Advanced biomedical signal and image processing

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Advanced biomedical signal and image processing

Ultrasound Imaging

Contents

▪ Introduction

Ultrasound imaging (sonography) or ultrasound scanning is a medical imaging technique that uses

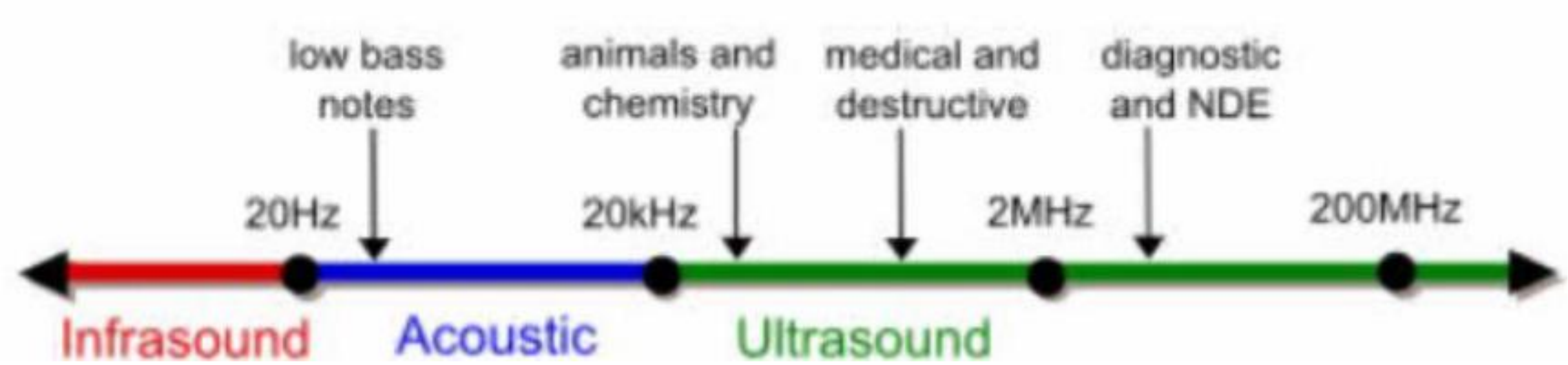
- high frequency sound waves and their echoes.
- The technique is similar to the echolocation used by bats, whales and dolphins, as well as SONAR used by submarines.
- non-invasive medical imaging technique
- uses high-frequency sound waves to produce images.
- three types of Ultrasound:
  - 2D Ultrasound
  - 3D Ultrasound
  - 4D Ultrasound.
- Limitations
  - affected by factors like obesity or the presence of gas in the intestines
  - Limited Infiltration

- **Sonography concept**
  - **Sound wave propagation and reflection**
    - **Speed of sound**
    - ***Time-of-flight principle:***
    - **Reflection and Impedance**
    - **Total Time Calculation**
  - **Image resolution and depth**
    - **Axial resolution**
    - **Lateral resolution**
    - **Beamforming**

▪ Sonography concept

The pulse of sound that is used should be short, and high frequencies are usually used, as they travel further without being absorbed.

- Sounds with a frequency above 20 kiloHertz (20 kHz) are called ultrasonic (beyond the range of human hearing).



- The sounds used for sonar are well into the ultrasonic range, with frequencies of 1 - 20 megaHertz (MHz).

- **Sonography concept**

- mathematical concepts behind ultrasound imaging are critical
  - understanding how sound waves interact with tissues
  - how signals are processed to create images
  - how advanced techniques like Doppler ultrasound and harmonic imaging function
- practical application of ultrasound in medical diagnostics.

- **Sonography concept**

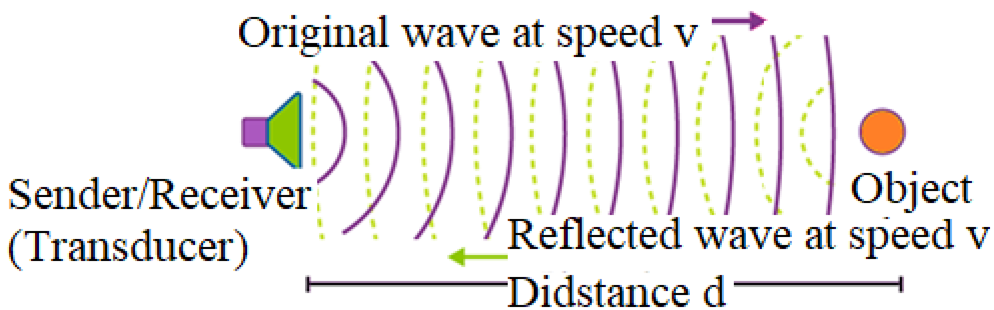
Sound waves are longitudinal waves.

- The speed of sound itself varies from one material to another.
- Typical speeds are approximately 330 m/s in air, 1500 m/s in water (body tissue) and 5000 m/s in a metal.
- $$\lambda=\frac{v}{f}=\frac{1500\ m\,s^{-1}}{2.0\,x\,10^{6}m}=7.5\,x\,10^{-4}\,mm\approx 1\,mm$$
- This means that 2.0 MHz ultrasound waves will be able to distinguish detailed features whose dimensions are of the order of 1 mm.

▪ Sonography concept

SOUND WAVE PROPAGATION AND REFLECTION

- **Speed of sound**
  - in human tissue is approximately 1540 m/s. This speed can vary depending on the type of tissue and its density
- **Time-of-flight principle**
  - The time it takes for an ultrasound pulse to travel to a tissue and back is used to calculate the distance to the tissue.



  - t time it takes for the echo to return.

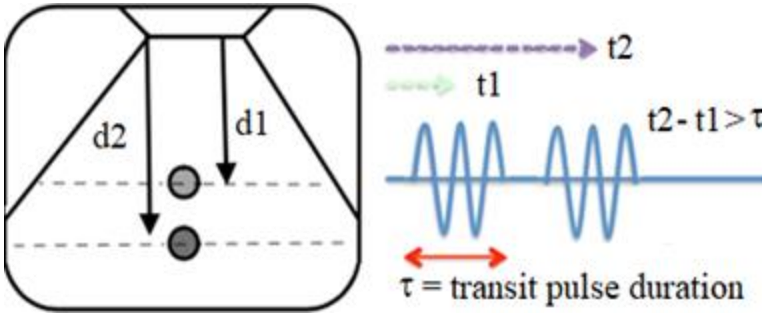
- **Sonography concept**

SOUND WAVE PROPAGATION AND REFLECTION

- **IMAGE RESOLUTION AND DEPTH**

- **AXIAL RESOLUTION**

- the ability to distinguish between two points along the axis of the ultrasound beam. depends on the pulse duration and the frequency of the transducer



- Higher frequencies provide better axial resolution but have less penetration depth

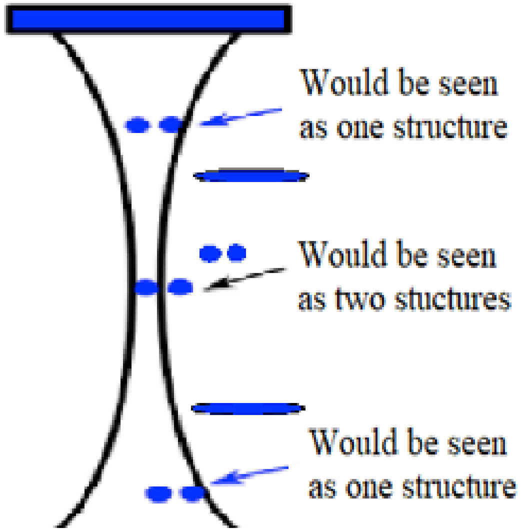
▪ Sonography concept

SOUND WAVE PROPAGATION AND REFLECTION

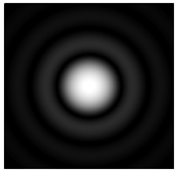
- **IMAGE RESOLUTION AND DEPTH**
  - **LATERAL RESOLUTION**

The ability to distinguish between two points perpendicular to the axis of the ultrasound beam.

Depends on the ultrasound beam and the focusing of the beam.

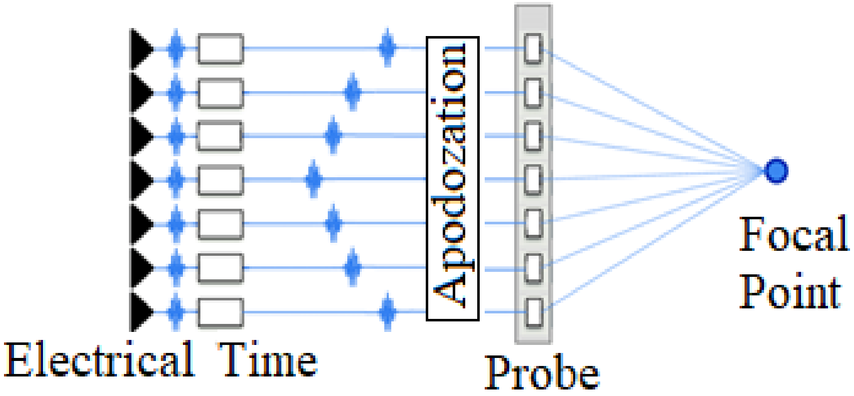


- **Sonography concept**



SOUND WAVE PROPAGATION AND REFLECTION

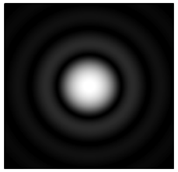
- **IMAGE RESOLUTION AND DEPTH**
  - **BEAMFORMING**



This technique is used to direct and focus the ultrasound beam.

It involves adjusting the timing of the signals received from different elements of the transducer array to construct a focused image

- ## Sonography concept

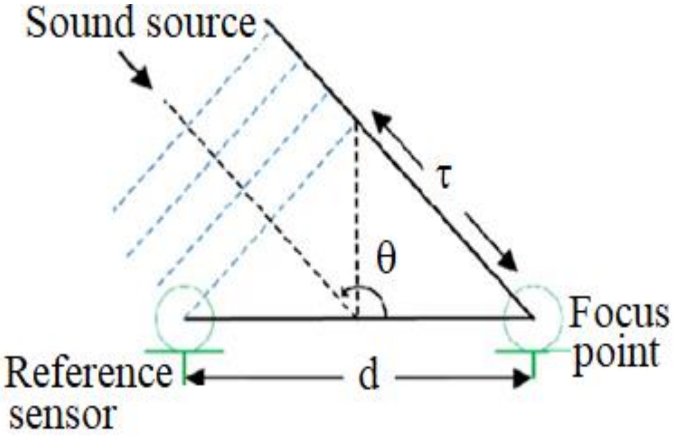


SOUND WAVE PROPAGATION AND REFLECTION

- **IMAGE RESOLUTION AND DEPTH**
  - **BEAMFORMING**

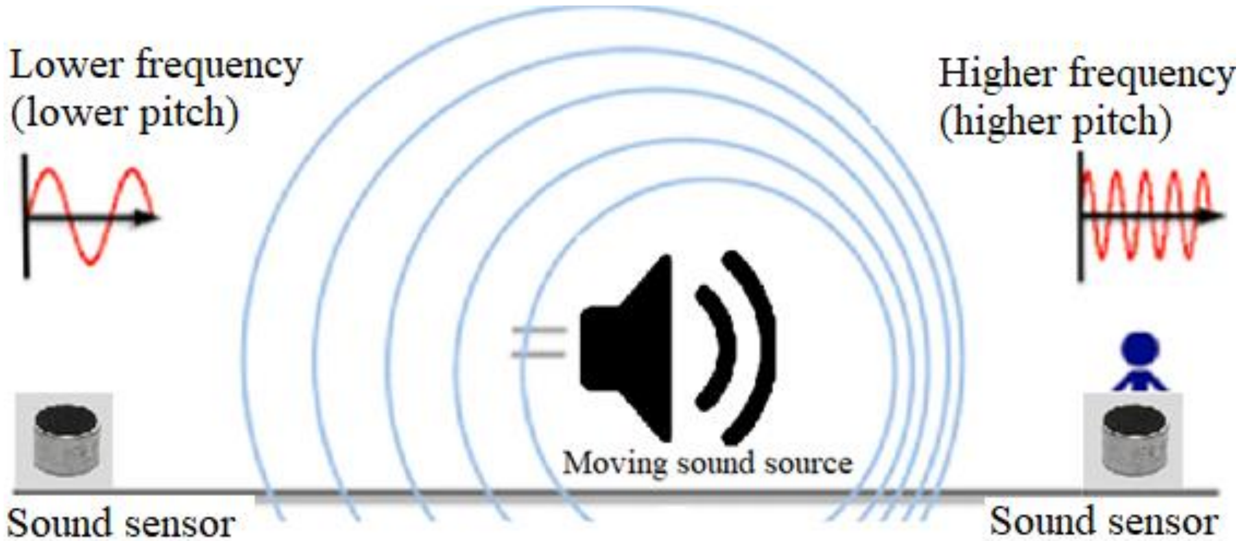
Summing the signals from different transducer elements with appropriate time decay

$$\tau = d\sin(\theta)/C$$



▪ Doppler-effect

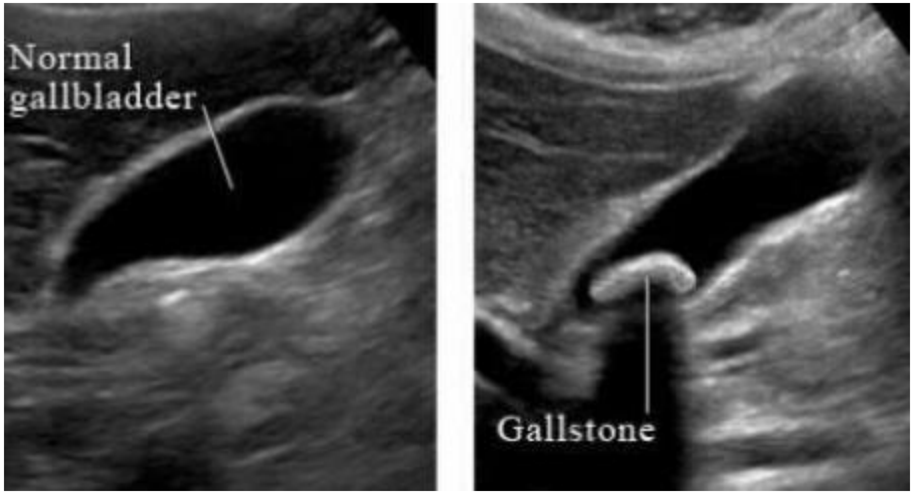
phenomenon that occurs when the frequency of a wave changes due to the relative motion between the source of the wave and the observer:



▪ Concept and application In medical imaging

Ultrasound scan is popularly used to:

- monitor fetus development
- analyzing abnormalities of the thyroid gland
- detect stones
  - in the gall bladder
  - kidneys
  - urinary system



▪ Concept and application In medical imaging

Doppler Shift (Frequency Shift)

$$\Delta f = \frac{2 f_0 v cos(\theta)}{c}$$

f_0 emitted frequency of the ultrasound wave
v velocity of the moving object (e.g., blood flow)
θ angle between the ultrasound beam and the direction of motion
c speed of sound in the medium.

- used to measure the velocity of moving structures (blood flow)
- analyzing the change in frequency of the returned echoes relative to the transmitted frequency:
- When a wave source moves towards an observer, the frequency of the wave increases.
- higher pitch (higher frequency in sound waves)
- When source moves away from the observer, the frequency decreases, resulting in a lower pitch or lower frequency.

Concept and application In medical imaging

Doppler Shift (Frequency Shift)

The observed frequency

$$f' = f(v + v_o)/(v - v_s)$$

f original frequency of the wave

v speed of the wave in the medium

v_o speed of the observer relative to the medium

v_s = speed of the source relative to the medium

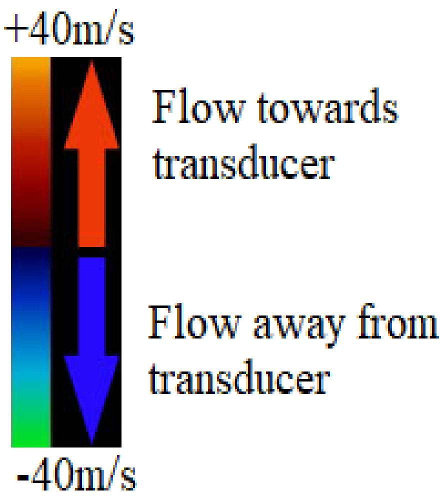
reflects the motion of both the source and the observer.

The sign depends on whether they are moving towards or away from each other.

▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

- **Color Doppler:**
  - uses color coding to visualize blood flow.
  - flow towards the transducer is in red
  - flow away is in blue
  - assess the direction and speed of blood flow



▪ Concept and application In medical imaging

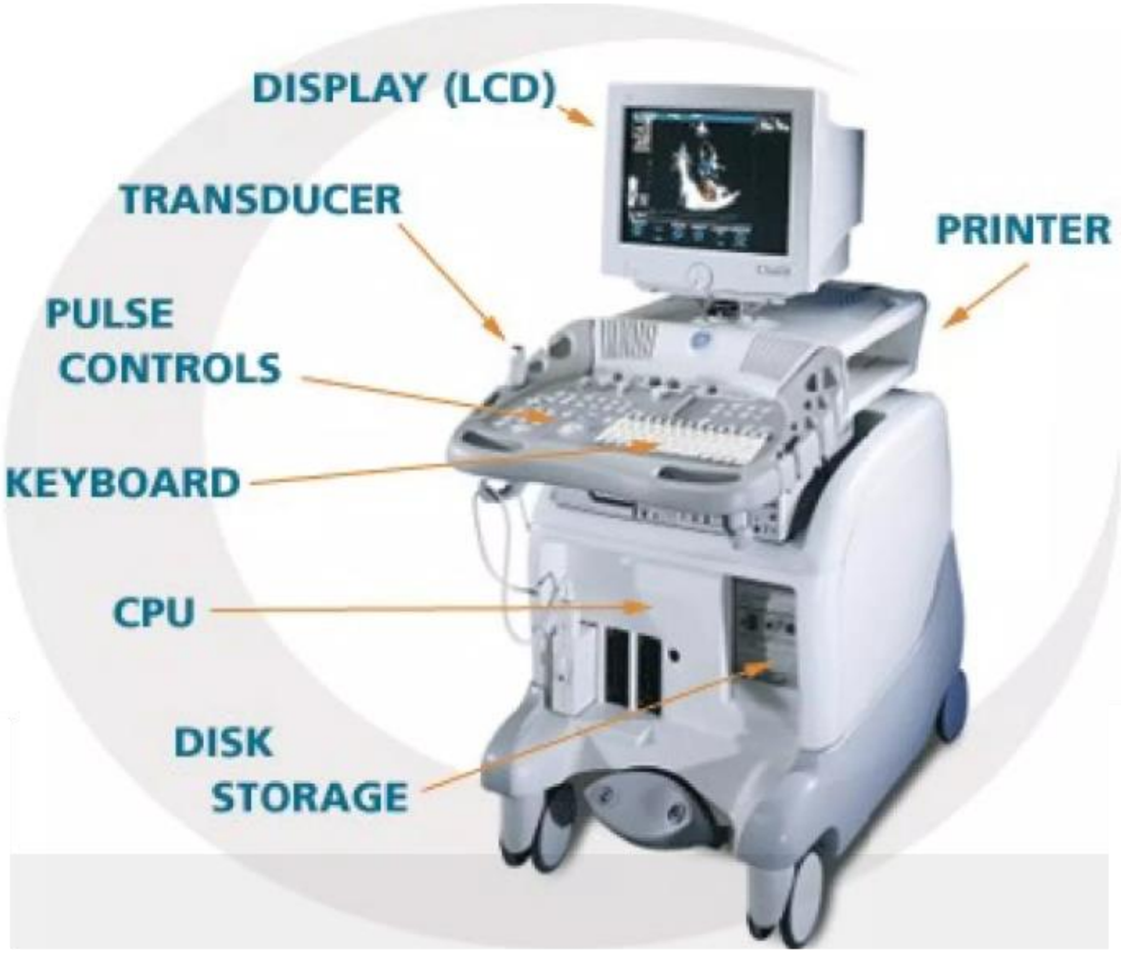
APPLICATION IN MEDICAL IMAGING

A basic ultrasound machine has the following parts:

- Transducer probe - probe that sends and receives the sound waves
- Transducer pulse controls - changes the amplitude, frequency and duration of the pulses emitted from the transducer probe
- Central processing unit (CPU) - computer that does all of the calculations and contains the electrical power supplies for itself and the transducer probe
- Display - displays the image from the ultrasound data processed by the CPU

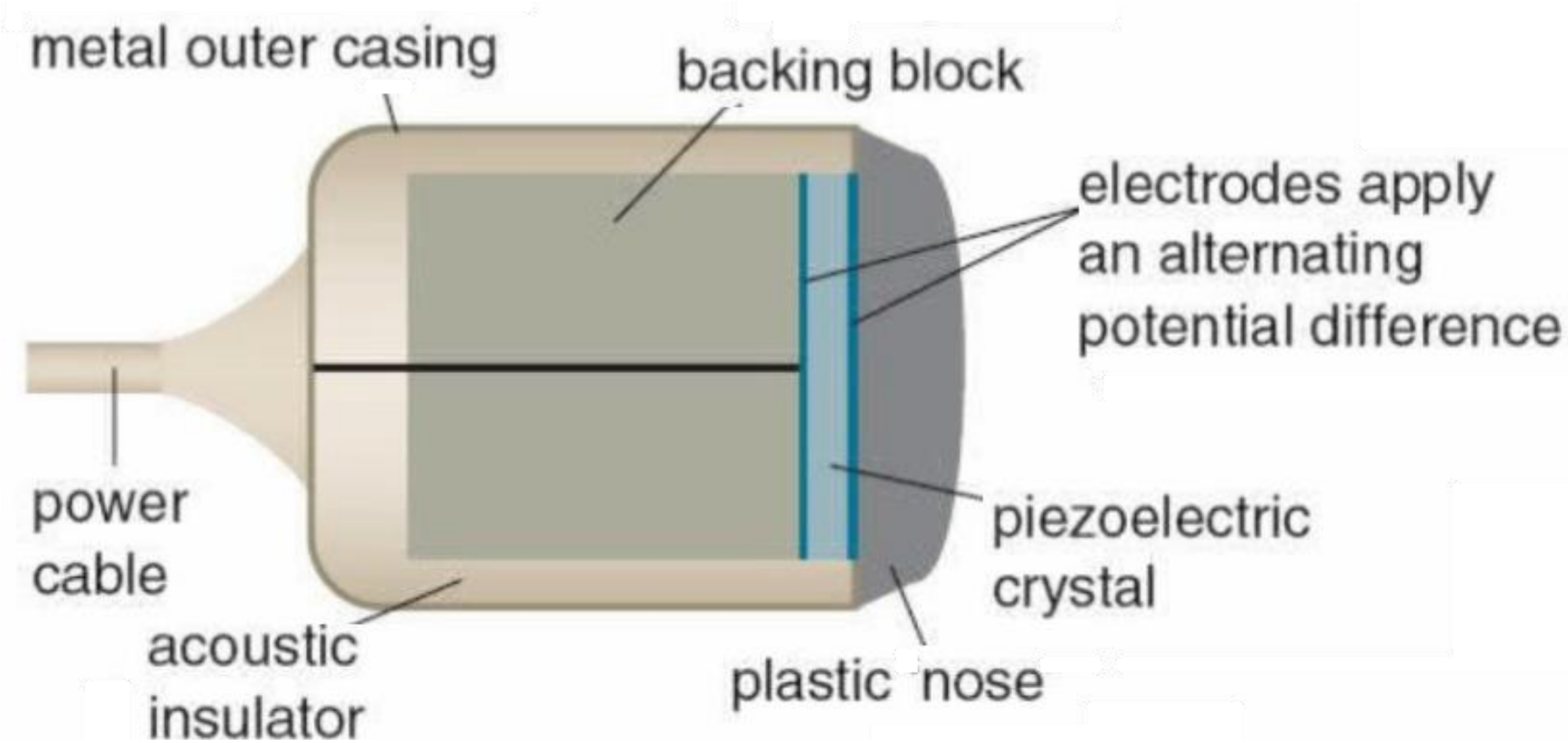
▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING



▪ Concept and application In medical imaging

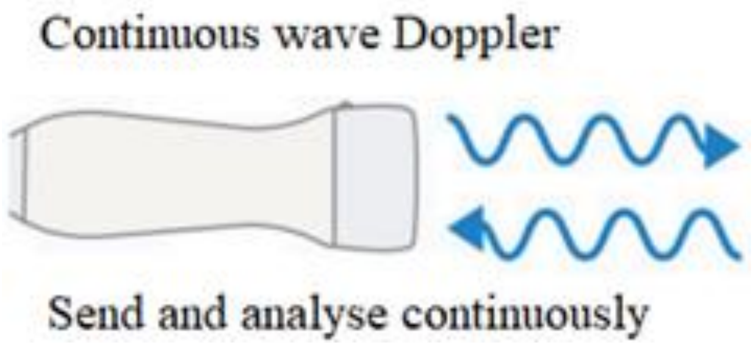
APPLICATION IN MEDICAL IMAGING



▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

- **Continuous Wave**
  - Principle: uses two crystals in the transducer: one that continuously emits ultrasound waves and another that continuously receives the reflected waves.

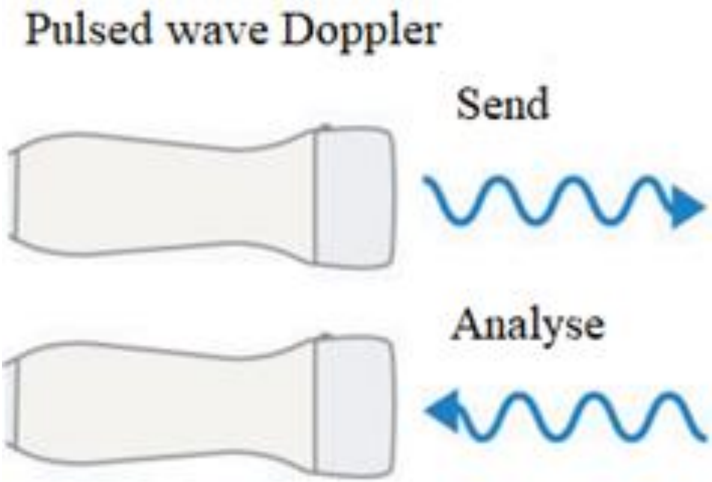


    - highly effective for measuring high-velocity blood flow, such as in cases of stenosis (narrowing of blood vessels).
  - Limitation: While it provides accurate velocity measurements, continuous wave Doppler cannot localize the source of the signal.

▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

- Pulsed Wave Doppler
  - Principle: sends ultrasound pulses and measures the frequency shift of the returning echoes.



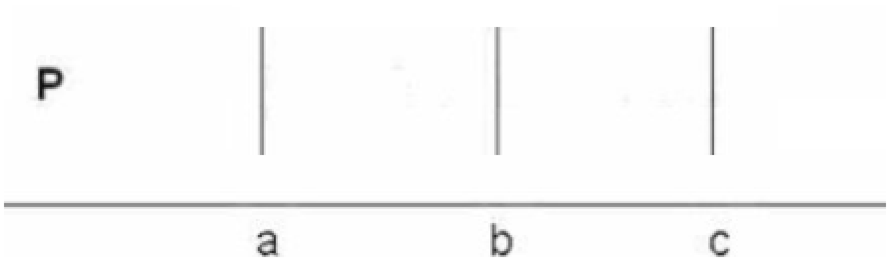
    - It allows for specific sampling at different depths, which is useful for measuring blood flow in a precise area.
  - Limitation: It is limited in its ability to measure high velocities, as very high velocities can cause aliasing (misinterpretation of the flow direction or speed).

▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

Ultrasound imaging

Performed by emitting a pulse
Partly reflected from a boundary between two tissue structures
Partially transmitted.
Reflection depends on the difference in impedance of the two tissues.



Reflection at tissue boundaries a, b and c.

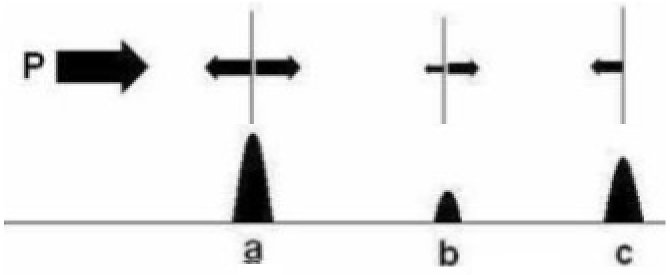
▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

Ultrasound imaging

An ultrasound pulse is emitted from the probe P.

- Part of the pulse energy is reflected from the scattered a, the rest is transmitted.
- Part of the energy transmitted at a is reflected from b and the rest transmitted.
- The energy transmitted at b will be reflected when it hits c



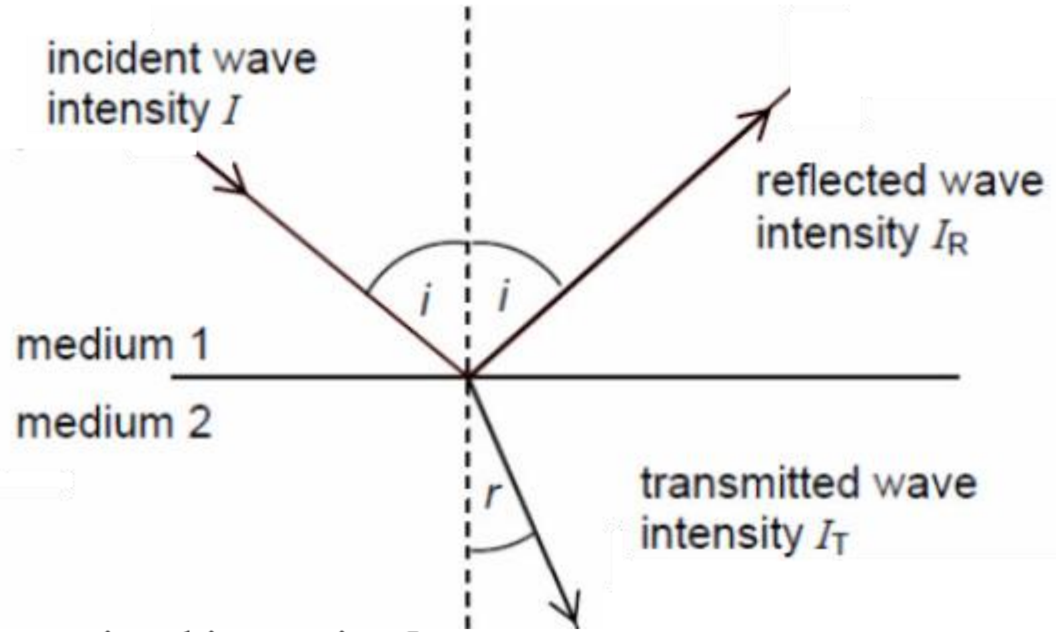
- When the pulse returns to P, the reflected pulse gives information of two measurements:
  - The amplitude of the reflected signal,
  - and the time it takes returning.

▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

Laws of Reflection & Refraction

Ultrasound obeys the same laws of reflection and refraction at boundaries as audible sound and light.



For an incident intensity I
Reflected intensity I_R and transmitted intensity I_T
From energy considerations, $I = I_R + I_T$.

▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

Acoustic Impedance

The relative magnitudes of the reflected and transmitted intensities depend not only on the angle of incidence but also on the acoustic impedance of the two media.

- The specific acoustic impedance Z of a medium is the speed of sound v in the material multiplies the density ρ :

$$Z = \rho \times v$$

- α the ratio intensity reflection coefficient for the boundary

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

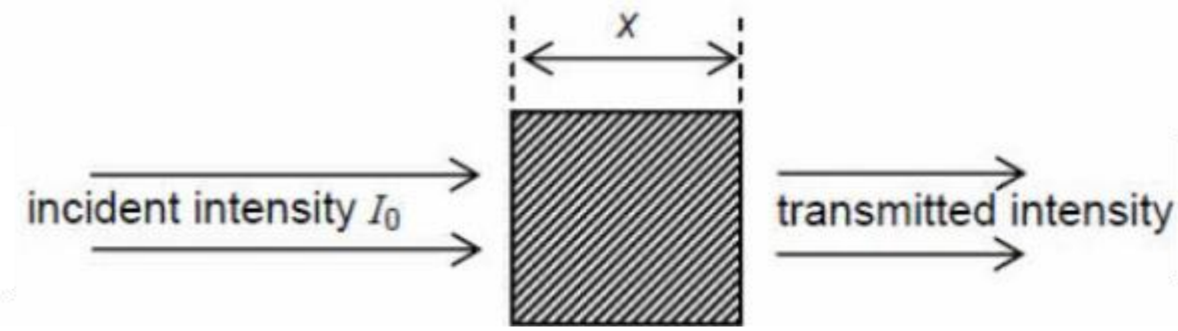
▪ Concept and application In medical imaging

APPLICATION IN MEDICAL IMAGING

Absorption of Energy

As a wave travels through a medium, energy is absorbed by the medium and the intensity of a parallel beam decreases exponentially.

$I = I_0 e^{-kx}$



K absorption coefficient depends on the frequency of the ultrasound.

- **Concept and application In medical imaging**

APPLICATION IN MEDICAL IMAGING

Some data

Material	Velocity (m/s)
Air	330
Water	1497
Metal	3000 - 6000
Fat	1440
Blood	1570
Soft tissue	1540

medium	$Z = \rho c$ / kg m^{-2} s^{-1}
air	430
quartz	1.52×10^{7}
water	1.50×10^{6}
blood	1.59×10^{6}
fat	1.38×10^{6}
muscle	1.70×10^{6}
soft tissue	1.63×10^{6}
bone	$(5.6 – 7.8) \times 10^{6}$

medium	absorption coefficient / m^{-1}
air	120
water	0.02
muscle	23
bone	130

END