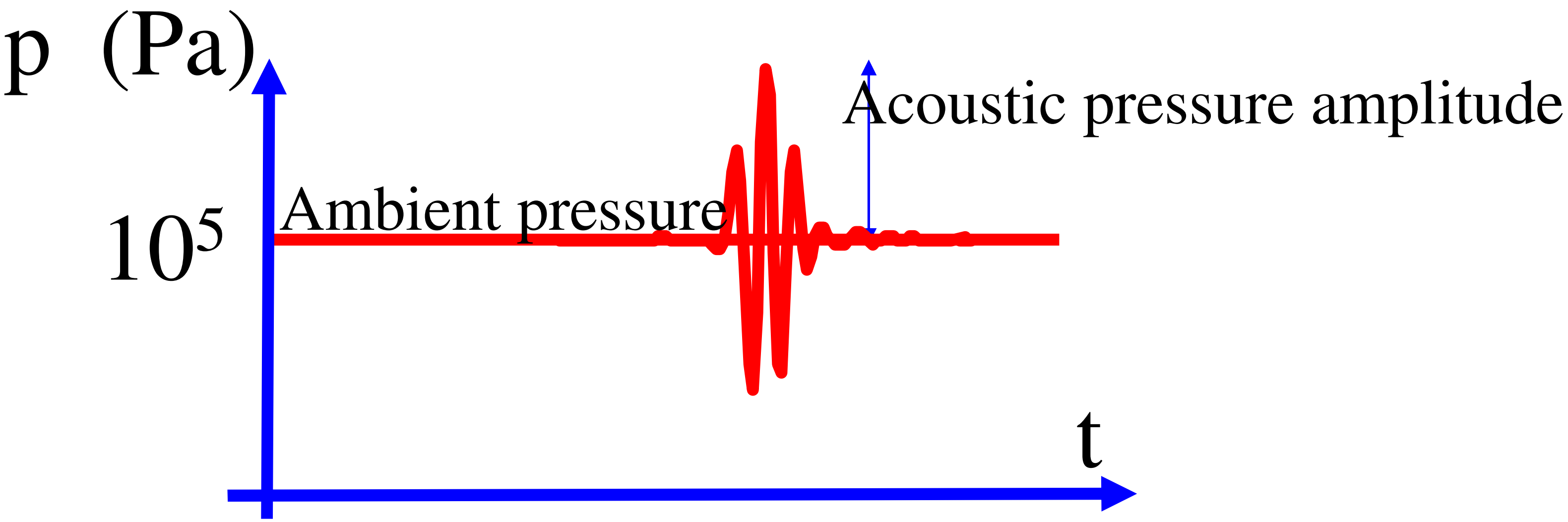
The sound is produced by the bell cannot be heard since sound cannot travel through a vacuum

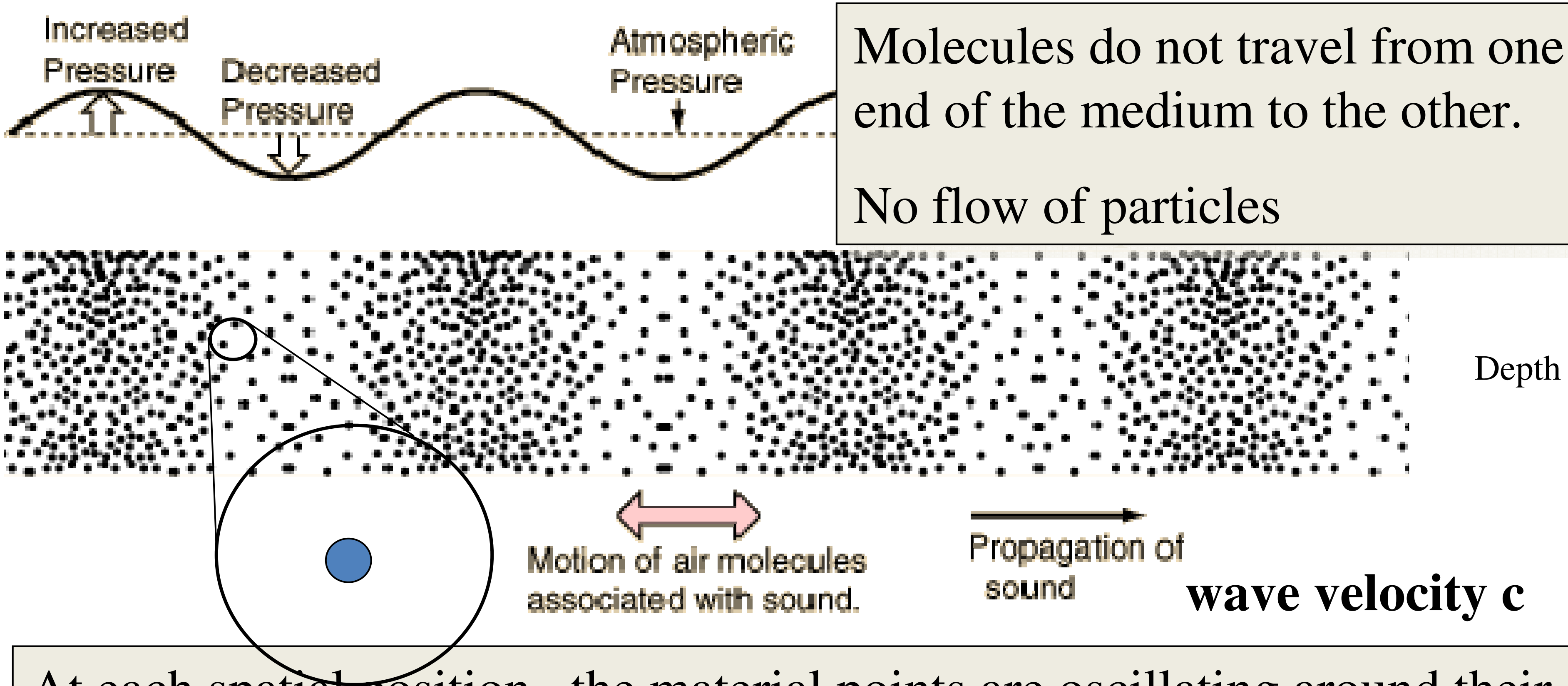
The acoustic pressure



- Ultrasound energy is exactly like sound energy, it is a variation in the pressure within a medium.
- Sound is a pressure wave

The acoustic pressure is the change of pressure around the static (ambient) pressure





Molecules do not travel from one end of the medium to the other.

No flow of particles

wave velocity c

At each spatial position , the material points are oscillating around their equilibrium position with **a particle velocity v**

if u is the displacement of the material point, v = du/dt

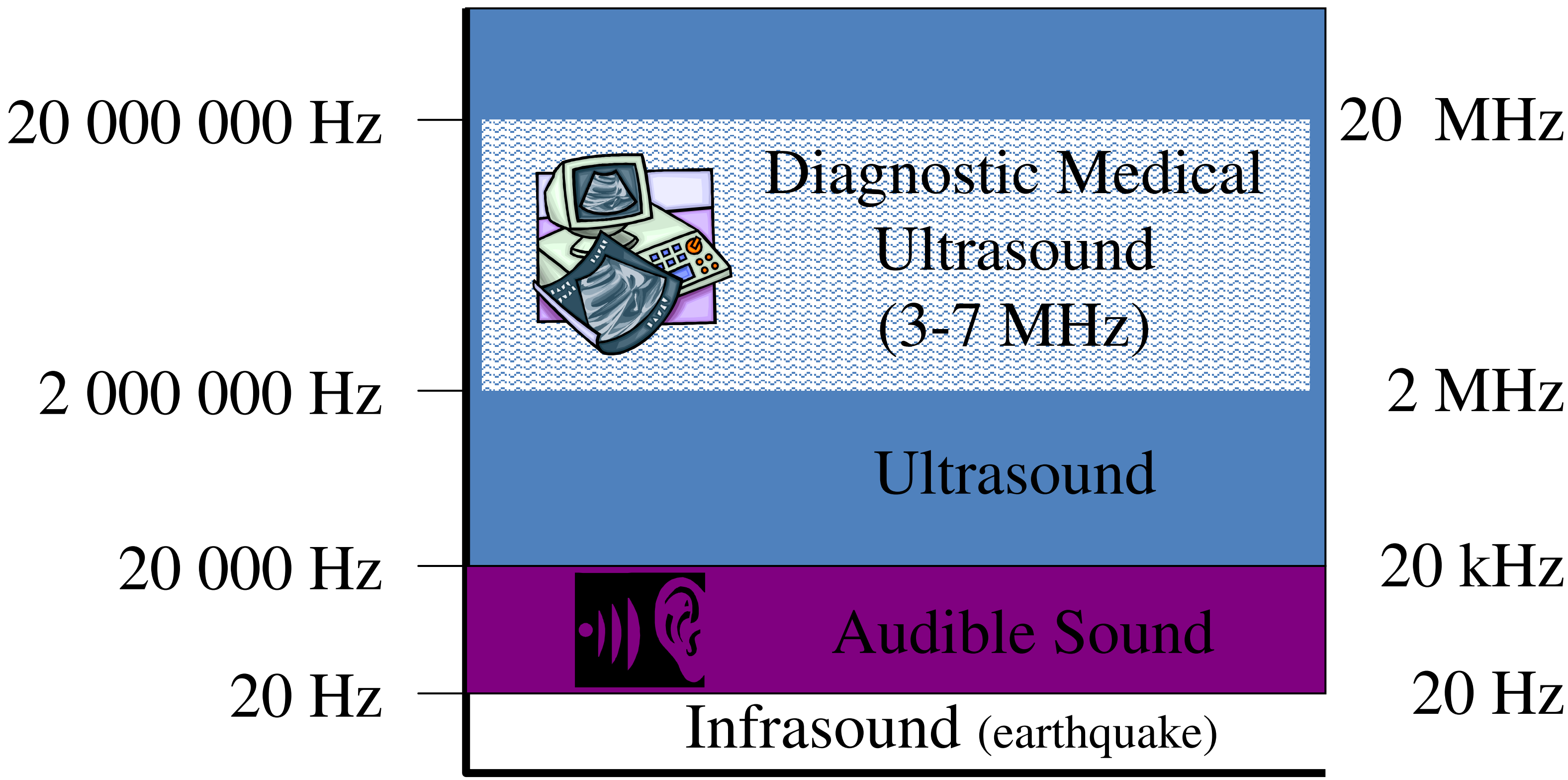
Molecules do not travel from one end of the medium to the other.

Example: f = 3 MHz, P_0 = 150 kPa, the order of u is 5 nm

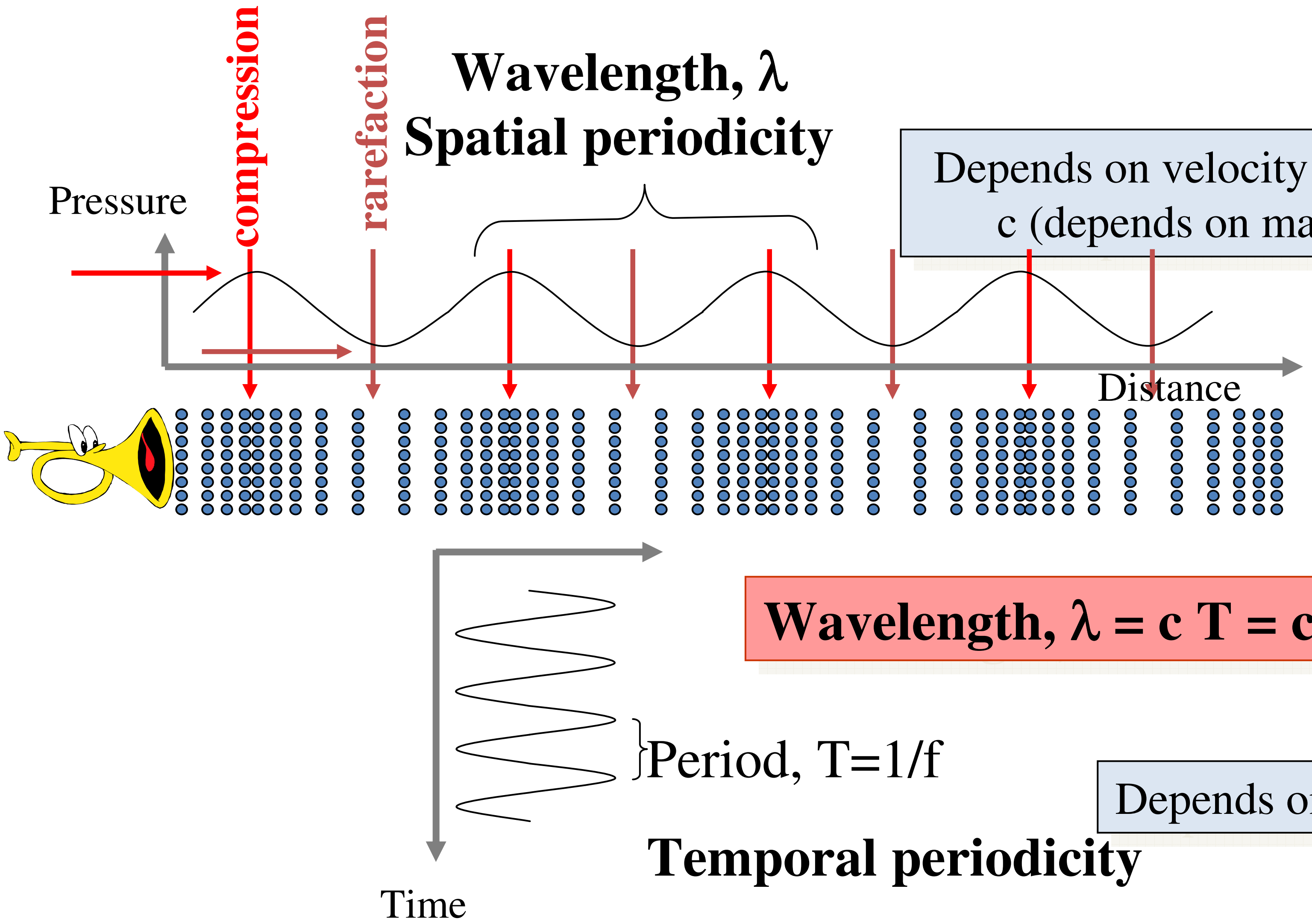
The Nature of a Sound Wave in tissue (liquids)

- **Sound is a mechanical wave**
  - Created by a vibrating object
  - Propagated through a medium
- **Sound is a pressure wave**
  - Consists of repeating pattern of high and low pressure regions
- **Sound is a longitudinal wave**
  - Motion of particles is in a direction parallel to direction of energy transport

Frequency of Sound



Wavelength and frequency of the wave



- **On ultrasound scanner the ultrasound wave is emitted as pulses (not a continuous sine)**

Length of pulse is about 3 to 5 periods

$f = 3$ MHz

$1\ \mu s < T_p < 1.66\ \mu s$

Velocity of the wave

If source is 3.3 kHz frequency

Air $c = 330$ m/s

$\lambda = 330 / 3.3 \cdot 10^3 = 0.5$ m

Water $c = 1500$ m/s

If source is 3 MHz frequency

$\lambda = 1500 / 3 \cdot 10^6 = 0.5$ mm

Speed of Sound

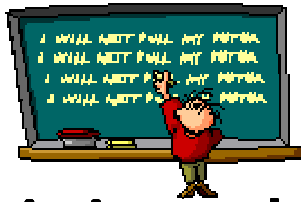
Air	330m/s
Water	1480m/s
Fat	1460m/s
Blood	1560m/s
Muscle	1600m/s
Bone	4060m/s

Average soft tissue value = 1540m/s

Programme the ultrasound machine with...

This can lead to small errors in the estimated distance travelled because of the variation in the speed of sound in different tissues.

Acoustic Impedance



- **Acoustic impedance analogous to electrical impedance**

$$z = \frac{P}{v}$$

P = local pressure

v = local particle velocity

$$z = \frac{U}{I}$$

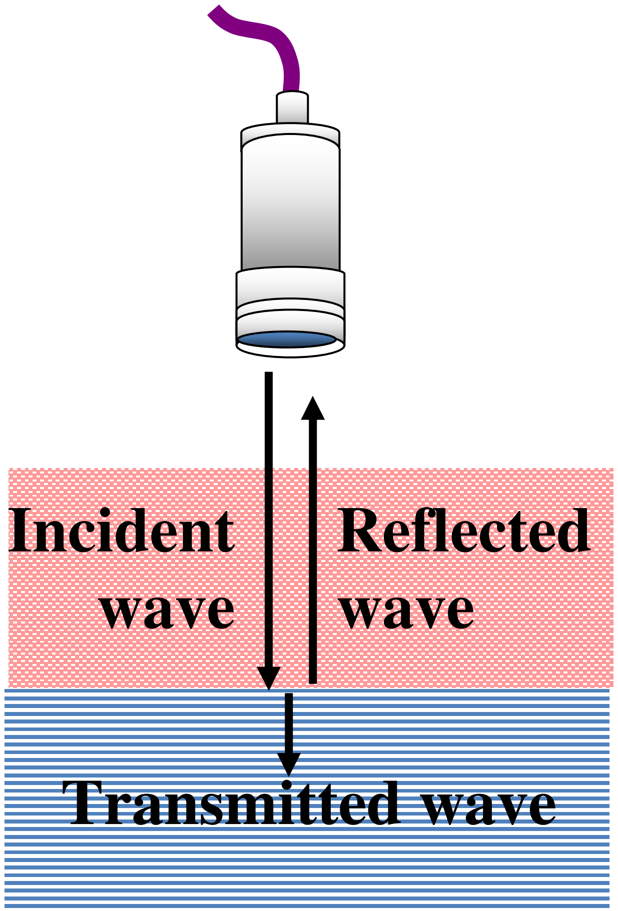
U : Potential

I : Intensity

Reflection at boundaries

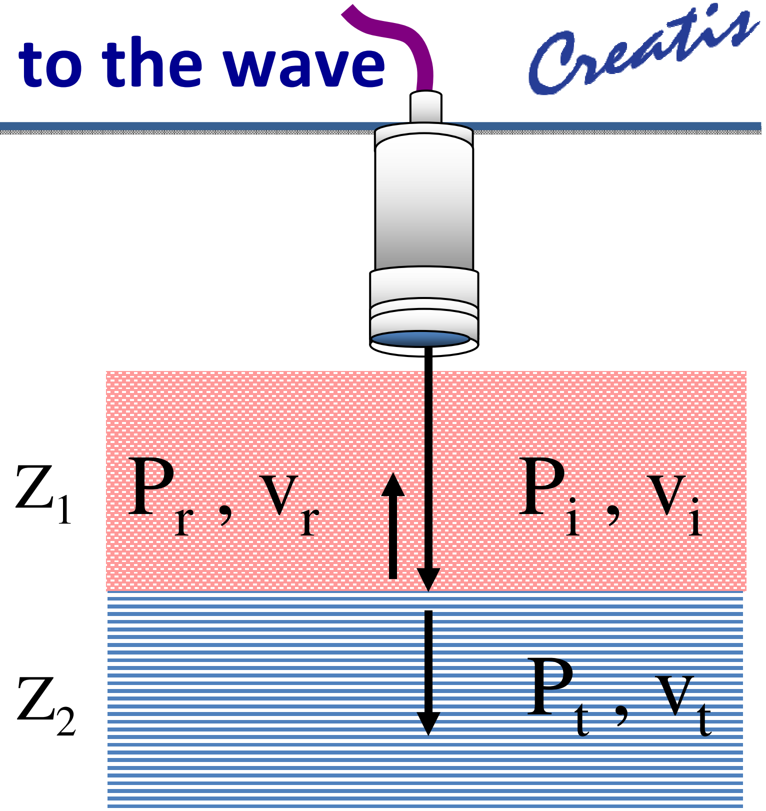
The laws of optics apply to ultrasound

- **At the boundary between tissues ultrasound is partially reflected**
- **The relative proportions of the energy reflected and transmitted depend on the <u>acoustic impedances</u> z_1 and z_2 between the two materials**



Reflection at interface perpendicular to the wave

$$\frac{P_r}{P_i} = \frac{z_2 - z_1}{z_2 + z_1}$$



- $z_2 \approx z_1$

$$\frac{P_r}{P_i} \approx 0$$

complete transmission

- $z_2 >> z_1$ or $z_2 << z_1$

$$\frac{P_r}{P_i} \approx 1$$

complete reflexion

Acoustic Impedance

- Air *0.0004* x 10^6 rayls
- Lung 0.18 x 10^6
- Fat 1.34 x 10^6
- Water 1.48 x 10^6
- Blood 1.65 x 10^6
- Muscle 1.71 x 10^6
- Skull Bone 7.80 x 10^6

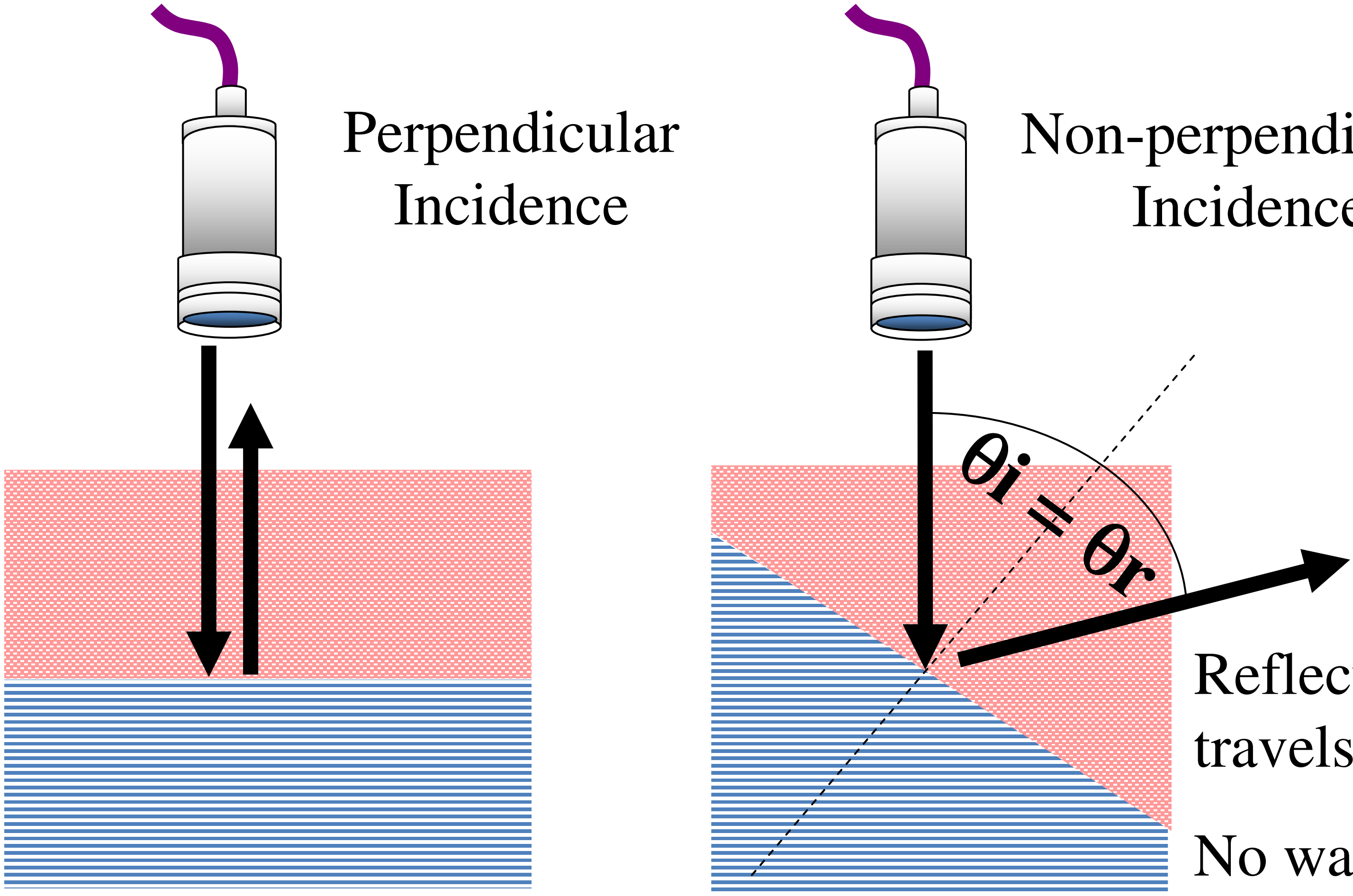
Similar Values (Lung, Fat, Water, Blood, Muscle)

- $z_2 >> z_1$ or $z_2 << z_1$ complete reflexion

  Air and tissue

Echographic gel

Specular Reflection

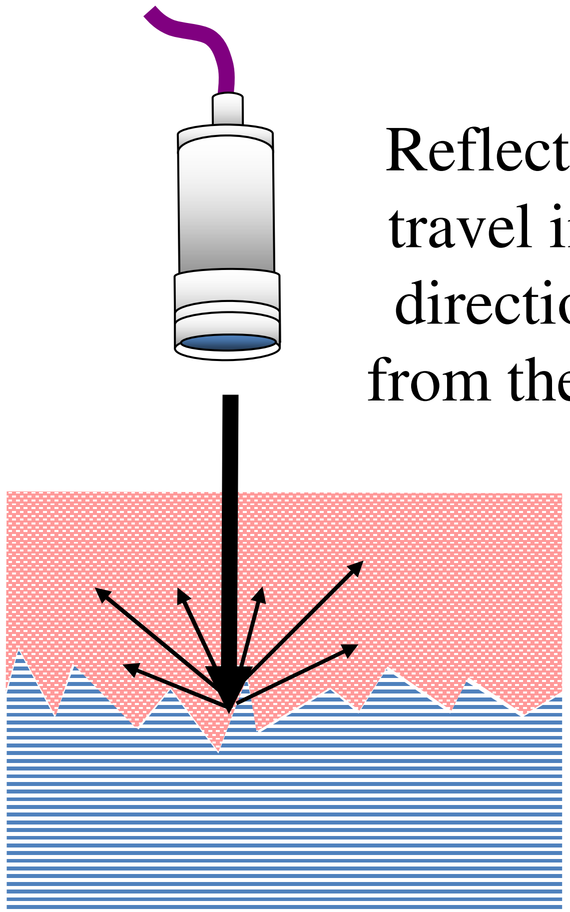


Reflected beam travels off at an angle.

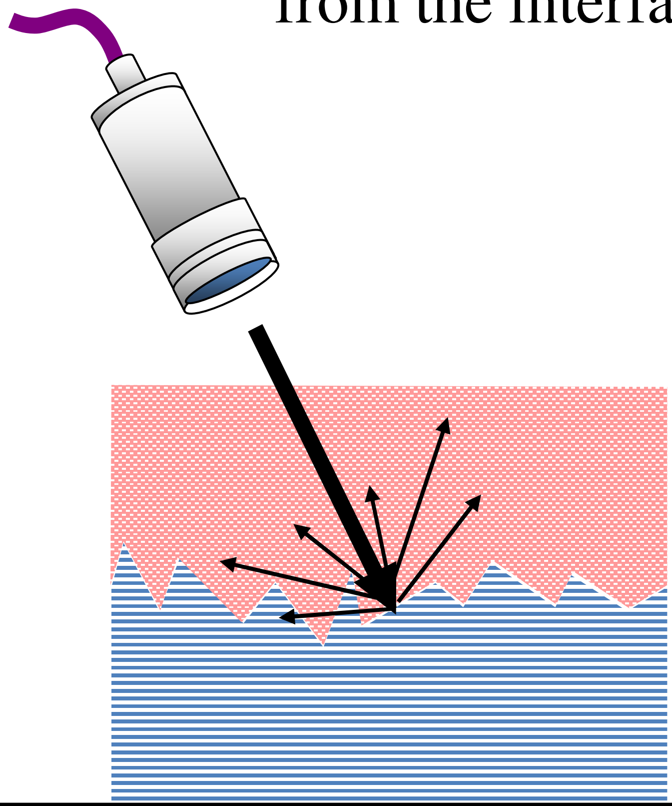
No wave go back to the probe

Strong orientation dependence

Diffuse Reflection



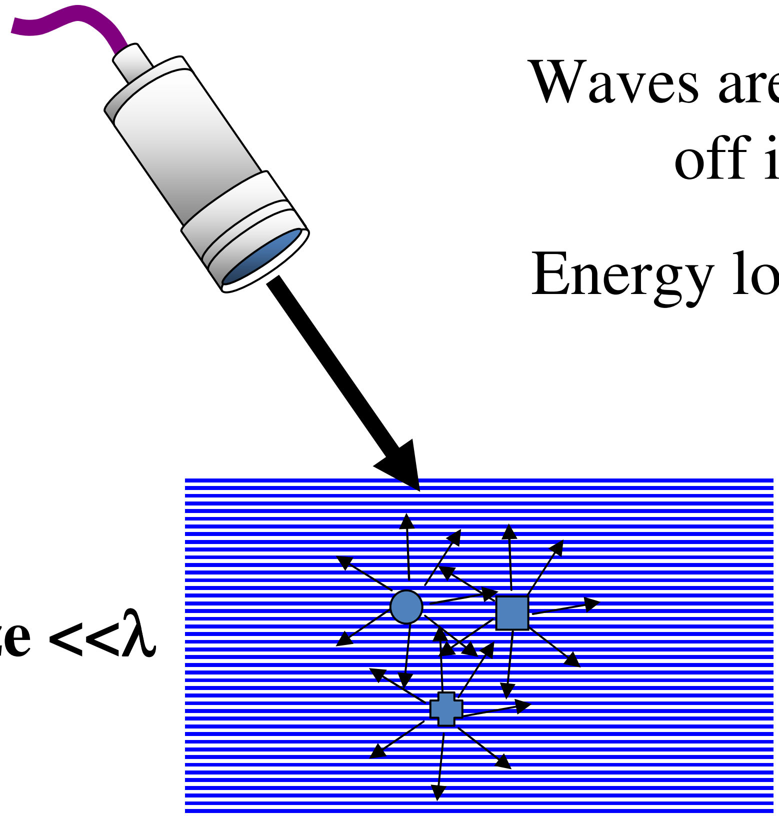
Reflected waves travel in various directions away from the interface



Reflected waves travel in various directions away from the interface

Some orientation dependence

Rayleigh Scattering



Waves are scattered and travel off in all directions

Energy loss proportional to f^4

Particles size <<λ

Little orientation dependence

Echo Amplitude - Beware!

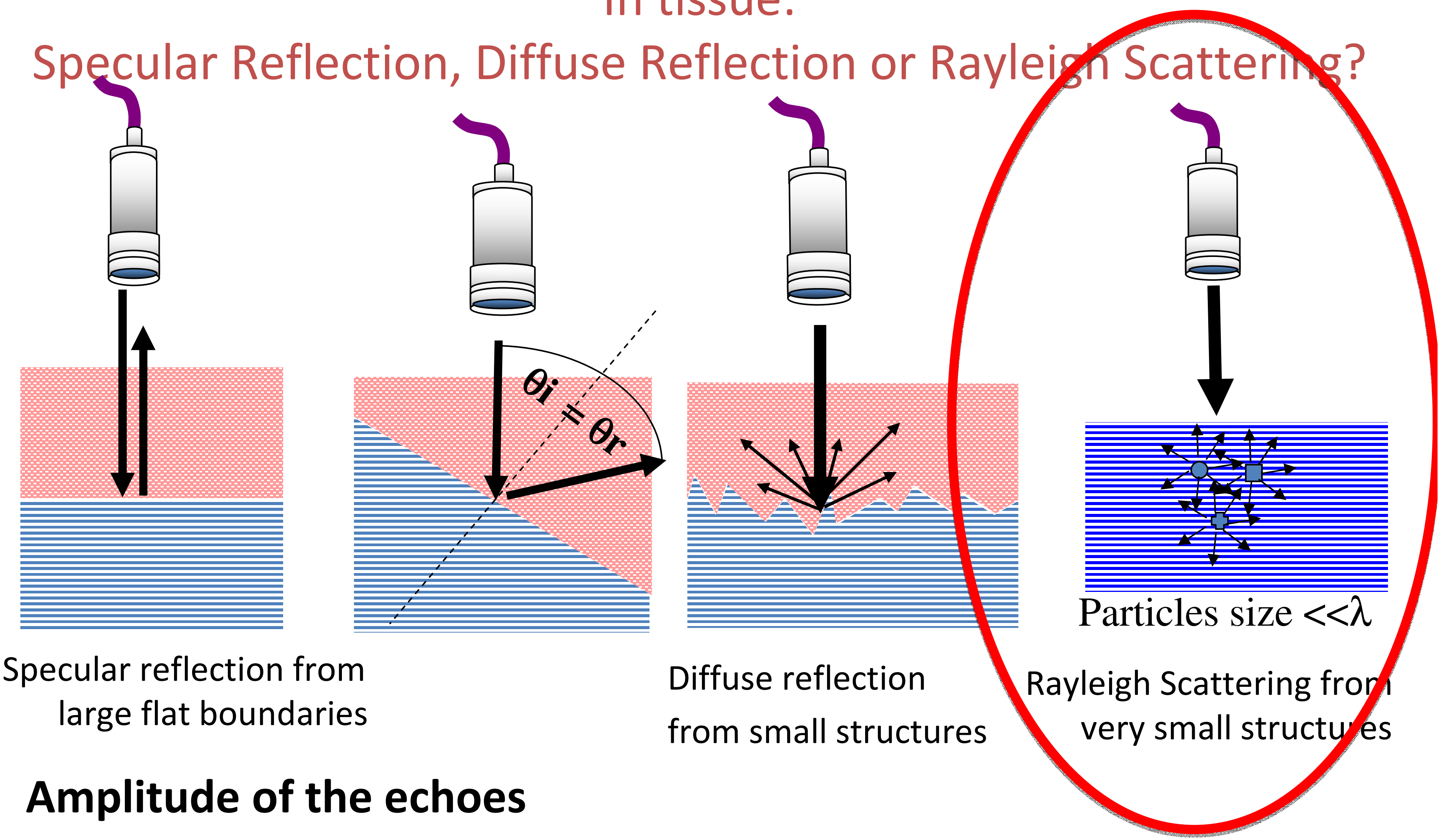
The amplitude of the echoes (image grey level) does *not* have a simple relationship with the tissue (unlike X-ray CT [Hounsfield numbers]).

- **Echo size depends on**
  - relative acoustic impedances across boundary
  - shape and orientation of boundary
  - size of structure compared with λ

Reflection or scattering?

In tissue:

Specular Reflection, Diffuse Reflection or Rayleigh Scattering?



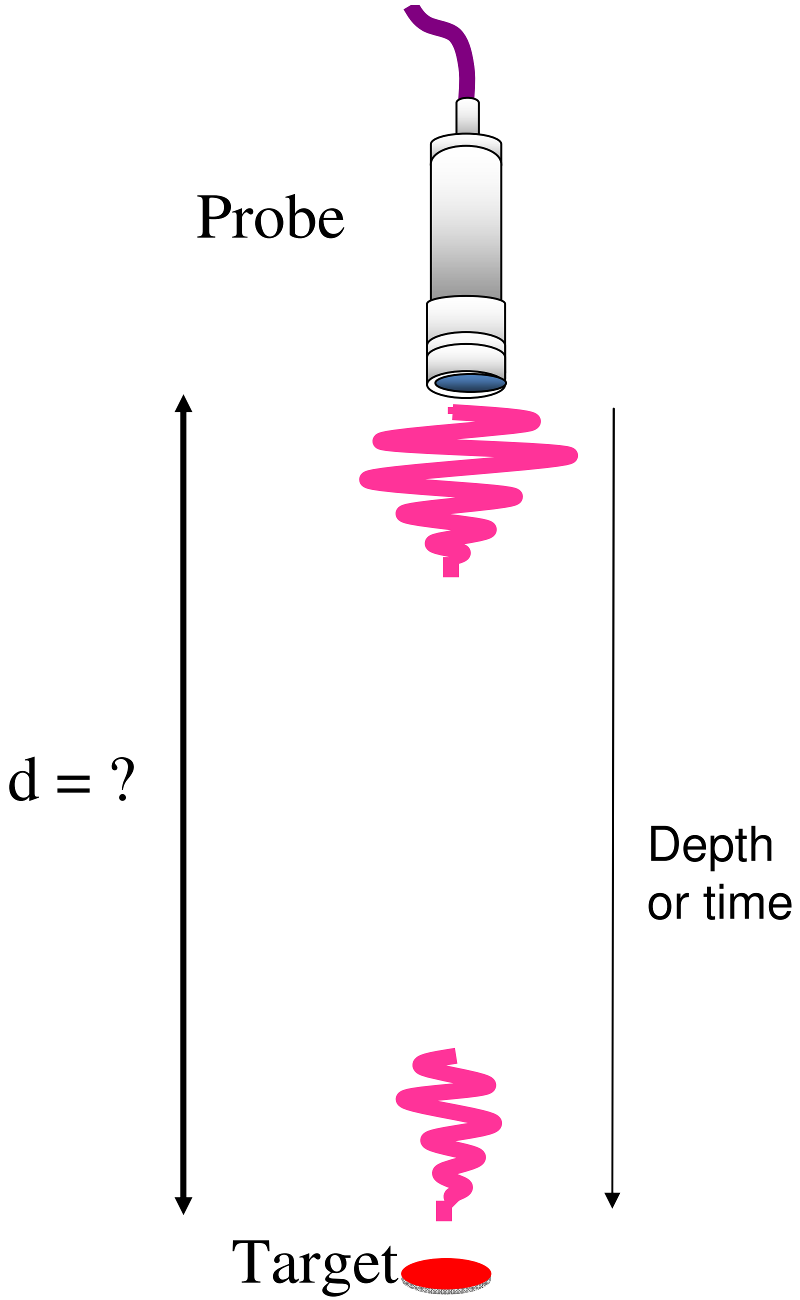
Specular reflection from large flat boundaries

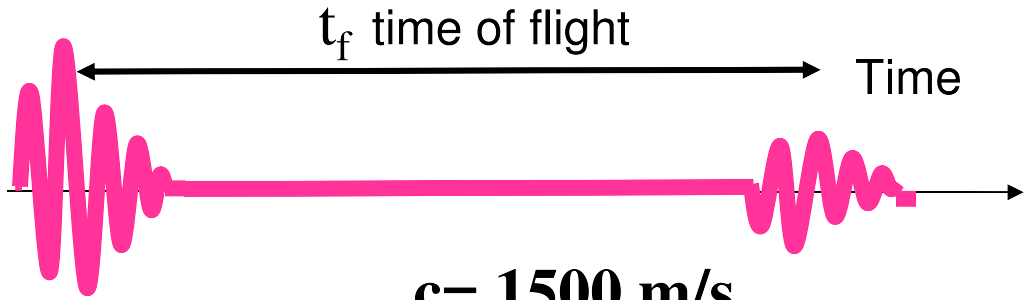
Diffuse reflection from small structures

Rayleigh Scattering from very small structures

- **Amplitude of the echoes**

Strong **Weak** **Very weak**





c= 1500 m/s

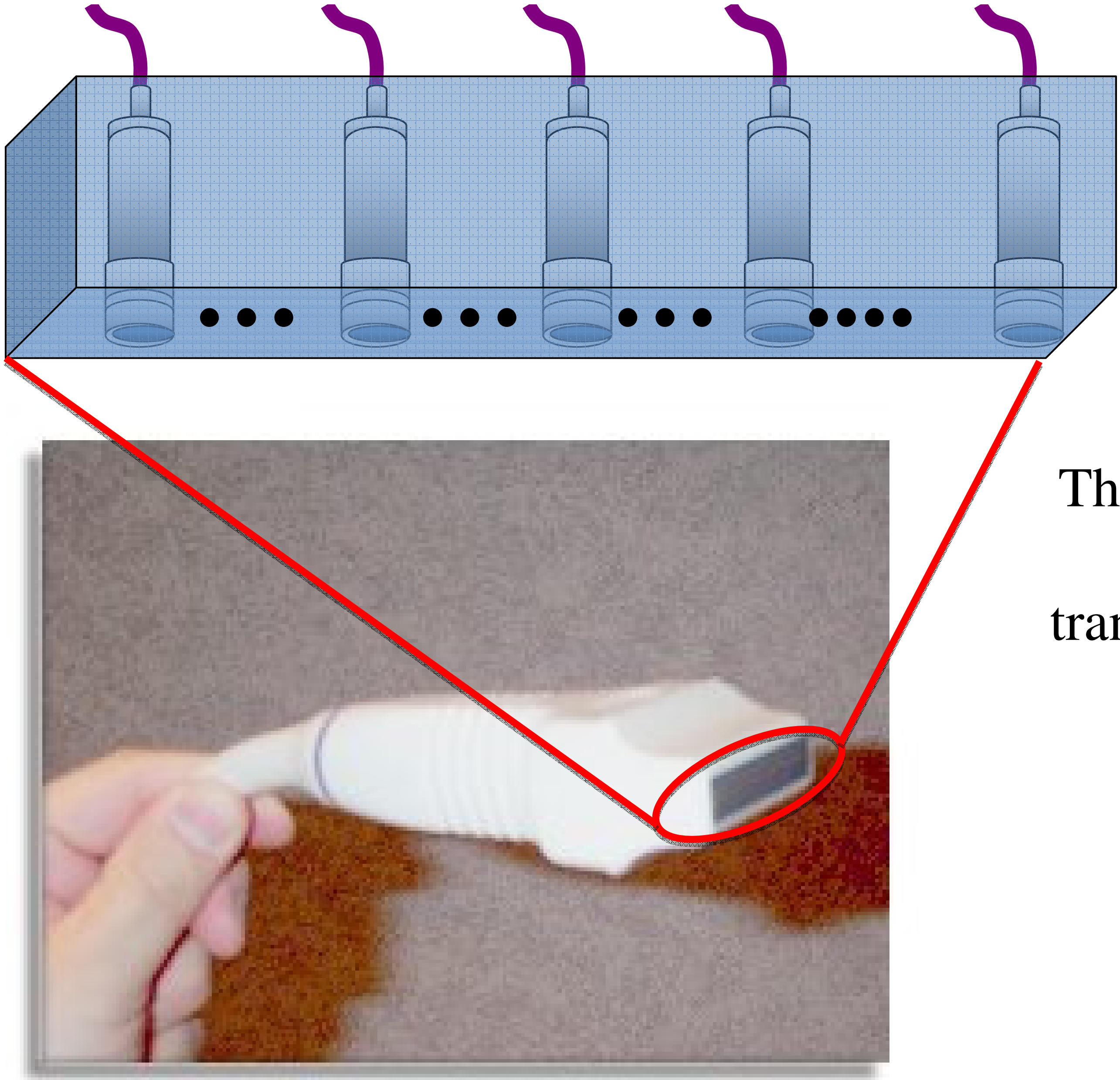
(sound velocity in water)

$$d = \frac{c \cdot t}{2}$$

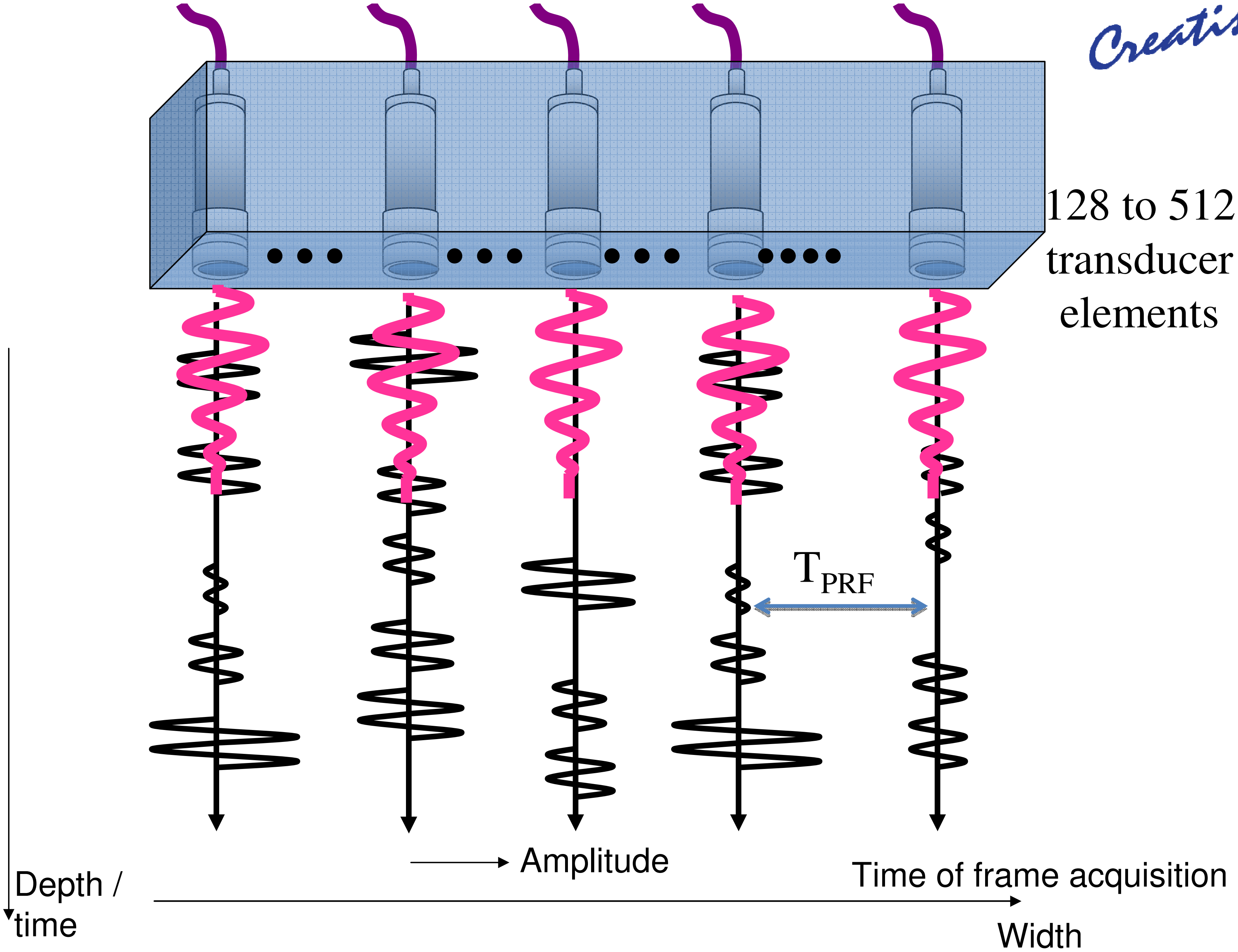
Range of depth and time of flight

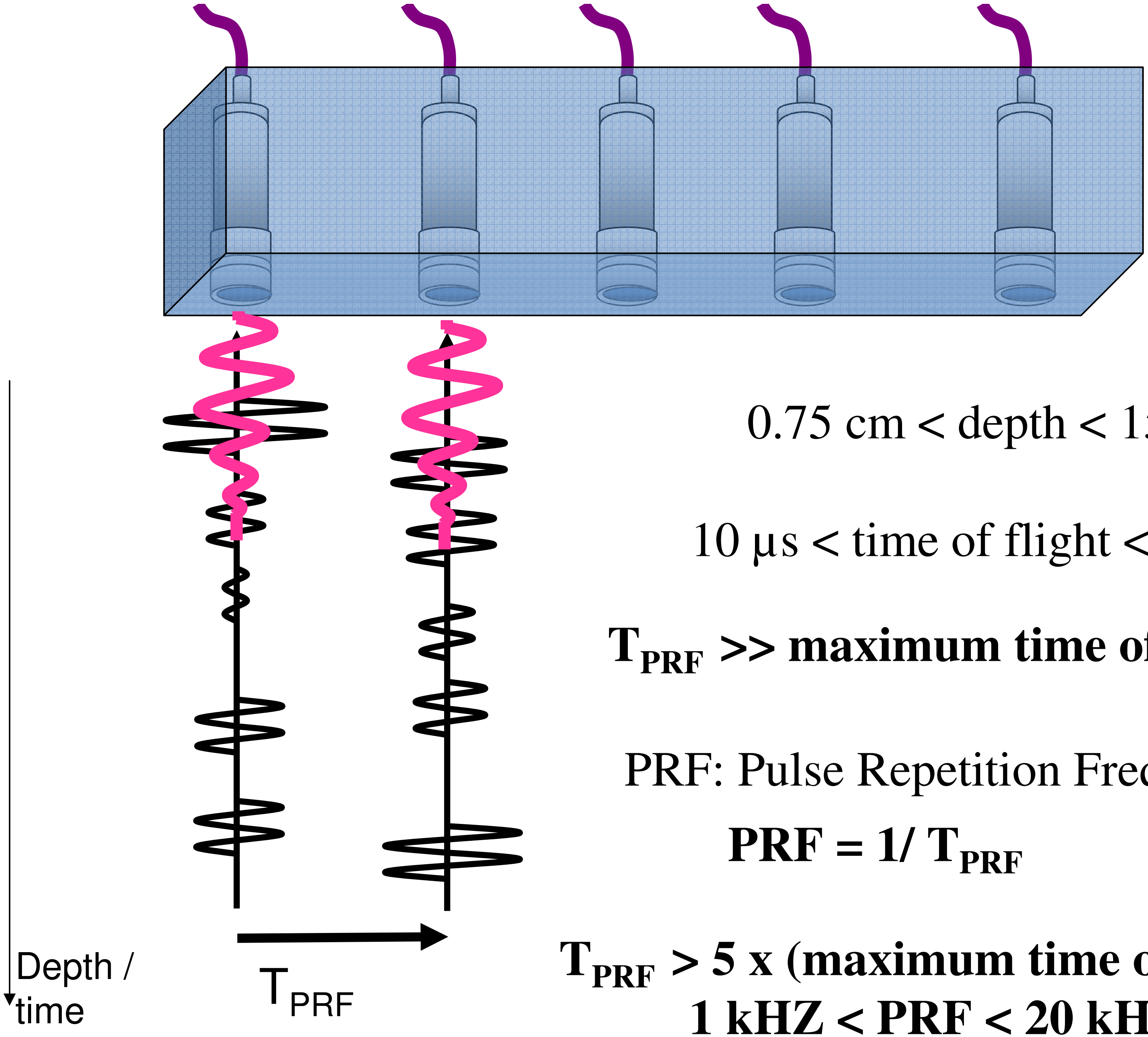
0.75 cm < depth < 15 cm

10 µs < t_f: time of flight < 200 µs



The probe includes 128 to 512 transducer elements


128 to 512 transducer elements
T_{PRF}
Amplitude
Time of frame acquisition
Depth / time
Width



0.75 cm < depth < 15 cm

10 μs < time of flight < 200 μs

T_{PRF} >> maximum time of flight

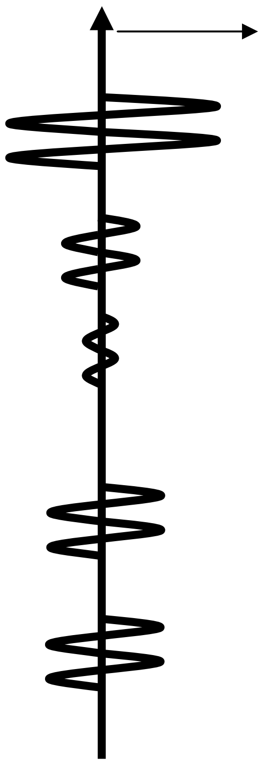
PRF: Pulse Repetition Frequency

$PRF = 1/T_{PRF}$

T_{PRF} > 5 x (maximum time of flight)

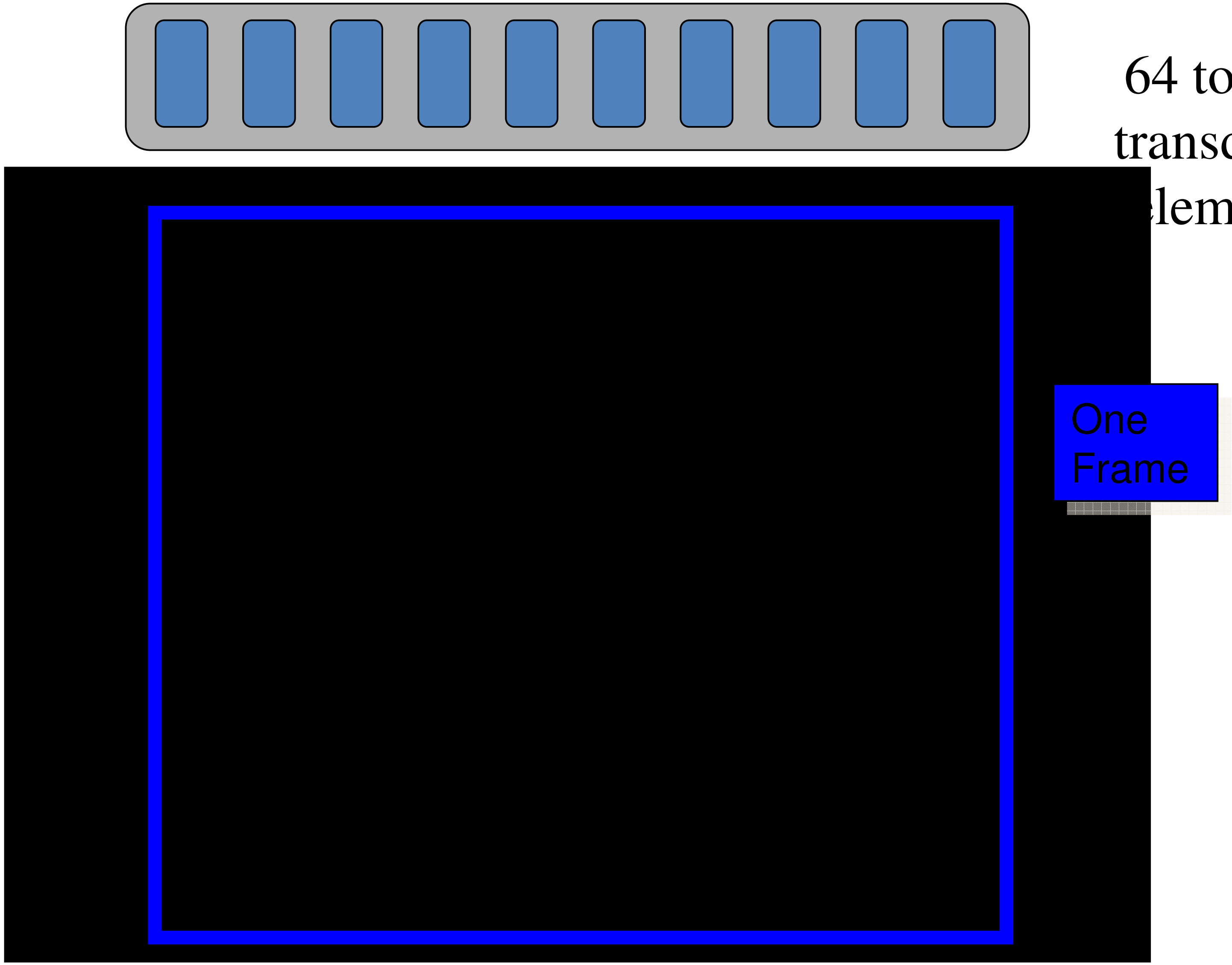
1 kHZ < PRF < 20 kHZ

Echoes from ONE pulse



The echo amplitudes are converted to shades of grey

B (Brightness) Mode Image

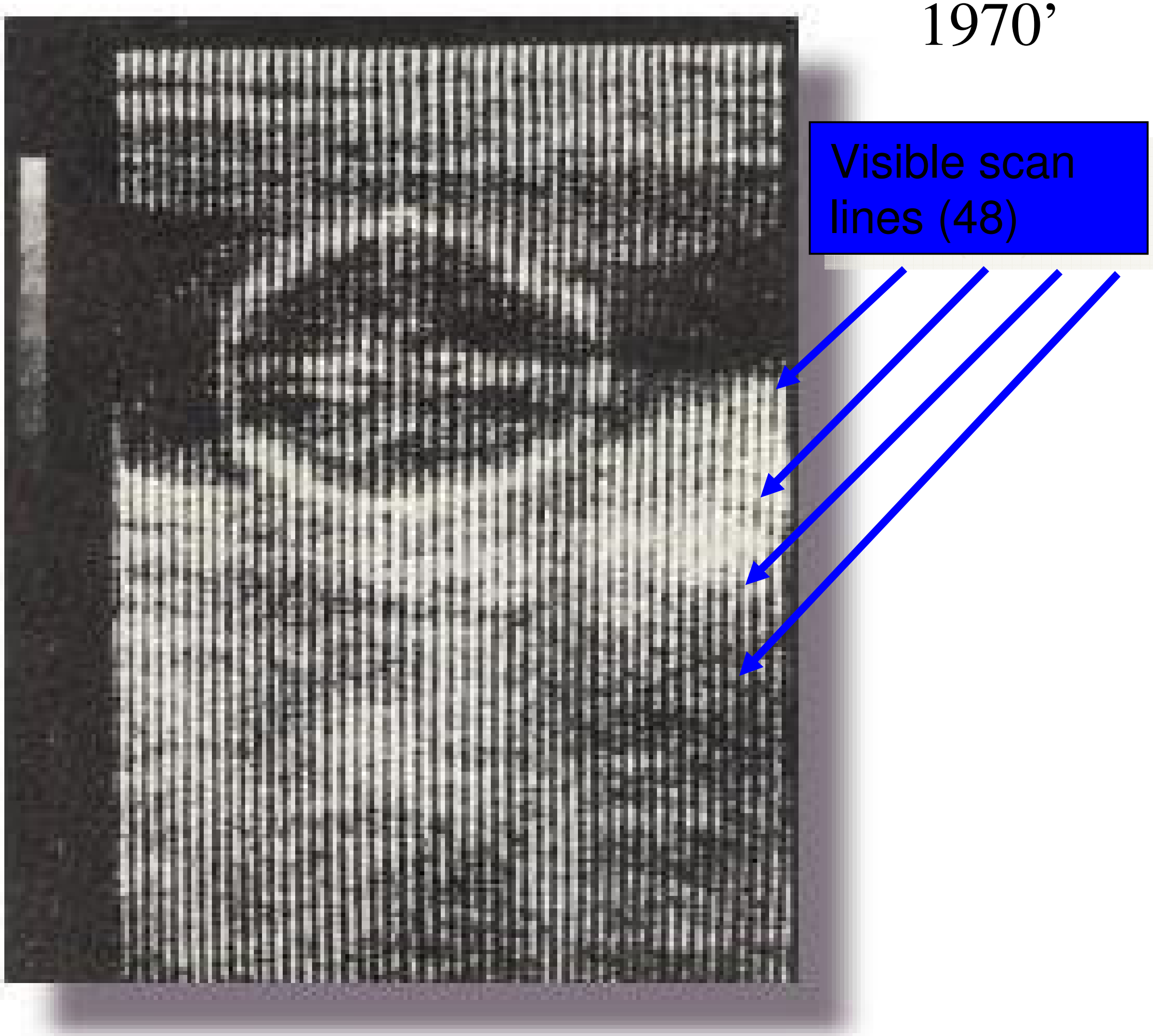


64 to 512 transducer elements

- **10 to 60 frames/s**

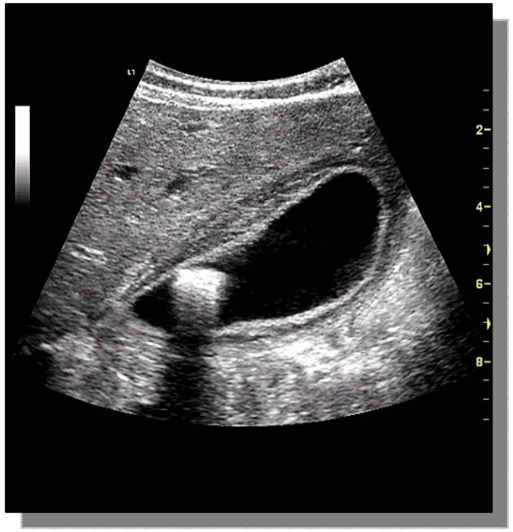
B mode image 1970'

1970'



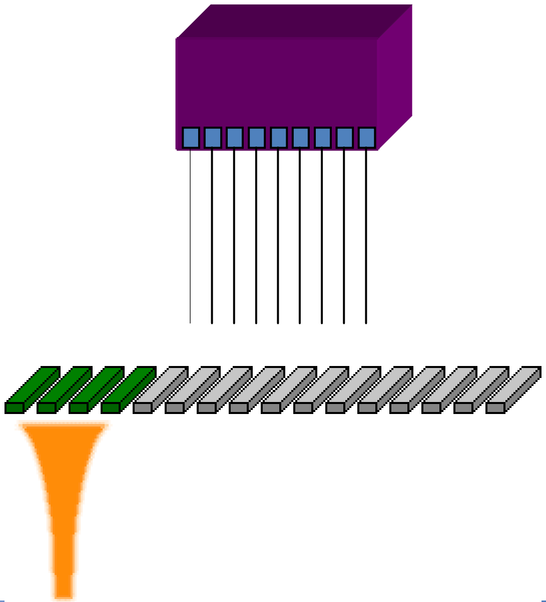
	Range
Frequency	1 MHz < frequency< 10 MHz
Time of pulse (length 3 periods)	0.3 µs < T_P< 3 µs
Time of flight	10 µs < time of flight < 200 µs
Pulse Repetion Frequency	1 kHZ < PRF < 20 kHZ
Number of elements	64 <N_{elt} < 512
Frame rate (PRF = 5kHz)	10 frame/s < N_{frame} <80 frame/s
Time of frame(PRF = 5kHz)	12 ms < Time of frame< 100 ms

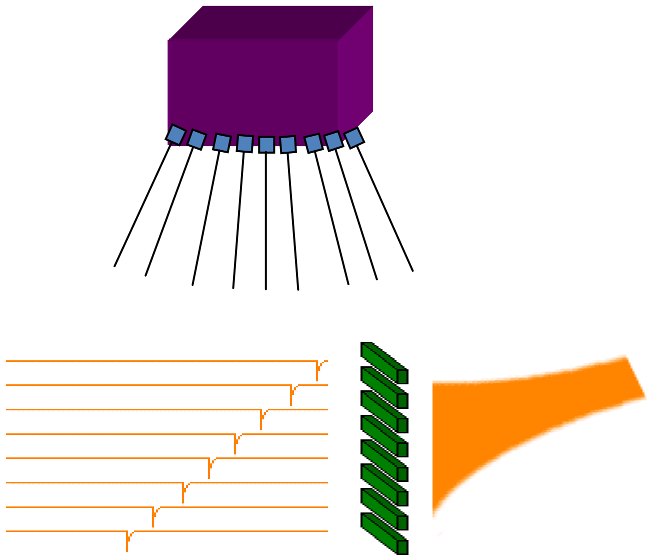
Shapes of the images: linear or sectorial



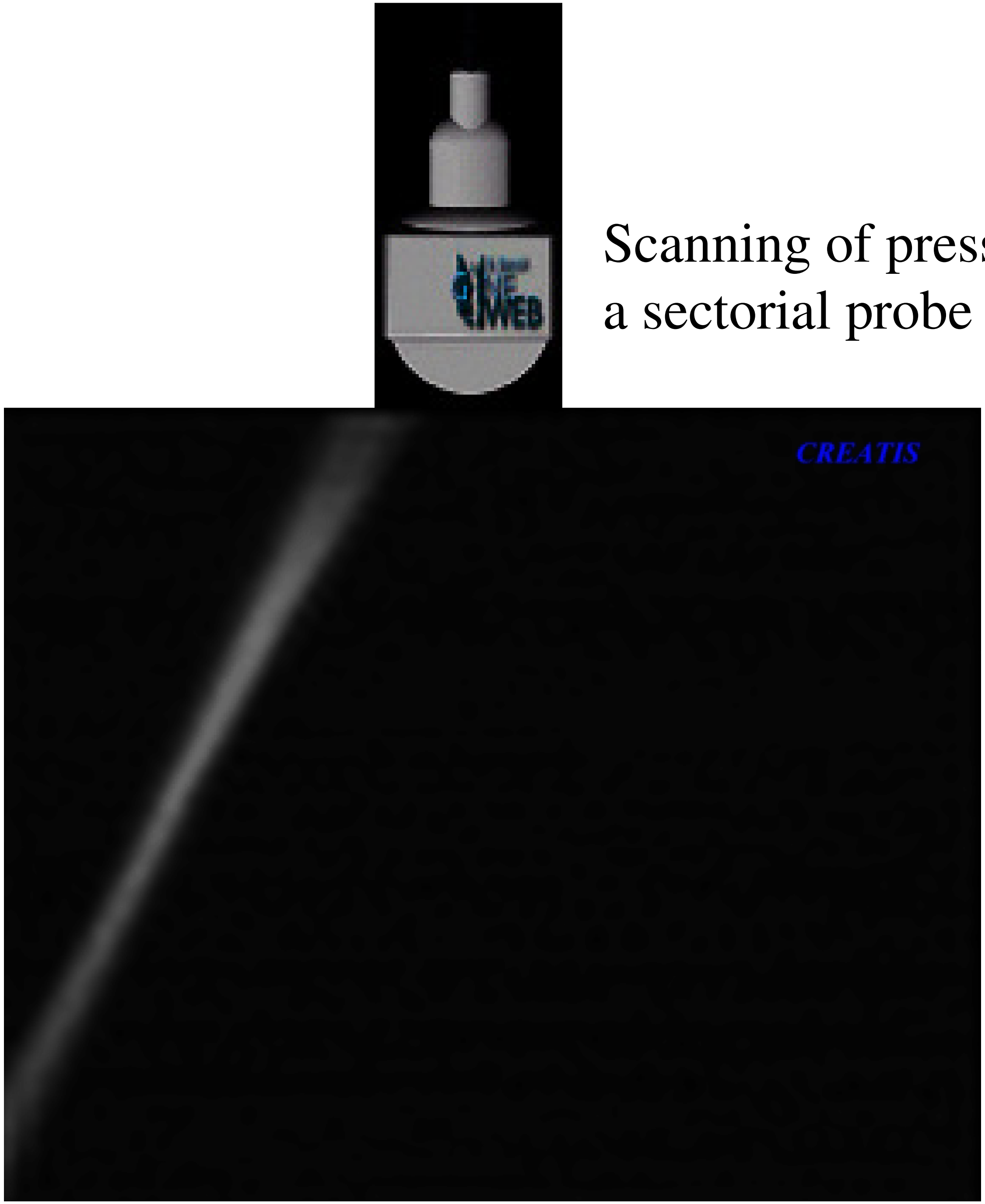
Linear probe

Sectorial probe





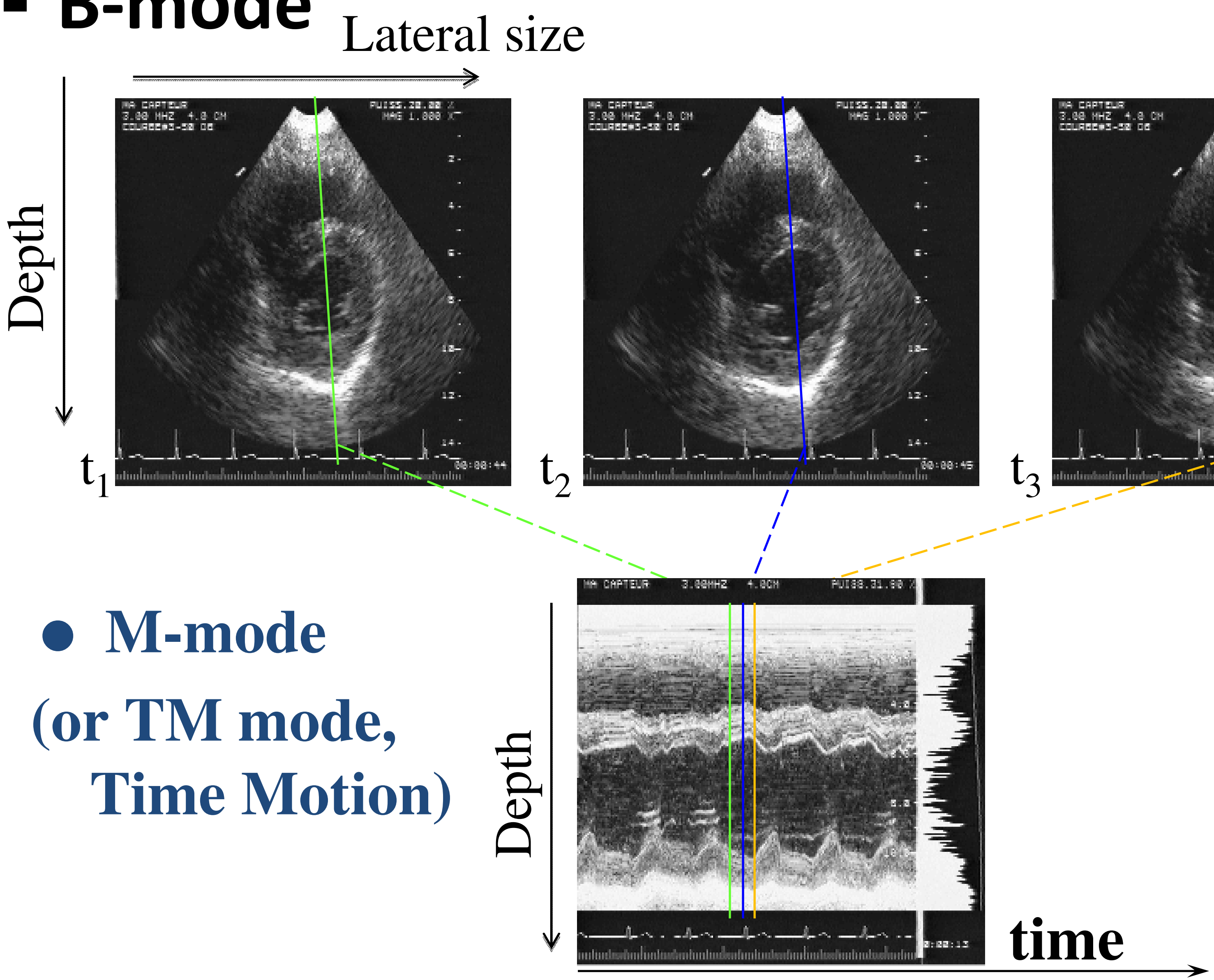
Creatis



Scanning of pressure beam with a sectorial probe

B mode and M mode

- **B-mode**



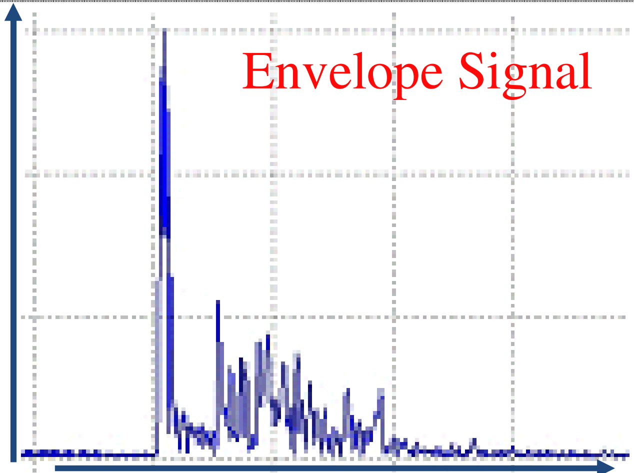
- **M-mode**

  (or TM mode, Time Motion)

Imaging modes

Scan plane

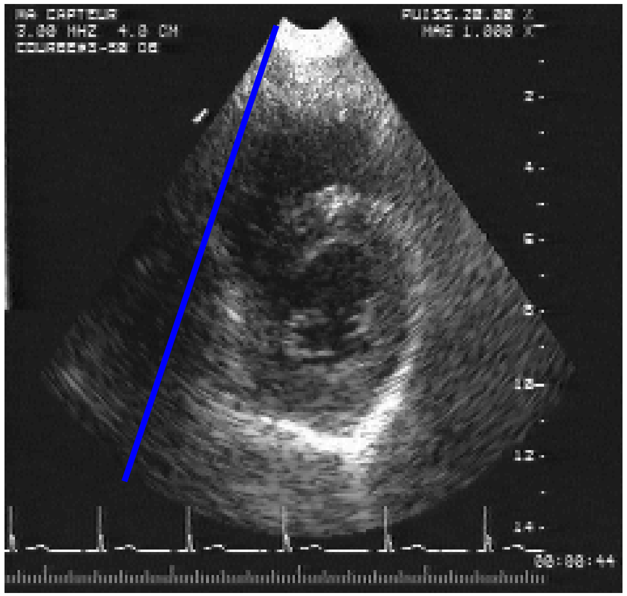
Distance (cm)



Depth (cm)

A mode

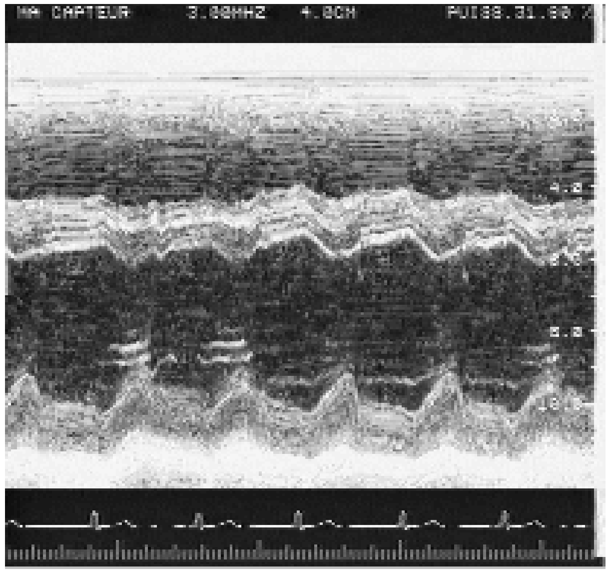
Time (s)



B mode

Depth (cm)

Depth (cm)

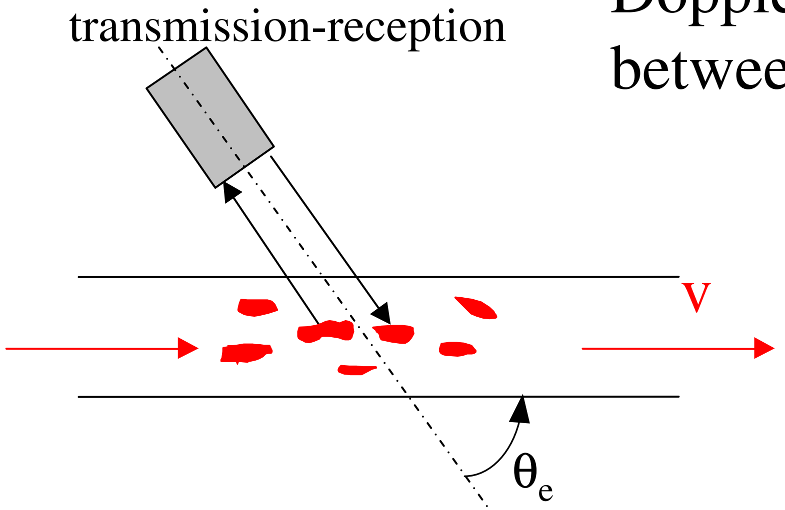


TM mode

One frame: 20 to 50 ms

One continuous image of 5 s

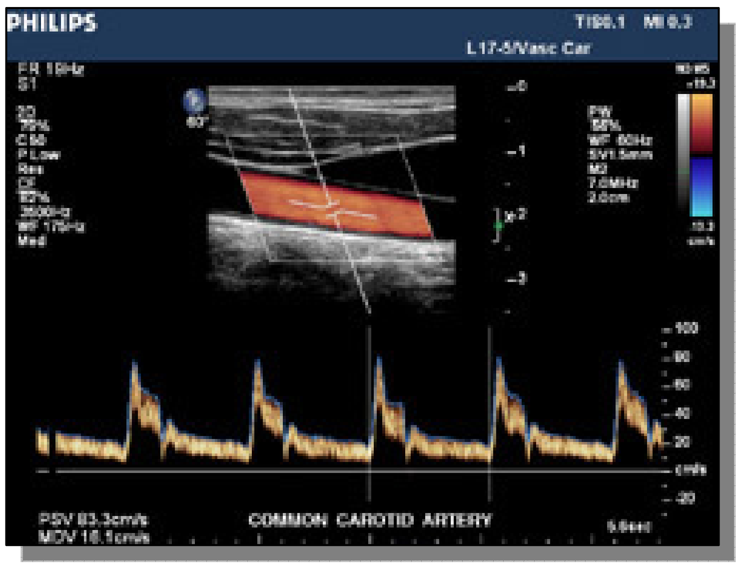
Doppler modes: velocity measurements



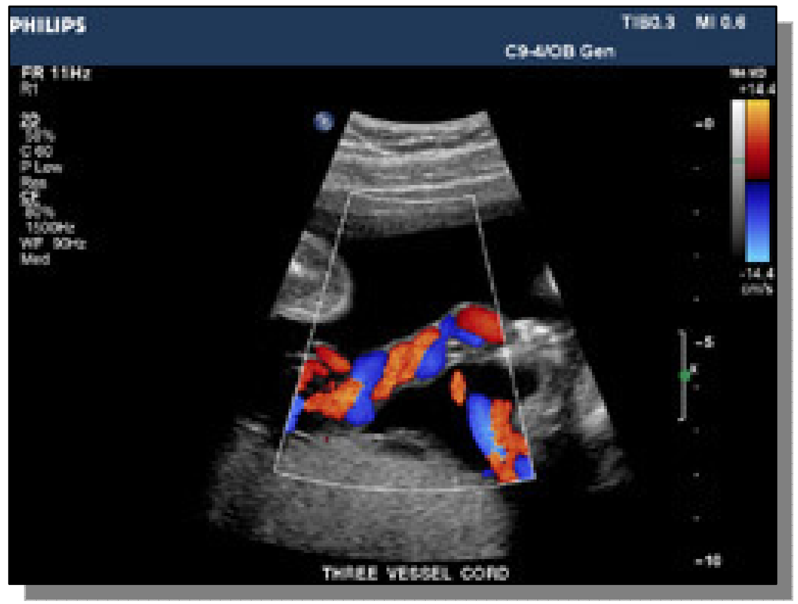
Doppler frequency : the frequency difference between the frequency transmitted and received

$$\mathbf{F = f_r - f_0}$$

$$\frac{F}{f_0} = \frac{v}{c} \, (-) \, 2 \cos\theta_e$$

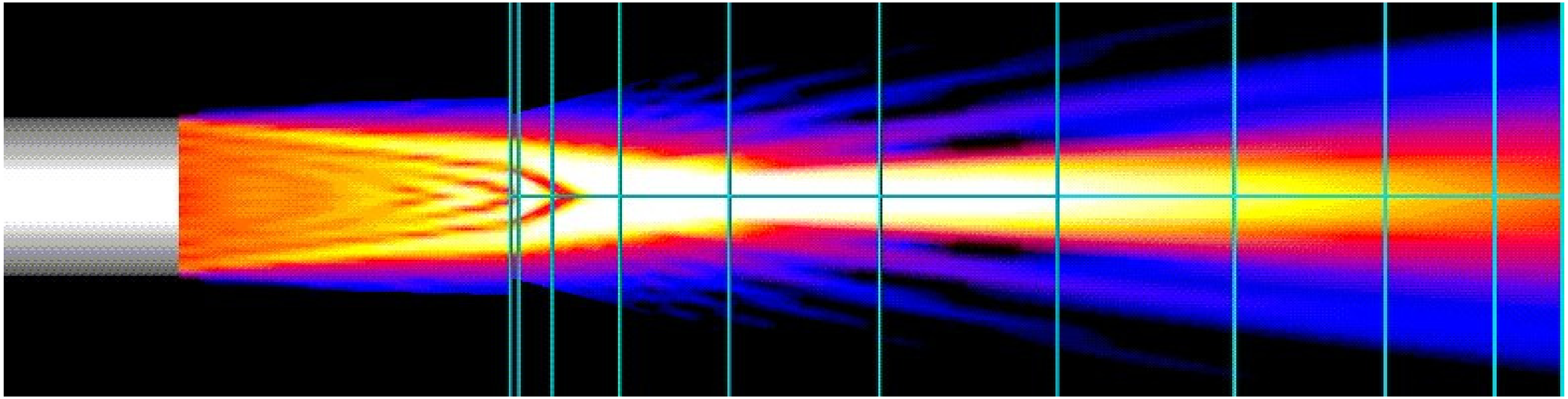


Spectral Doppler

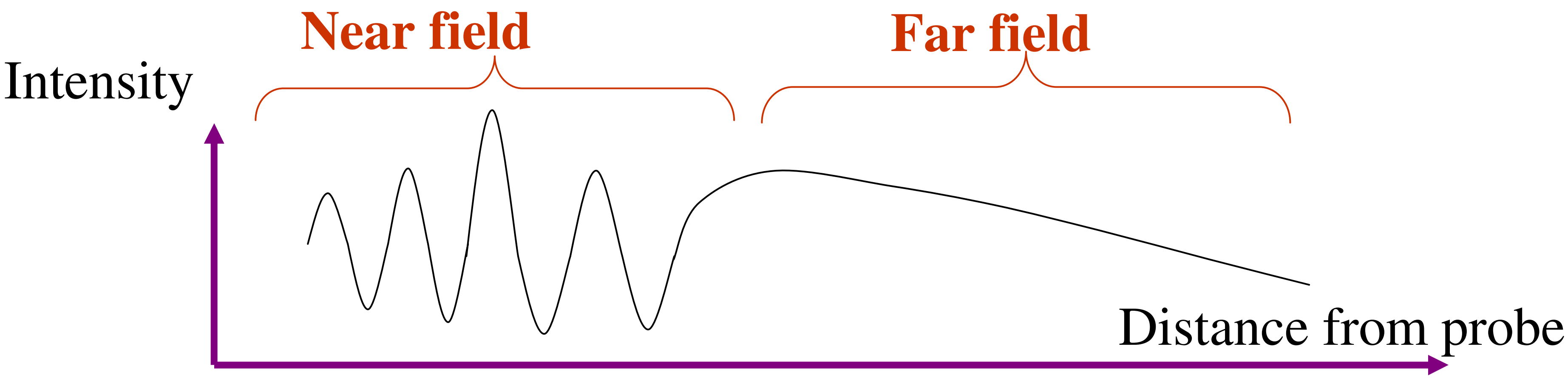


Colour Doppler

Ultrasound beam from a plane disc source



Intensity on axis propagation

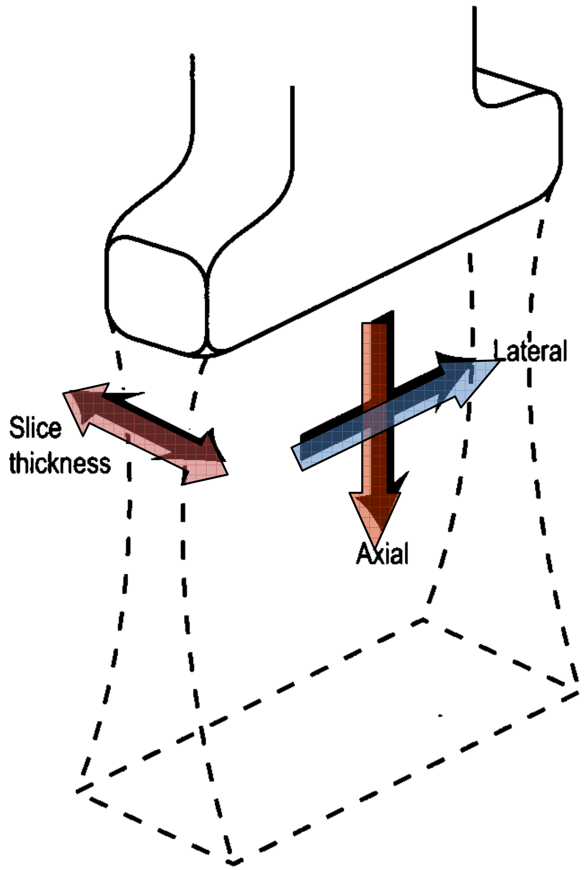


Avoid measurements in the near field

Imaging Resolution

- **Spatial Resolution**
- **Temporal Resolution**
- **Contrast Resolution**

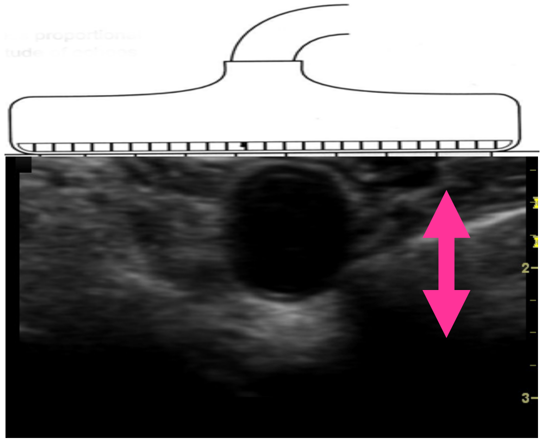
Spatial Resolution

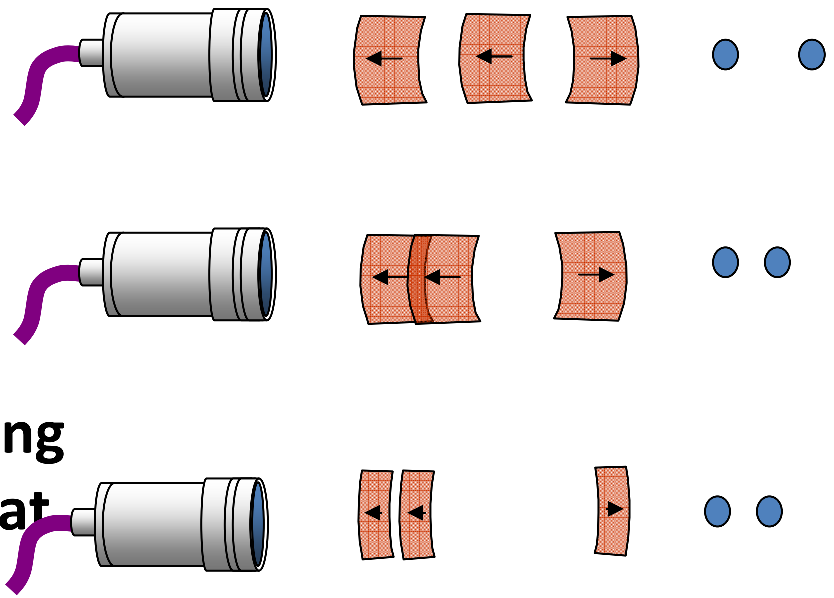


Spatial (in space)

- **axial (along the beam)**
- **lateral (across the beam)**
  - azimuth (in the scan plane)
  - elevation or slice thickness (perpendicular to the scan plane)

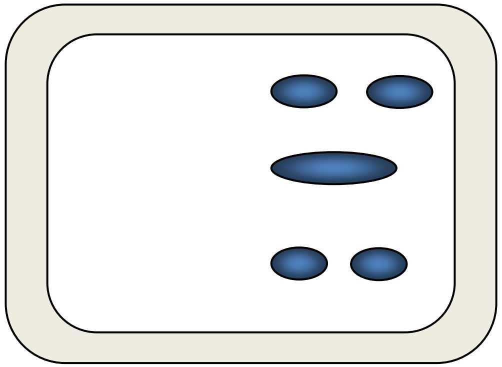
Axial Resolution





- **The minimum reflector spacing along the axis of the ultrasound beam that results in separate, distinguishable echoes on the display.**

    - **Higher is the frequency, shorter is the pulse length, better is the axial resolution**



Axial Resolution

First definition

r_a = number of cycles of the transmitted pulse x $\lambda \approx 3\lambda$

- **Example 3 MHz transducer**

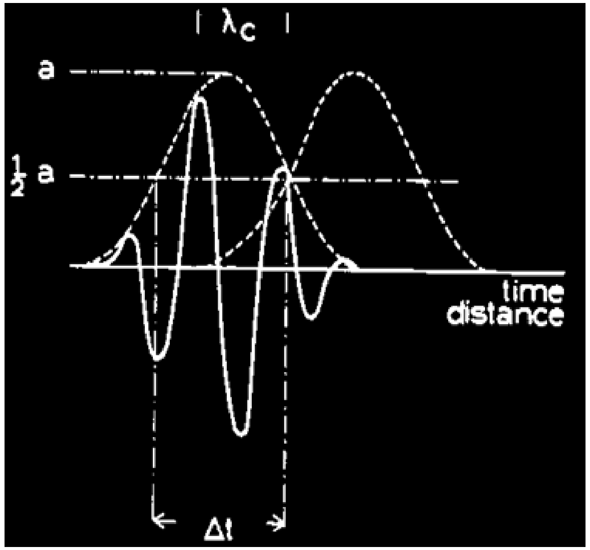
$$\lambda = \frac{c}{f} = \frac{1540m/s}{3{,}000{,}000Hz} = 0.5mm$$

r_a =3 x 0.5 = 1.5 mm

- **Example 10 MHz transducer**

$$\lambda = \frac{c}{f} = \frac{1540m/s}{10{,}000{,}000Hz} = 0.15mm$$

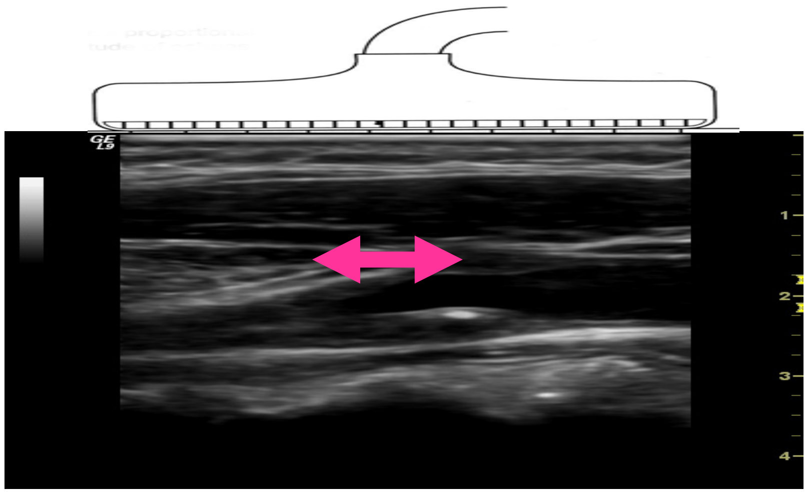
r_a =3 x 0.15 = 0.45 mm

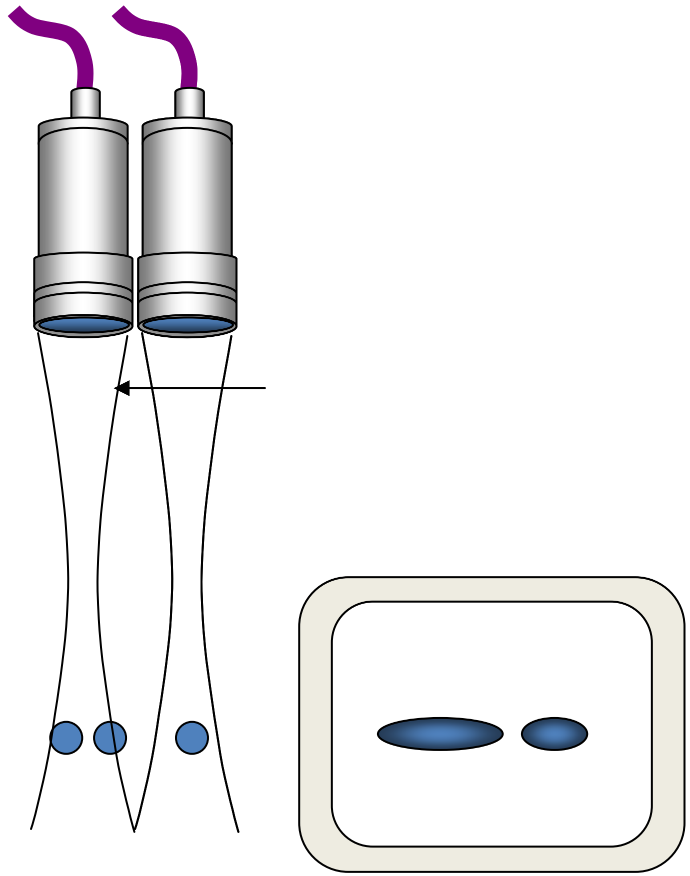


Second definition

Resolution is length at half size

Lateral Resolution

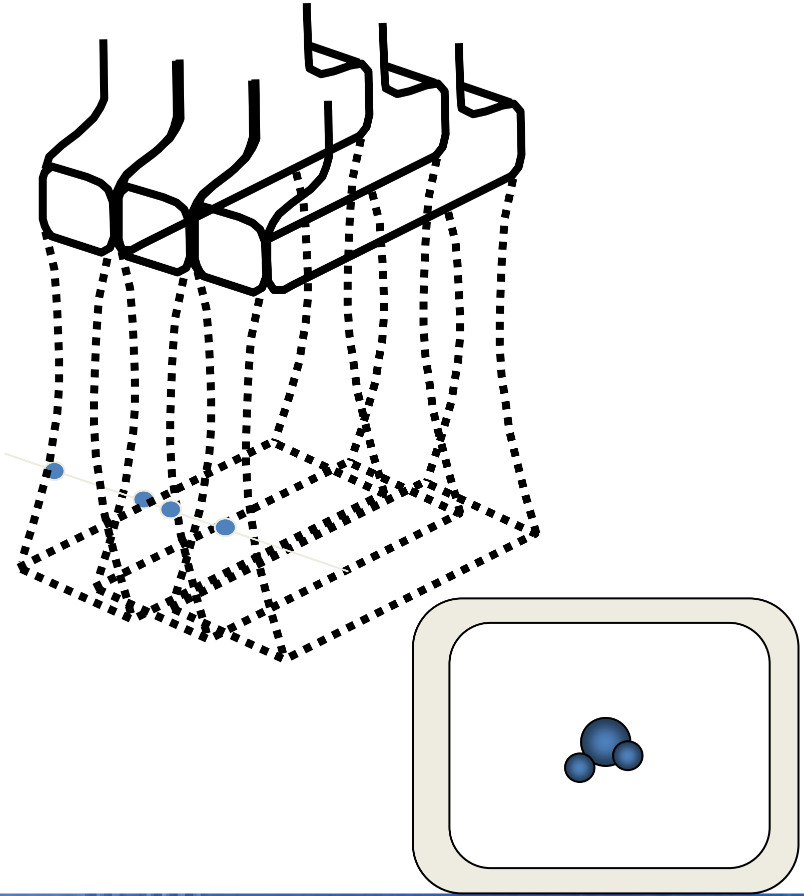




- **The ability to distinguish two closely spaced reflectors that are positioned perpendicular to the axis of the ultrasound beam.**

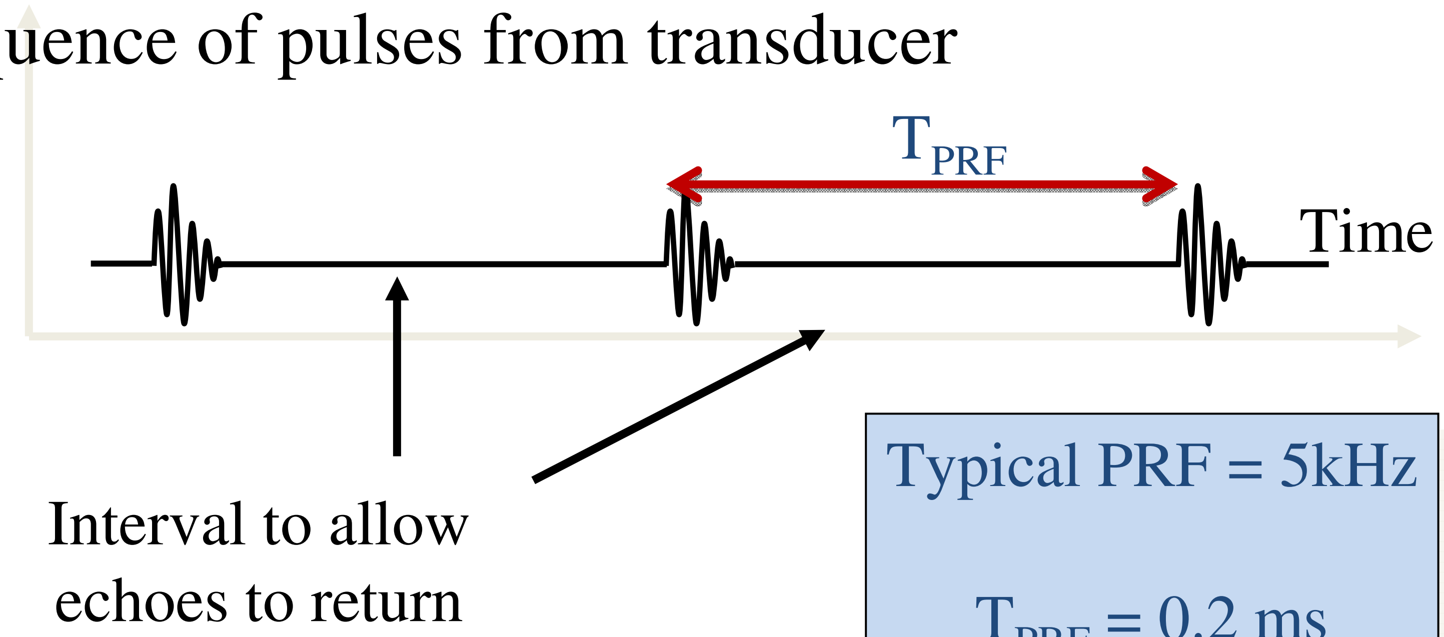
Elevational Resolution (slice thickness)

- **Works in a direction perpendicular to the image plane.**
- **Dictates the thickness of the section of tissue that contributes to echoes visualized on the image.**



Temporal Resolution

Sequence of pulses from transducer



Typical PRF = 5kHz

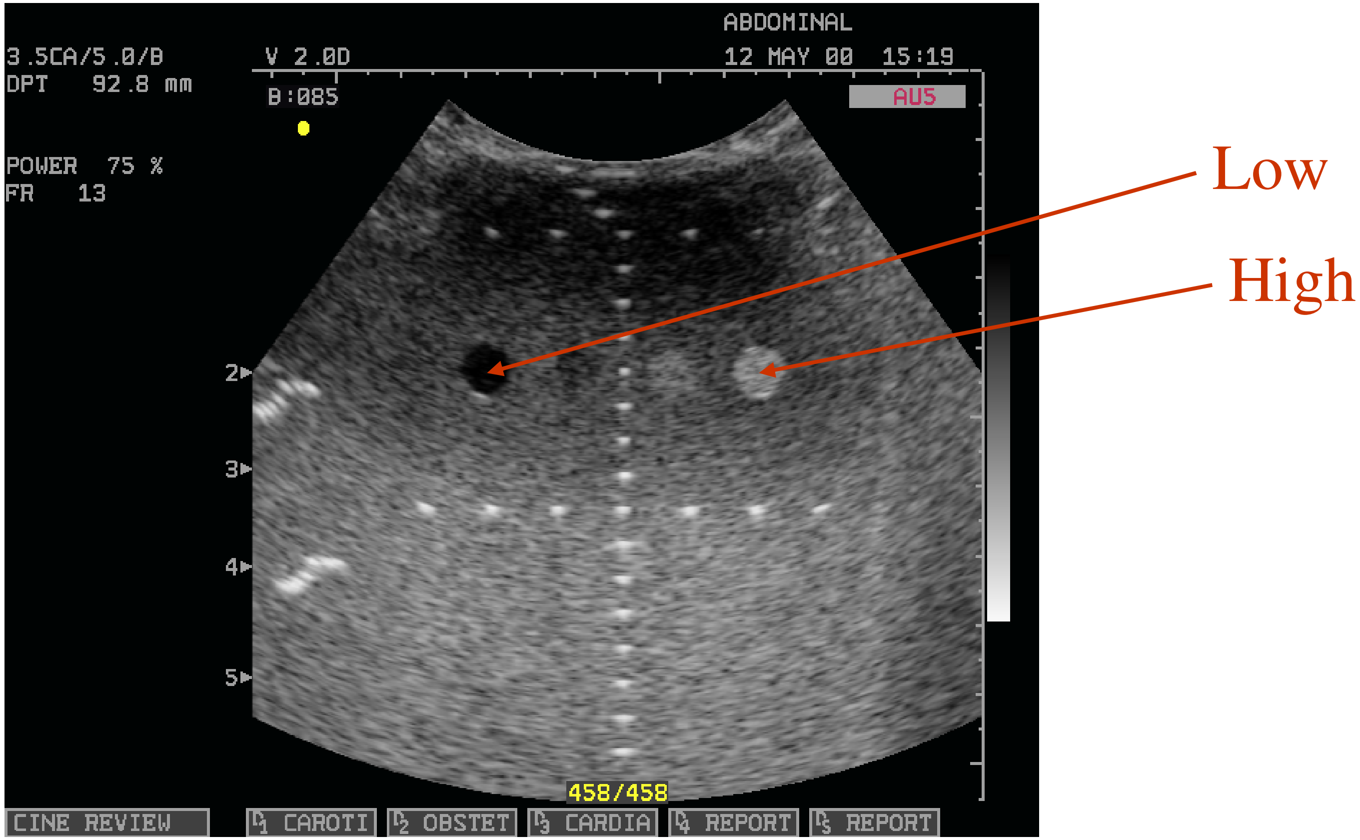
T_{PRF} = 0.2 ms

T_{PRF} is usually set so that there is sufficient time for the most distant echo to return to the transducer before the next pulse is launched

T_{PRF} can be chosen as the delay of five times the maximum observed distance

Contrast Resolution

The ability to display regions of differing echo size



Attenuation

The energy of the ultrasound beam is reduced with distance

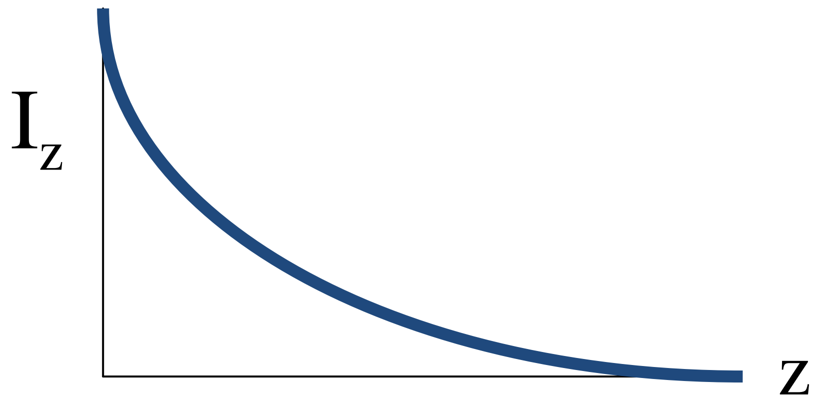
Energy is lost from the beam by:

Scattering (reflection out of beam confines, refraction, divergence)

Absorption (conversion into heat)

The intensity, I_z, of an ultrasound beam is related to distance from the source, z, thus:

$$I_z = I_0 e^{-\alpha z}$$



Where I_0 is the intensity at z = 0, the transducer face.

Attenuation Coefficient

Attenuation is approximately exponential,

the slope of the logarithmic graph is constant.

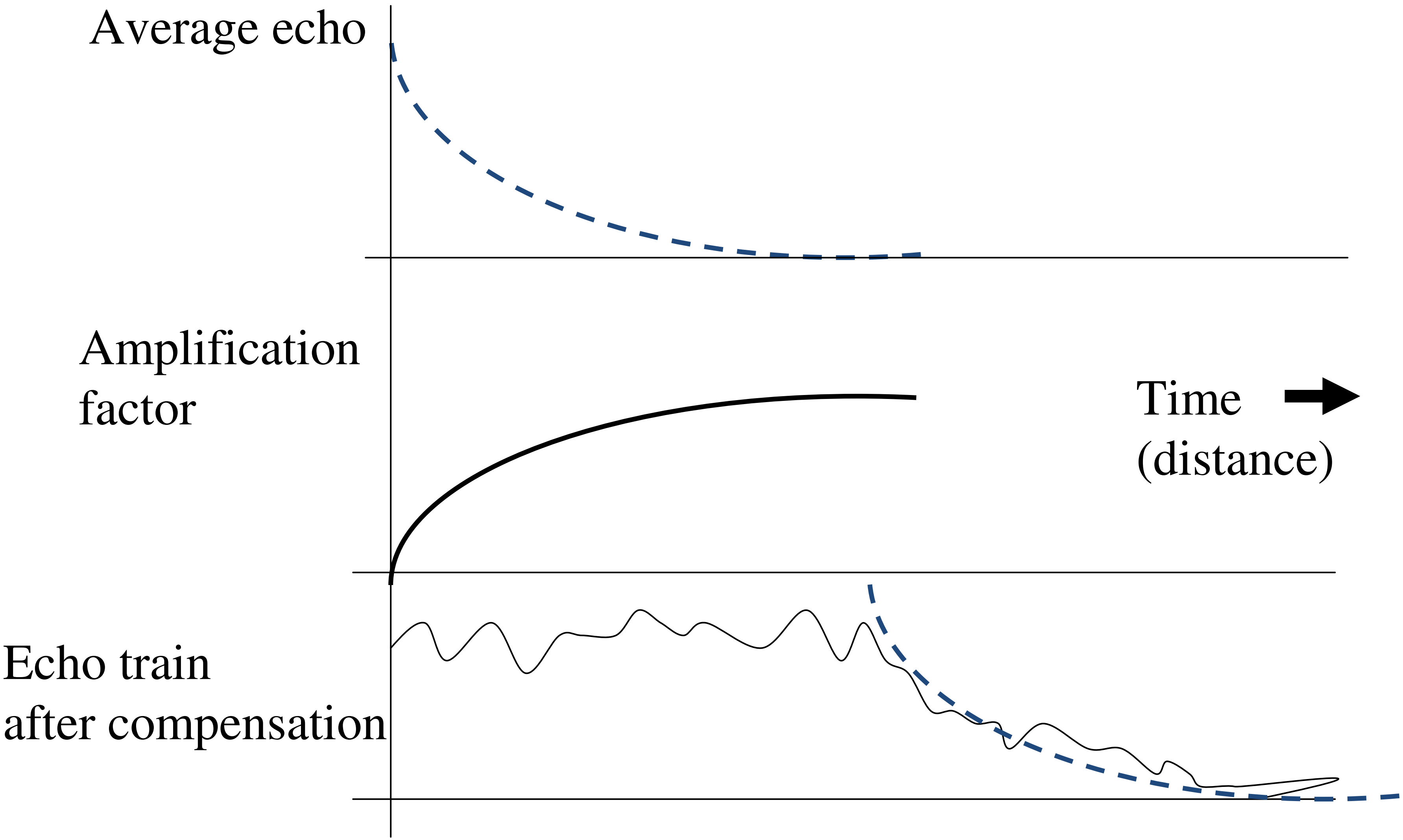
Attenuation coefficient is quoted in dB/cm

In addition, for soft tissue,

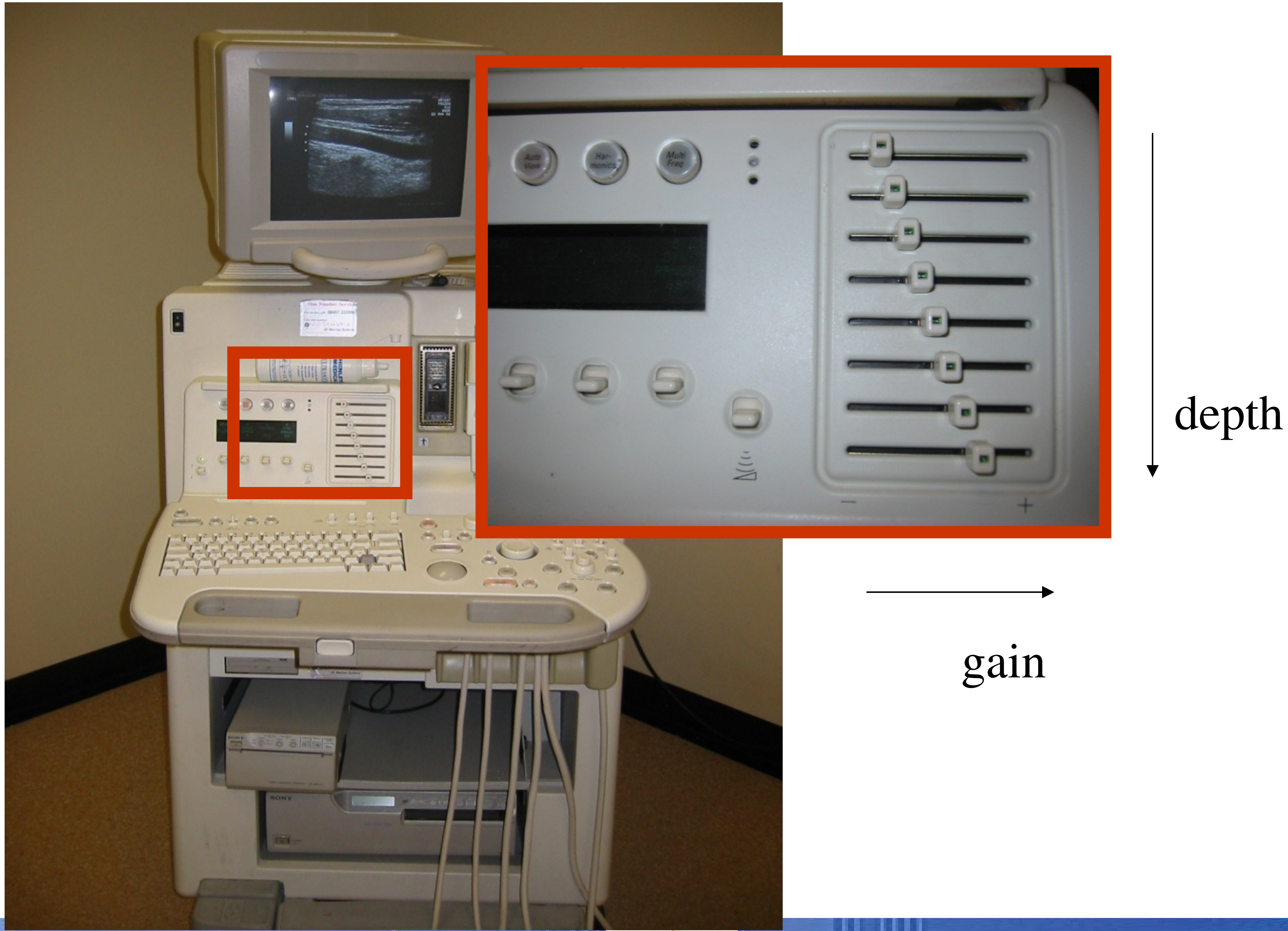
attenuation is proportional to frequency.

The attenuation coefficient for soft tissue is 0.5 - 0.7 dB/cm/MHz

Attenuation – compensation: TGC



TGC: Time Gain Compensation



Scanner settings

- Fixed settings : MI, TCG, gain
- Adjustement: focus, sector size

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References

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