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Lecture notes:

# Ultrasound diagnostic methods

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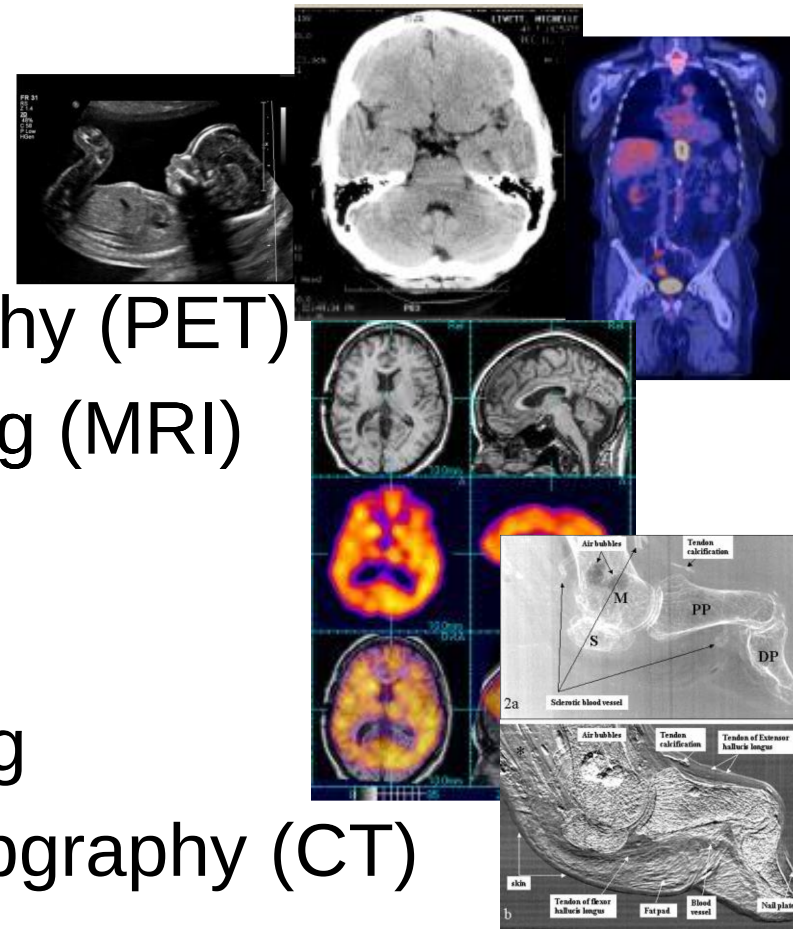
# Medical imaging

- **Diagnostic testing** - produces images of organs and tissues within the body for use in diagnosis and treatment.




- **Ultrasound**
- Positron Emission Tomography (PET)
- Magnetic Resonance Imaging (MRI)
- SPECT
- Fluoroscopy
- Diffraction Enhanced Imaging
- X-rays and Computed Tomopgraphy (CT)

# Outline

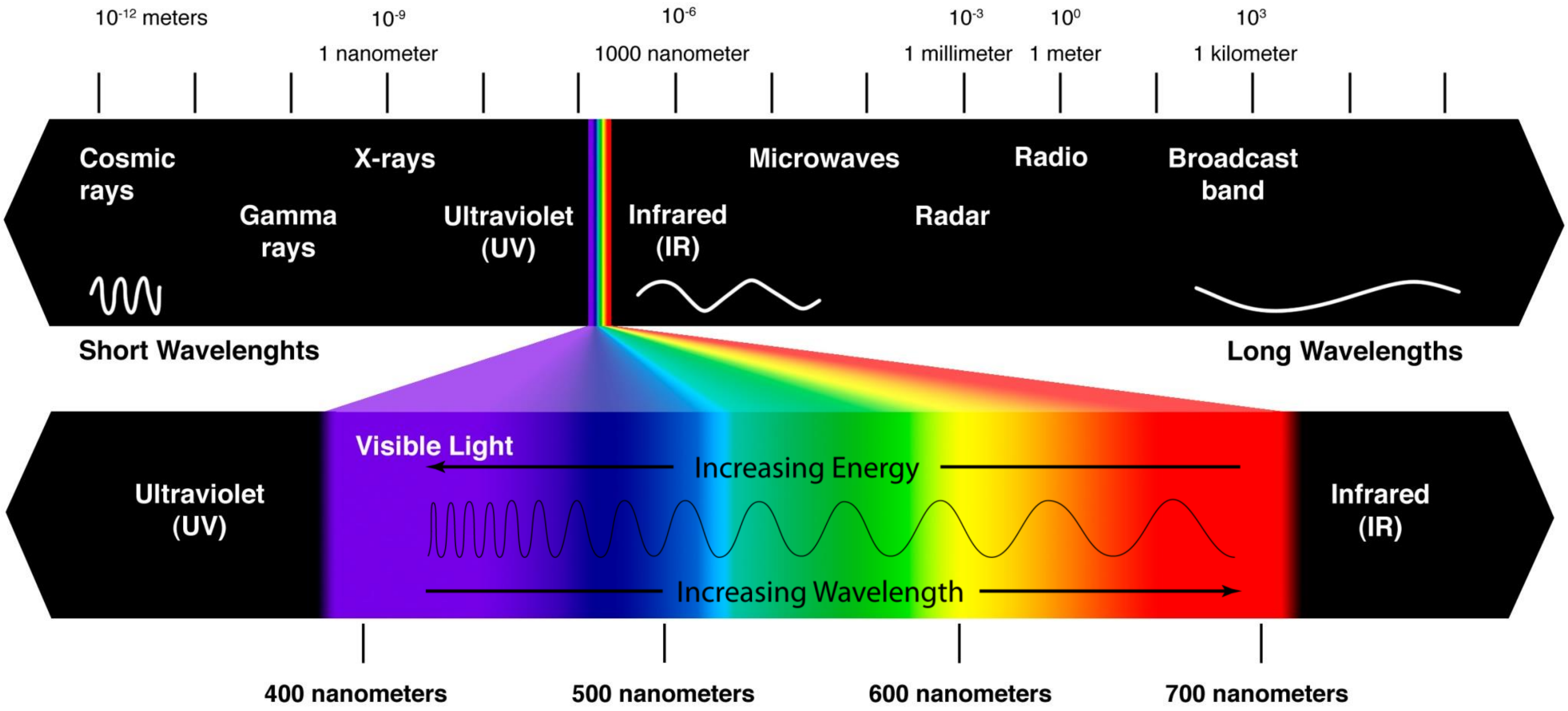
- Fundamentals of sound propagation
- Interactions of ultrasound with matter
- Generation of ultrasound
- Effects of ultrasound
- Ultrasound imaging modes A, B, M, Doppler, Color Doppler
- Quantification in ultrasound
- Ultrasound safety and risks

# Physical characteristics of ultrasound


**Sound** - a disturbance in pressure that propagates through a compressible medium.

Mechanical wave motion in a solid or fluid medium that propagates via the action of elastic stresses that involves local compression and expansion of the medium.

# The electromagnetic spectrum



# Acoustic waves

**Pressure waves that propagate through matter via compression and expansion of the material**

– Generated by compressing and releasing a small volume of tissue

- **Longitudinal wave**

– Particles in the medium move back and force in the same direction that the wave is traveling

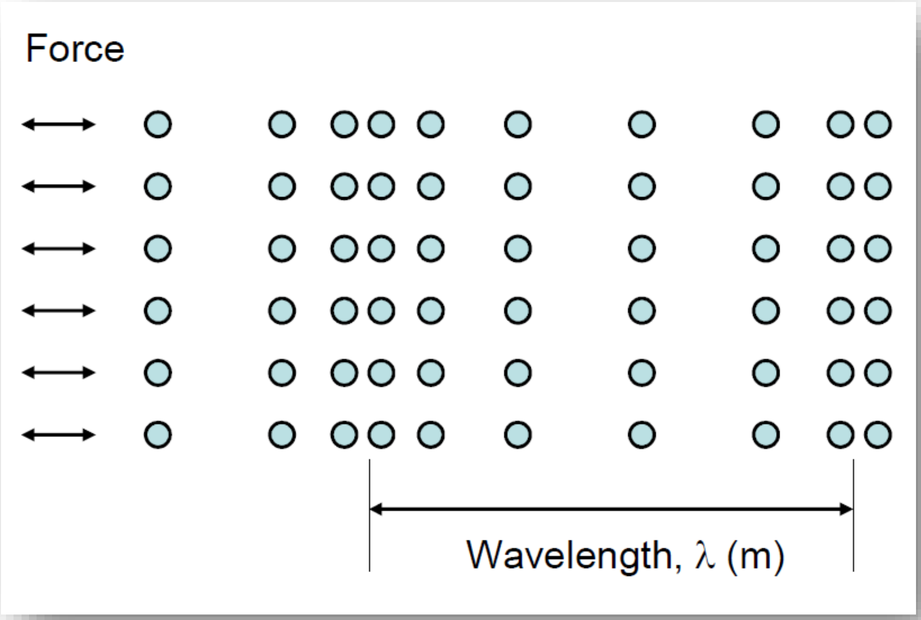
- **Shear Wave**

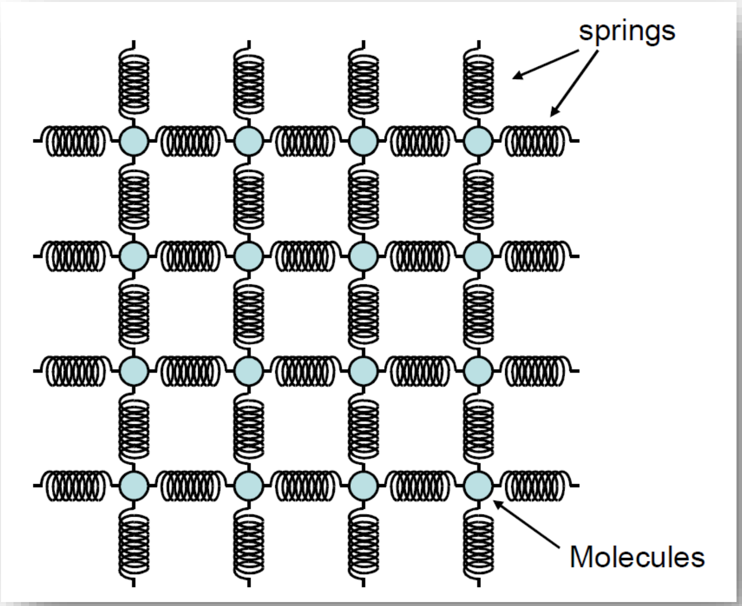
– Particles move at right angles to the direction of the wave

– Not used for medical ultrasound imaging

# Longitudinal acoustic propagation

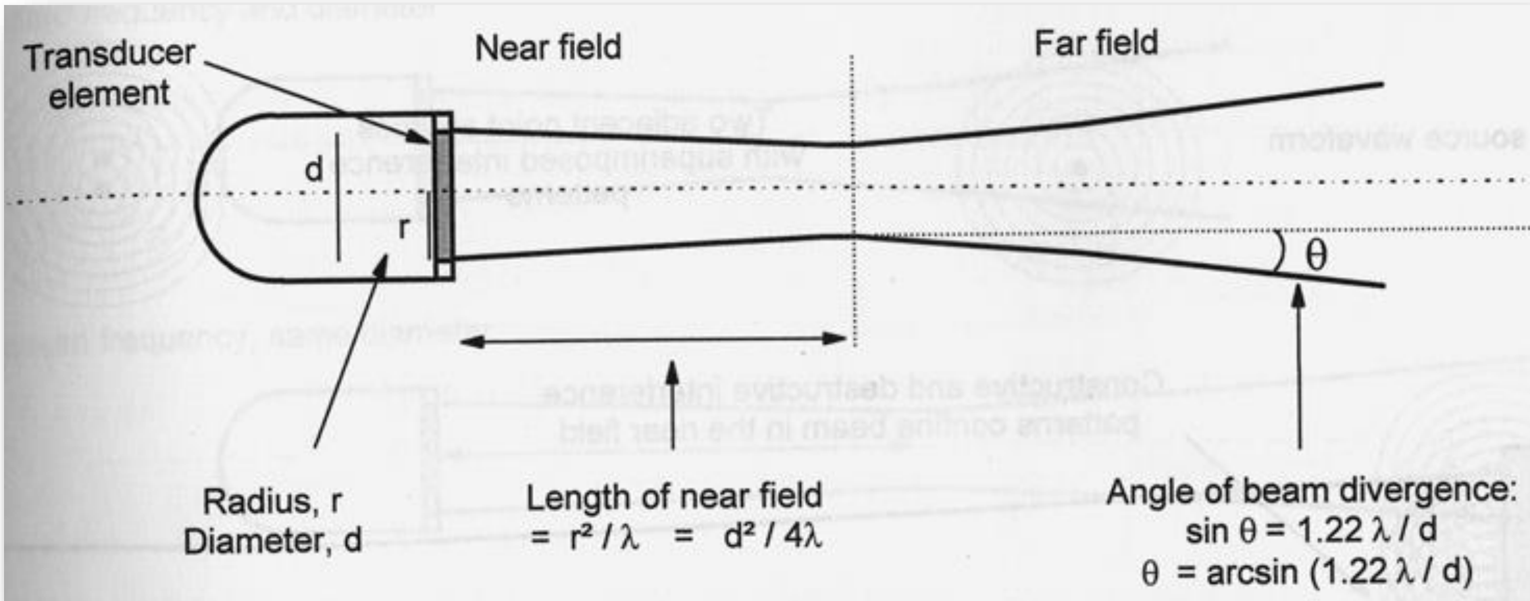
The wave propagates as a longitudinal wavefront from the transducer into the propagation medium.




- Consider only 2-D lattice
- The driving force is back and fourth - particles oscillates at the same way

# Longitudinal acoustic propagation




- **The near field** distance will increase as the frequency increases or the diameter of the transducer increases.

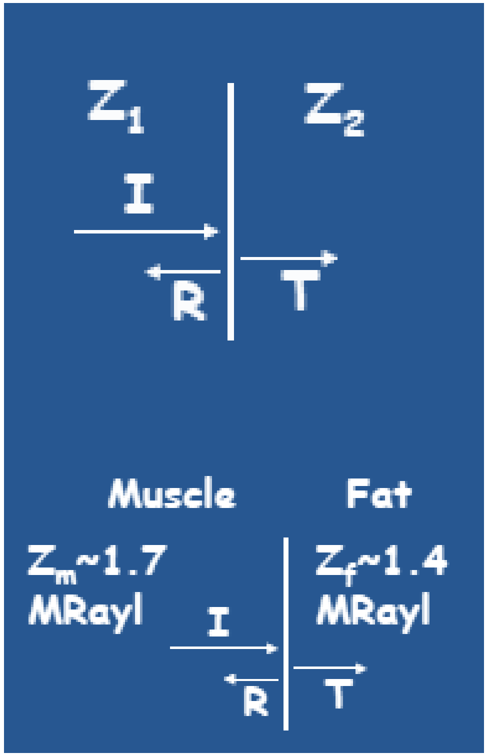
- **The far field** is characterized by a diverging, conical shaped ultrasound beam of diminishing energy.

# Reflection at interfaces

- Reflection is the return of the incident ultrasound, which echoes directly back to the transducer if the angle of incidence is perpendicular of the tissue it hits.

Reflection (normal incidence):

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




Transmission:
Intensity of the ultrasound beam transmitted across the interface

$$T = \frac{2Z_2}{Z_2 + Z_1}$$

# Acoustic Impedance

– describes how much resistance an ultrasound beam encounters as it passes through a tissue
– defines the amplitude of the reflected waves at interface

$$Z = \rho \cdot c$$

ρ - density
c – propagation velocity

Acoustic Impedance of Soft Tissues

| Tissue | Impedance (rayls) |
|---|---|
| Air | $0.0004 \times 10^6$ |
| Fat | $1.3400 \times 10^6$ |
| Water | $1.4800 \times 10^6$ |
| Liver | $1.6500 \times 10^6$ |
| Blood | $1.6500 \times 10^6$ |
| Kidney | $1.6300 \times 10^6$ |
| Muscle | $1.7100 \times 10^6$ |
| Skull Bone | $7.8000 \times 10^6$ |

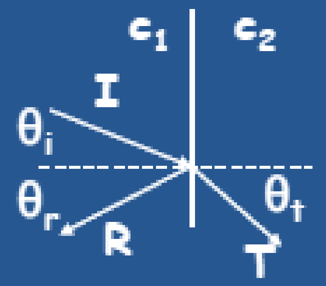
| Material | Impedance (M rayls) |
|---|---|
| PZT Composite | 10 |
| PZT Ceramics | 30 |
| Matching Layer | 7 |
| Soft Tissues | 1.7 |

# Refraction: Snell's Law

- Refraction occurs when the sound waves meet a tissue boundary other than 90 degrees, which is governed by Snell's law.

$$\frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{c_1}{c_2}$$

$$\theta_i = \theta_r$$



# Attenuation of ultrasound

Energy loss through interactions between ultrasound waves and soft tissues which occurs due to absorption and scattering events.

Absorption – *Power deposited in tissue (Heat)*
Scattering –*Ultrasound radiated away from transducer*

- The acoustic impedance of the tissue effects reflection of the sound wave.
- Attenuation leads to a decrease in amplitude of the ultrasound signal and is frequency dependent

# Consequences of frequency dependent attenuation for imaging:

– Penetration of ultrasound is limited by frequency
– Frequency of ultrasound decreases with increasing depth of imaging

- Imaging artifacts – Artificial bright & dark regions
- Image acquisition – Weak scatterers deep objects unable to detect
- Prevents quantization – Echoes via different paths not comparable

# Resolution in Ultrasound Imaging

- **Axial**

– Resolution in propagation direction

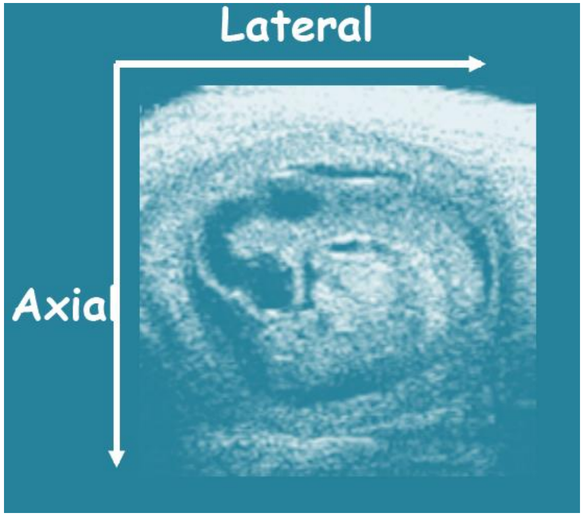
– Determined by length of pulse propagating in tissue

- **Lateral**

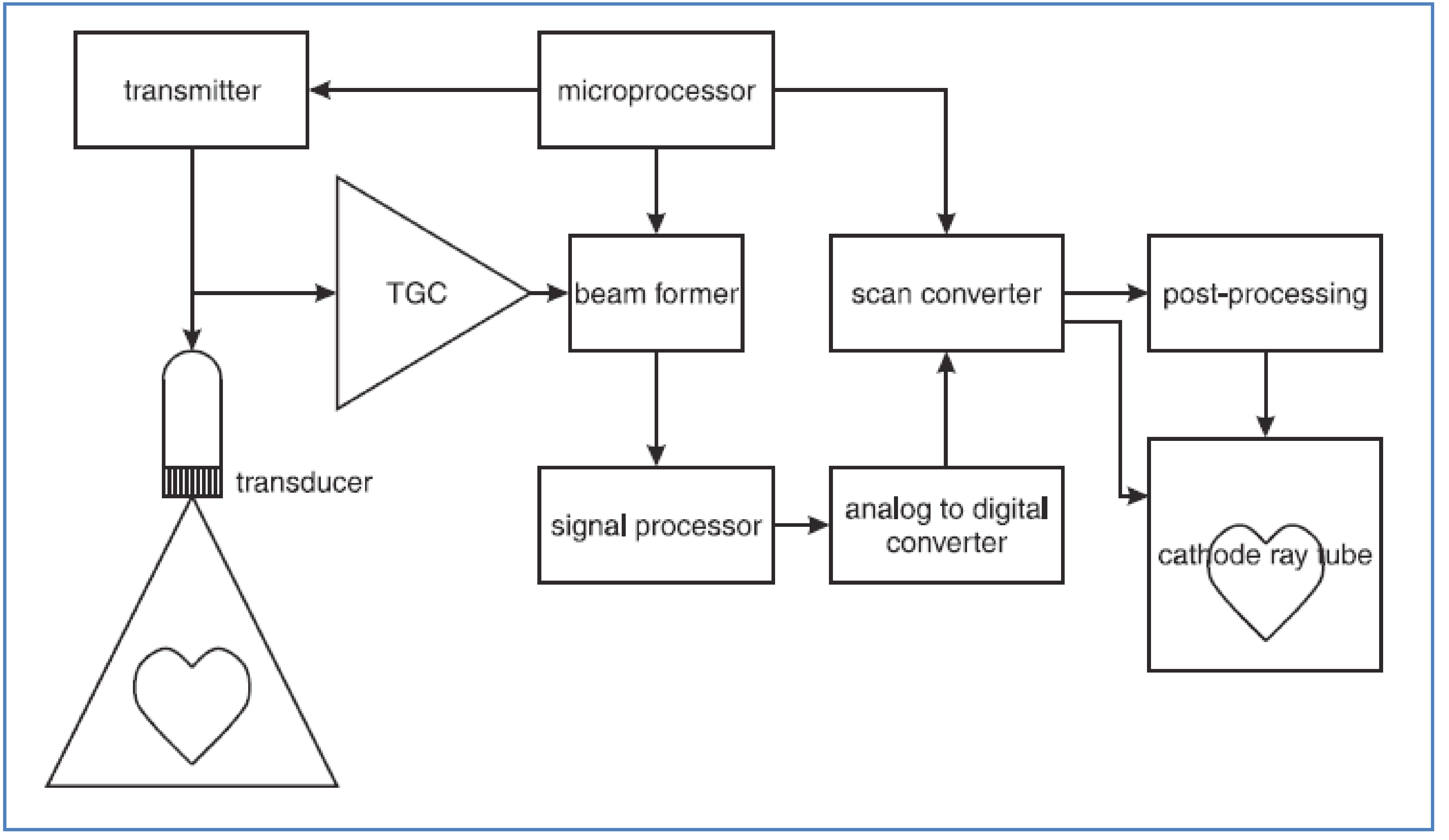
– Resolution orthogonal to propagation direction

– Determined by focusing properties of transducer

**Compromise between resolution and penetration !**

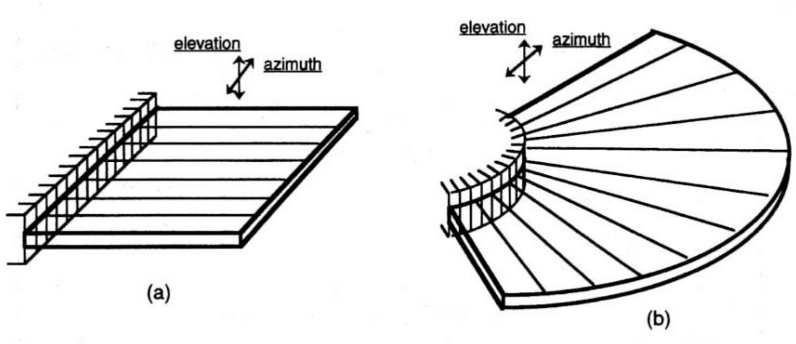



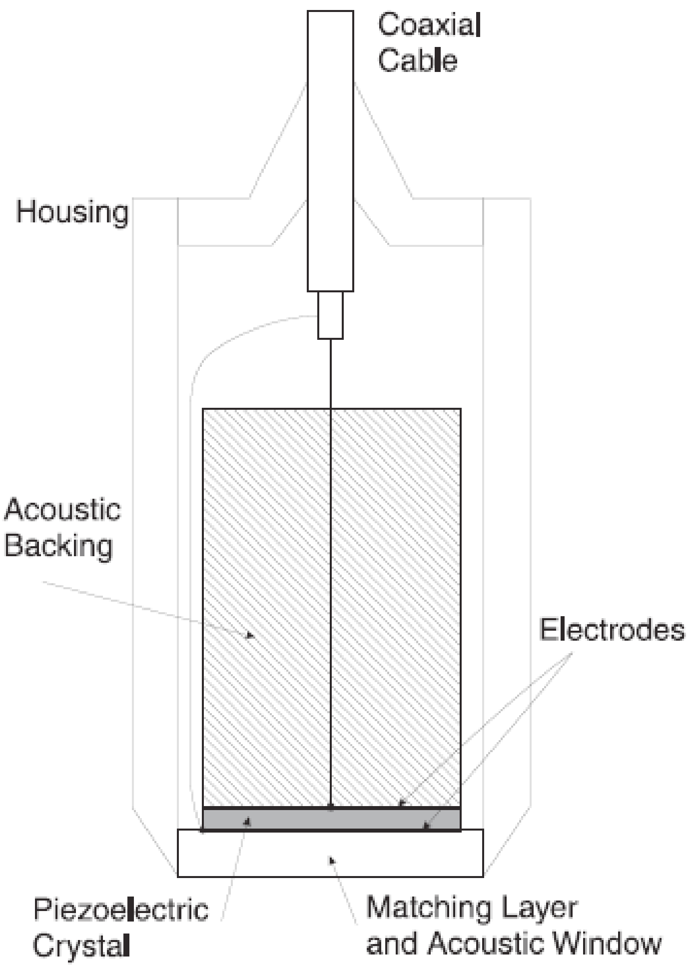
# Scheme of the ultrasonic system



# Function of transducer

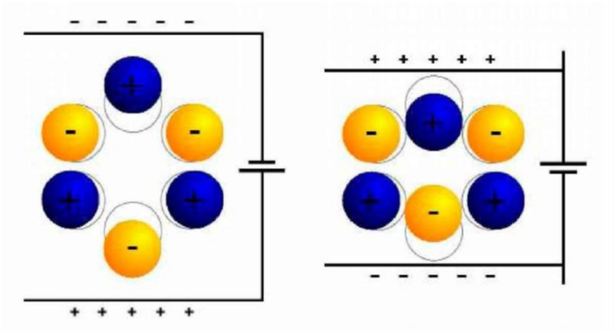
- Transmission mode: converts an oscillating voltage into mechanical vibrations
- Receiving mode: converts backscattered pressure waves into electrical signals



# Piezoelectric Material

- Converts electrical voltage to mechanical vibration
- The thickness of the crystal varies with the applied voltage
- When an AC voltage is applied across the crystal, the thickness oscillates at the same frequency of the voltage



**Piezoelectric Materials:**

- Crystalline (quartz)

- Ceramic (PZT, lead zirconium titanate)

- Polymers (PVDF)

# Effects of Ultrasound

**Energy transfer**

- Energy of the sound waves increases with the square of the frequency, $W.cm^{-2}$
- Thickening and thinning of medium leads to rapid pressure variations up to $10^5$ g overload.
- Absorption of ultrasound in liquids and solids is less in comparison with the absorption in gases.

## Intensity scale

**Up to 1.5 W / cm $^2$** has bio-positive effects on tissues and therefore USG has medical importance:

- increasing the flow of blood at the injection site
- thereby accelerating healing,
- reducing pain by reducing swelling and edema
- accelerating diffusion in tissues.

## Intensity scale

**Up to 3 W / cm²** the effects of the increase in cytoplasmic vacuoles appear and fat droplets as well.

These changes are still reversible.

**Intensity greater than 3 W / cm²** result in irreversible changes consisting - destruction of the cell nucleus

- protein denaturation by heat
- chemical effects - the formation of free radicals
- all effect lead to tissue necrosis

# Biological Effects of Ultrasound

**Interaction of the object with ultrasound**

- Passive interaction – intensity scale up to 0,1 W / cm $^2$
- Active interaction – intensity scale over 0,1 W / cm $^2$

- Thermal phenomena
- Cavity phenomena
- Mechanical phenomena

# Thermal phenomena

Heat generation in ultrasonic field is a typical manifestation of thermal phenomena that occurs as a result of conversion of acoustic energy during a wave absorption by the biological objects.

**Heat is generated in biological environments by:**

1. internal friction
2. relaxation processes

# 1. internal friction

Critical thermal levels

- Over 39,5 °C the embryonic tissues can be damaged
- Over 41 °C tissue of adult human can be damaged

- The amount of the energy/heat conversion

**2αI** α - absorption coefficient of the surrounding tissue

I – intensity of the ultrasound wave

$$T = \frac{2 \propto I t}{c_m} + T_0$$

$T_0$ – beginning temperature
T – final increased temperature
I - intensity of ultrasound
t – time
$c_m$ – thermal capacity of the object

## 2. relaxation processes

- Occurs between the body and the surrounding environment  the exchanges of heat by conduction, convection or radiation.
- If we consider a point source of heat at $T_0$, then the portion of the heat uniformly lead away according the thermal conductivity K in all directions
- After some time balance between the body temperature and ultrasound  heat dissipation is created

# Cavity phenomena

- Formation of vacuum tubes (bubbles).
- Gases absorb ultrasonic energy more than the fluid, formed tubes and bubbles absorb considerable heat, which leads to expansion and breaking of the cavities.
- **Rezonance cavity** – bubbles oscillate with the frequency given by the frequency of the ultrasonic wave.
- **Collapse cavity** – bubbles periodically increase the volume and after the critical value they widely collapse.

# Mechanical phenomena

**Mechanical effects of viscous and radiation forces**

- Associated with changes of pressure, tension, stress, expansion, compression and changes of speed and acceleration of particles
- Damage of cell membranes or translation/rotation movement of particles
- in the vicinity of the acoustic interface the micro convection can be created (influence the biological pathways)

# Ultrasound safety and risks

- If the live object is located in the ultrasonic field then it leads to their interaction
- Effects of ultrasound on humans and other organisms are not yet sufficiently explored.
- Although ultrasound is considered safe, its effects on living organisms may present some potential risks.
- Guidelines for safe ultrasound scanning

A fundamental approach to the safe use of diagnostic ultrasound is to use the lowest output power and the shortest scan time consistent with acquiring the required diagnostic information.

**ALARA principle**
**As Low As Reasonable Achievable**

**Used intensity or test duration should not exceed what is strictly necessary for obtaining the required diagnostic information !!!**

# Thermal Index (TI) Mechanical Index (MI)

were introduced to provide the operator with an indication of the potential for ultrasound induced bio-effects.

- TI provides an onscreen indication of the relative potential for a tissue temperature rise.

  **TIS** – Soft Tissue Thermal Index
  **TIC** – Cranial Bone Thermal Index
  **TIB** – Bone Thermal Index

- MI provides an onscreen indication of the relative potential for ultrasound to induce an adverse bio effect by a non thermal mechanism such as cavitation.

# Ultrasound Imaging Modes

- Ultrasound medical imaging is a non-invasive method that is used to detect and identify diseases, health problems and complications.
- Mainly used measurement methods based on ultrasound echoes from different interfaces of dense environment, ie the interface of two media with different acoustic impedance.
- Diagnostic Ultrasound normally produce waves with a frequency of 1-20 MHz Examination of all organs except the air body cavities

Examination of bone - densitometry

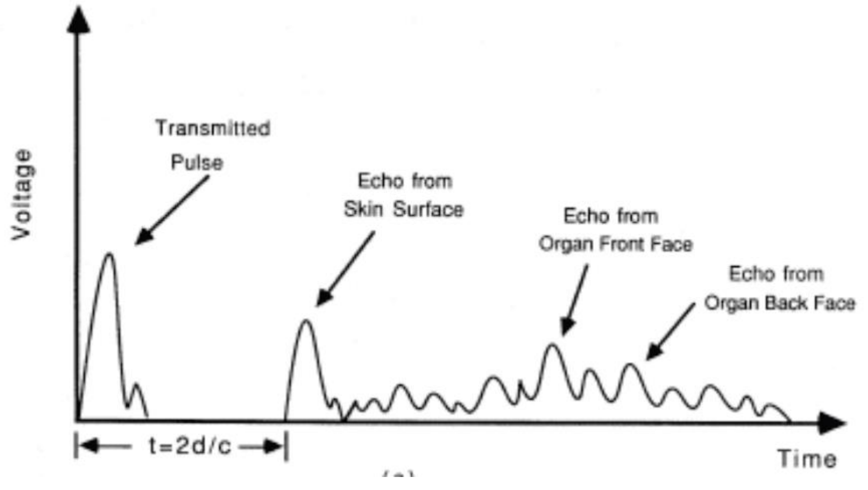
## A-mode - Dynamic display

- Oldest, simplest type
- It measures the reflectivity at different depth below the transducer position

**Applications:**

ophthalmology (eye length, tumors), myocardium infarction

- Frequencies: 2-5 MHz for abdominal, cardiac, brain (lower for brain); 5-20 MHz for ophthalmology, pediatrics, peripheral blood vessels



# M-Mode

Applications: localization of brain midline, liver cirrhosis, heart function

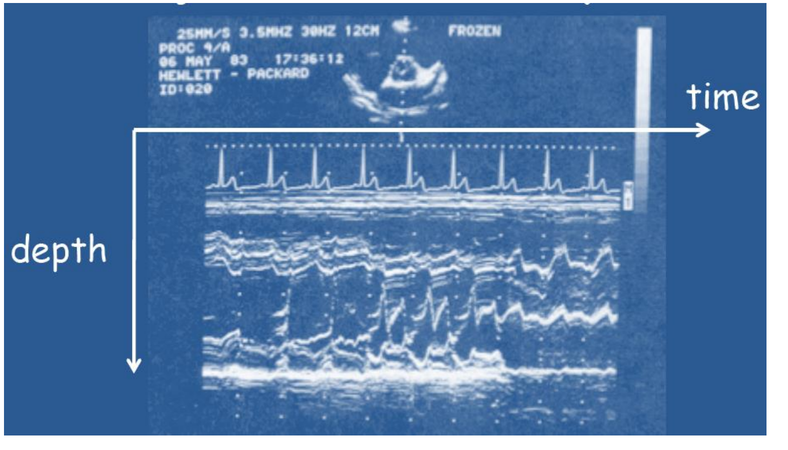
Display the A-mode signal corresponding to repeated input pulses in separate column of a 2D image, for a fixed transducer position

– Motion of an object point along the transducer axis (z) is revealed by a bright trace moving up and down across the image

– Used to image motion of

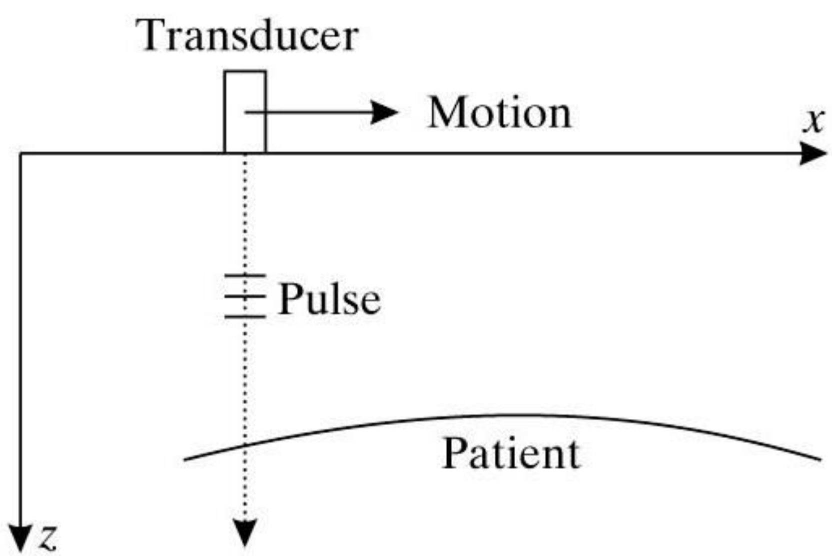
the heart valves,

in conjunction with the ECG



# B-Mode Display

- Move the transducer in x-direction while its beam is aimed down the z-axis, firing a new pulse after each movement
- Received signal in each x is displayed in a column
- Unlike M-mode, different columns corresponding to different lateral position (x)



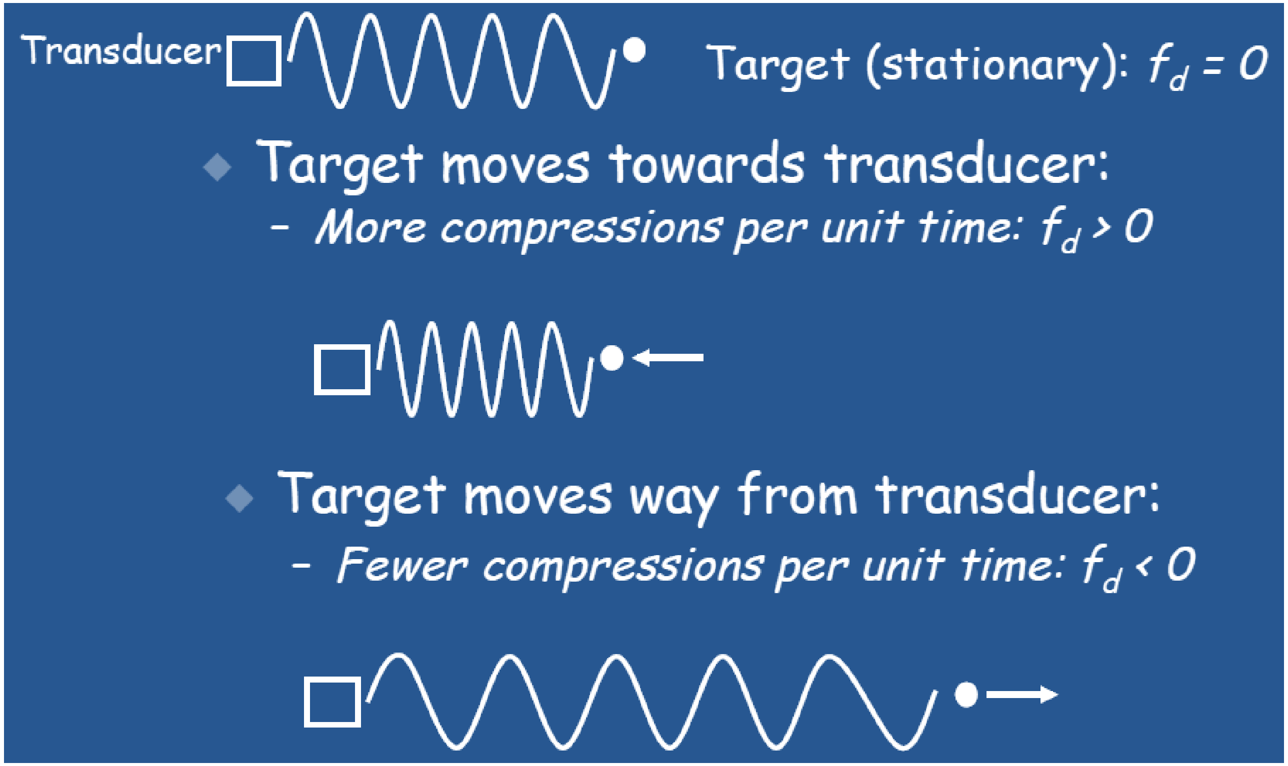

## Application of B-Mode

- Can be used to study both stationary and moving structures
- High frame rate is needed to study motion
- Directly obtain reflectivity distribution of a slice

– No tomographic measurement and reconstruction is necessary!

# Doppler Ultrasound: Basic Concepts

- Ultrasound wave reflected from moving targets
- Frequency shift in received ultrasound wave compared to transmitted wave: **Doppler Shift Frequency, $f_d$**



# Doppler Imaging

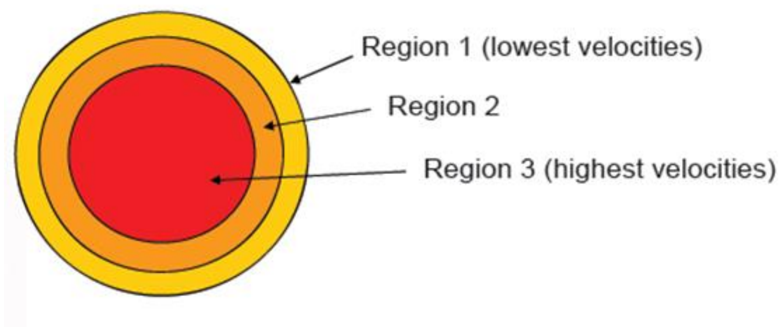
The Doppler effect can be used to detect tissue or organ movement, or blood flow in blood vessels

**Two system configuration**

– Continuous-wave (CW)

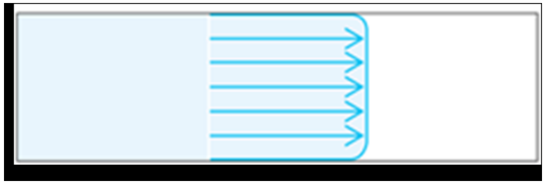
– Pulsed-wave (PW)

Doppler Effect in vessel lumen



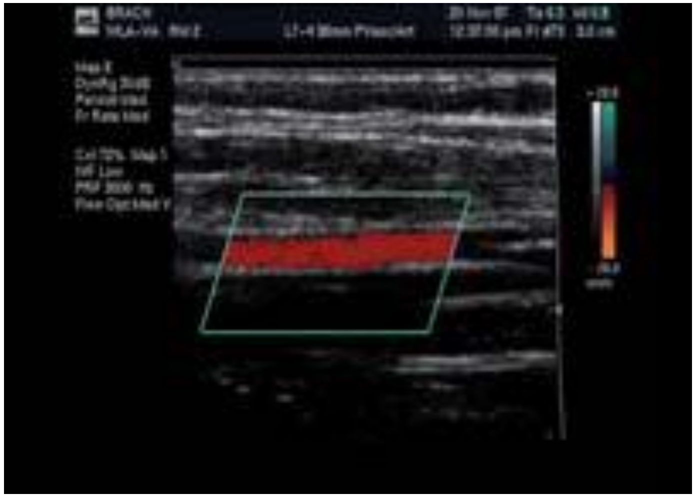

Domination by low velocity

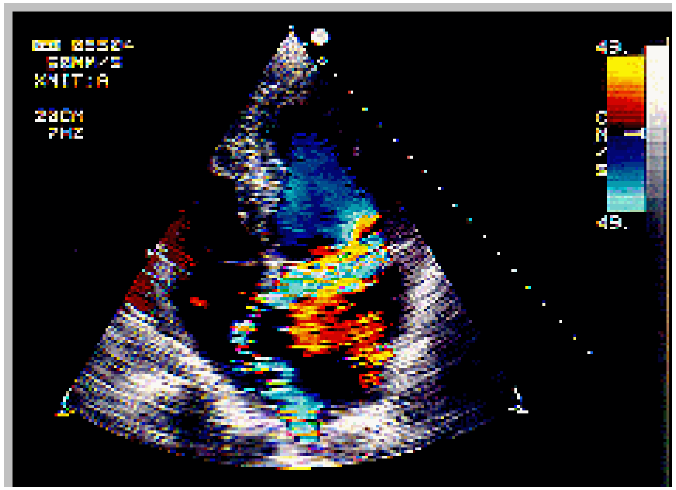
Domination by high velocity



# Color Doppler

- Provides an estimate of the mean velocity of flow within a vessel by color coding the information and displaying it superimposed on the gray-scale image.
- The flow direction is arbitrarily assigned the color red or blue, indicating flow toward or away from the transducer, respectively.
- Provides a global depiction of blood flow in a region.





# Clinical Applications

- Ultrasound is considered safe
- Instrument is less expensive and imaging is fast

  - Obstetrics and gynecology
  - Musculoskeletal structure
  - Cardiac diseases
  - Denzitometry
  - Contrast agents

# Clinical Applications

- ❖ Imaging of the vascular capillaries in the organs (capillary volume) and quantification via contrast agent through the vascular system in real time (capillary flow).
- ❖ The use of microbubbles, consisting of a container closed in it / adsorbed gas.