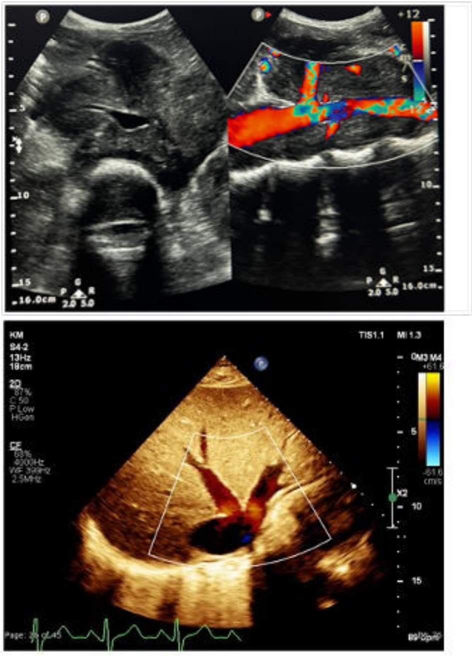
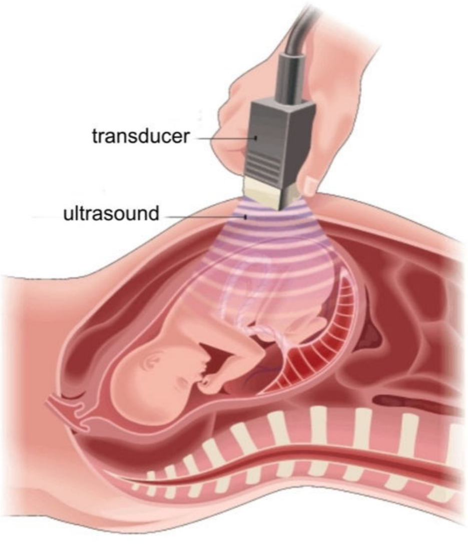
ULTRASOUND

DIAGNOSTIC SONOGRAPHY AND THERAPEUTIC APPLICATION OF ULTRASOUND





SUMMARY:

ULTRASOUND: mechanical oscillation or wave with a frequency (pitch) exceeding the upper limit of the audible range of the human ear, which is 20 000 Hz.

DIRECT PIEZOELECTRIC EFFECT: Piezoelectric insulators (e.g. crystals) accumulate electric charge and become electrically polarized when mechanically strained (by pressure or tension). A measurable potential difference builds up on the electrodes placed on the opposite sides of the strained crystal.

INVERSE PIEZOELECTRIC EFFECT: If an electric voltage is applied on the electrodes of the piezoelectric material, it becomes deformed (contracted or stretched).

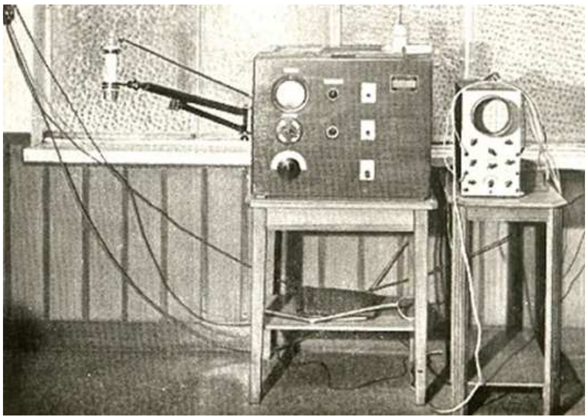
TRANSDUCER: a device that converts electric signals into mechanical, and *vice versa*.

ACOUSTIC IMPEDANCE: an important parameter that characterizes the acoustic properties of the medium. It is defined as the product of the medium density (ρ) and the velocity (c) of the ultrasound in the medium ($Z = \rho \cdot c$). The surface of a medium is called boundary surface (or interface) if the acoustic impedance changes.

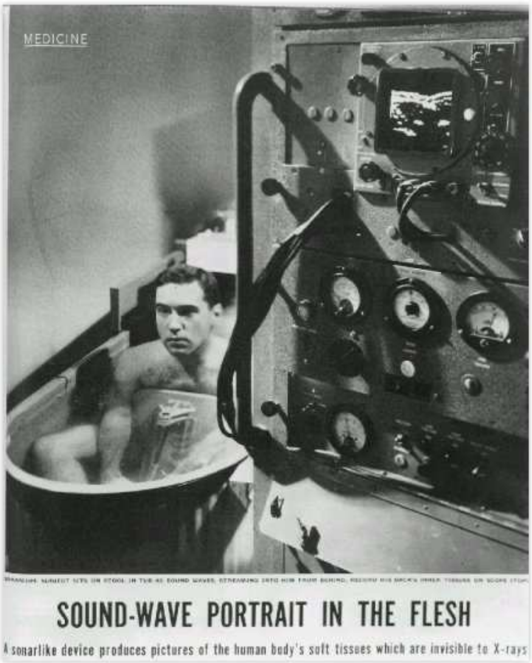
REFLECTIVITY: measure of reflection on the boundary surface of media of different acoustic impedances. Reflectivity is defined as the ratio of the reflected and incident intensity as: $R = \frac{J_R}{J_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$, here Z_1 and Z_2 are the known acoustic impedances of the media ($R = 0$ for no reflection, and $R = 1$ for total reflection).

PULSE-ECHO METHOD: The distance (d) between the reflecting boundary surface and the transducer can be calculated from the time (Δt) elapsed between the emission of the wave packet-like ultrasound pulse into the medium and the return of its echo, provided that the velocity of the sound (c) is known in the given medium (Fig. 3) as follows: $d = \frac{c \cdot \Delta t}{2}$.

DOPPLER EFFECT: change in the frequency (and wavelength) of the wave as a result of the relative motion of the source and the observer.



A. Denier's ultrasonoscopic apparatus from 1946.



MEDICINE

SOUND-WAVE PORTRAIT IN THE FLESH

A sonarlike device produces pictures of the human body's soft tissues which are invisible to X-rays

Taking ultrasound images of the human body's soft tissues(kidney) in 1954 (Life magazine).

Ultrasound is a mechanical oscillation of sufficiently high frequency, which is applied in medicine for both diagnostic and therapeutic purposes. ***Diagnostic*** *ultrasonic applications (ultrasonography, medical sonography) are non-invasive methods which have developed enormously in recent decades (2D, 3D, 4D, Doppler methods, etc.).* ***Therapeutic*** *applications include those used in rheumatology for the treatment of musculoskeletal disorders or ones used for the removal of dental plaques, both operating above 20000 Hz.*

Further readings: Damjanovich-Fidy-Szőlősi: II / 2.4., VII / 1. 2. 4., VII / 1. 7., VIII. / 4.2., IX / 5. 1.

THEORETICAL OVERVIEW

PROPAGATION, DAMPING AND REFLECTION OF ULTRASOUND

Ultrasound is a mechanical wave, which is longitudinal in liquids and gases, and it is both longitudinal and transverse in solids.

Ultrasound is sound with a frequency greater than the upper limit of the hearing range of an average human ear. That is, its frequency exceeds 20 000 Hz (see chapter 25. AUDIOMERTY).

Propagation of ultrasound

Ultrasound propagates with velocity (c) that is characteristic for the medium, and it displays wave properties (see refraction). The propagation speed depends on the density (ρ) and compressibility (κ) of the medium:

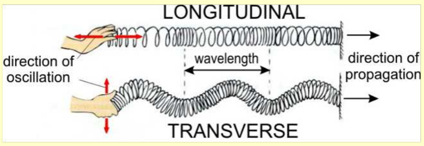
$$c = \frac{1}{\sqrt{\rho \cdot \kappa}} \quad , \qquad (1)$$

Compressibility (κ) is the relative change in volume ($-\Delta V/V$) of a material per unit increase in pressure (Δp), at constant temperature:

$$\kappa = -\frac{\Delta V/V}{\Delta p} \, .$$

The unit of compressibility is [1/Pa]. The more a material compresses in response to pressure, the greater its compressibility.

Direction of propagation of the **longitudinal** wave is the same as the direction of the oscillation. Sound wave in air or in water is longitudinal (but waves on the water surface are not longitudinal!).



Direction of propagation of the **transverse** wave is perpendicular to the direction of the oscillation. Vibration of a string is transverse.

Damping of ultrasound

Part of the energy that propagates in the ultrasound is dissipated in the medium **in the form of heat**, hence transmitted intensity is attenuated. According to the general attenuation law of radiation:

$$J = J_0 e^{-\mu \cdot x} \, , \qquad (2)$$

where J and J_0 are the intensities measured at distance x and 0, respectively, and μ is the **absorption coefficient**.

The **damping** is used to characterize the decrease of intensity, which is similar to the concept of optical or X-ray density. Damping is defined as: $\alpha = 10 \lg \frac{J_0}{J} = 10 \mu \cdot x \cdot \lg e$. As μ is proportional to the frequency (f), this holds for α as well. Absorption property of tissues is often characterized by **specific damping** which has a unit of dB/(cm·MHz).

Reflection of ultrasound

At the **boundary surface** of different media part of the incident ultrasound wave is **reflected** (**reflection**) and part of it penetrates into the medium (Fig. 1). If the direction of propagation of the incident ultrasound wave is not perpendicular to the boundary surface (skewed incidence), then the ultrasound wave will **change its direction of propagation** (**refraction),** similarly to the refraction of light.

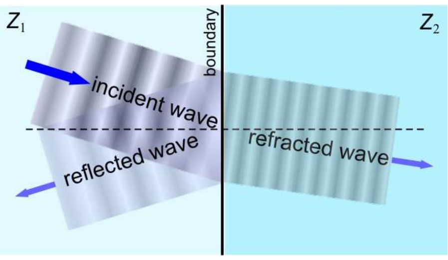


Fig. 1. *Reflection and refraction of the ultrasound wave ($Z_1 > Z_2$). The law of refraction is valid for sound.*

Acoustic impedance (Z) is an important parameter that characterizes the acoustic properties of the medium. It is defined as:

$$Z = \rho \cdot c \, , \qquad (3)$$

where ρ is the density of the medium, and c is the velocity of the ultrasound in the medium. The measure of reflection from a surface is the **reflectivity** (R), which is defined as the ratio of the reflected (J_R) and the incident (J_0) intensity.

$$R = \frac{J_R}{J_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 \, , \qquad (4)$$

Reflectivity can be calculated from the formula above, using the known acoustic impedances (Z_1, Z_2) of the media.

GENERATION AND DETECTION OF ULTRASOUND

piezoelectric effect
piezoelektromos hatás
piezoelektrischer Effekt

Direct piezoelectric effect

Certain solid materials (e.g. quartz, $BaTiO_3$) **accumulate electric charge and become polarized** when **mechanical strain** (pressure, tension) is applied on them. This results in measurable potential difference between the electrodes placed on the opposite sides of the crystal (Fig. 2.). Detection of mechanical oscillations such as caused by ultrasound is based on this phenomenon. By the help of the direct piezoelectric effect ultrasound is converted into an electric signal.

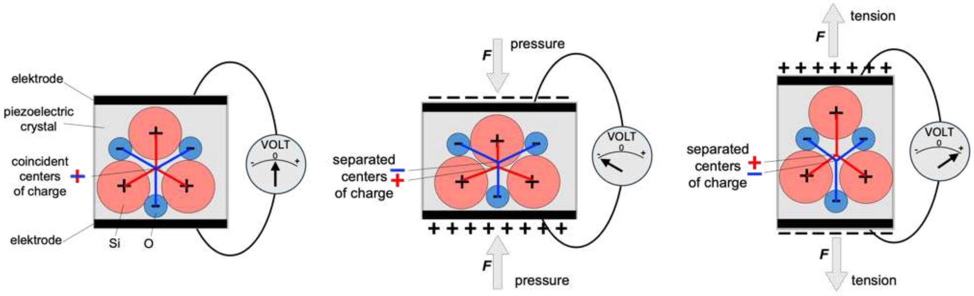


Fig. 2. *Direct piezoelectric effect.*

Inverse piezoelectric effect

Piezoelectric effect is reversible. **If voltage is applied on the electrodes of the piezoelectric material, it becomes deformed** (contracted or stretched), hence the thickness of the crystal changes (Fig. 3.). Ultrasound radiation is generated based on this inverse piezoelectric effect.

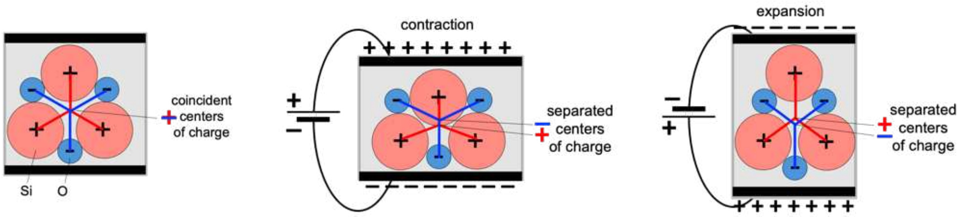


Fig. 3. *Inverse piezoelectric effect.*

All solids, including piezoelectric materials, have a natural **resonance frequency** (see Chapter 21. ESONANCE). This is the frequency at which the material vibrates with maximum amplitude. The resonance frequency depends on the object's **mass**, **dimensions**, and **elastic properties** (as seen in examples like tuning forks).
To maximize the efficiency of ultrasound generation and detection, the piezoelectric material is excited using an electrical signal that matches its resonance frequency.

An almost instant emission and detection of ultrasound is essential in medical ultrasonography.

Ultrasound source

Alternating voltage of high frequency, which is converted into ultrasound, is produced by a sine wave oscillator (see chapter 19. SINE WAVE OSCILLATOR). This electric signal is actually a short wave package of several MHz frequency, that contains only a few periods of a sine wave. Thus, for practical purposes it is an electric pulse (Fig. 4.). This electric pulse is conducted to the **transducer** (emission and detector head), which contains the piezoelectric material equipped with the electrodes.

The transducer is a signal-converting device that converts the electric signal into ultrasound and vice versa. When ultrasound is produced the electric signal in the transducer is converted into the ultrasound. When detected, the ultrasound echo signal is converted to the electric signal in the same transducer.

The transducer converts the electrical energy into mechanical, thereby generating an ultrasound pulse (via the inverse piezoelectric effect) which is directed into the investigated part of the body. As mentioned above, this **ultrasound pulse (“transmission”)** is short and lasts only a few time periods (wave packet), just like the pulse-like ultrasound whistles of the bat.

Detection of ultrasound

echo
visszhang, echo
Echo

In the “silent” phase that follows pulse transmission the transducer “**switches into receiver mode**” and waits for the echo signals reflected from the tissue surfaces of the examined body part. After a while echoes of reduced intensity reach and deform the transducer material (just as it happens in the ultrasound-sensitive ear of the bat). As a consequence of electric polarization in the transducer, the ultrasound is converted back into the electrical oscillation (via the direct piezoelectric effect), and this signal is then conducted through a cable into the electronic amplifier (see chapter 18. AMPLIFIER).

DIAGNOSTIC APPLICATION OF THE ULTRASOUND: MEDICAL ULTRASONOGRAPHY

🇬🇧 transducer
🇭🇺 transzducer
🇩🇪 Transducer

In the past decades, enormous progress has been made in the diagnostic applications of ultrasound. The method is based on the **reflection of ultrasound from the surfaces of biological tissues having different acoustic impedances.** Distance of the examined boundary surfaces is calculated from the time measured between the emission of ultrasound pulse and the arrival of the echo signal, and subsequently an image of these surfaces is reconstructed.

Because the frequency of the reflected ultrasound changes if the **reflecting surface is in motion** (Doppler effect, see later), the frequency spectrum of the echo contains further information as well.

Pulse-echo principle

The **distance (d)** between the reflecting boundary surface and the transducer can be calculated from the **time (Δt)** elapsed between the **emission of the** wave-packet-like **ultrasound pulse** into the medium and the **time of the arrival of the ultrasound echo** signal, if the velocity of the sound (c) is known in the given medium (Fig. 4.), as follows:

$$d = \frac{c \cdot \Delta t}{2}, \tag{5}$$

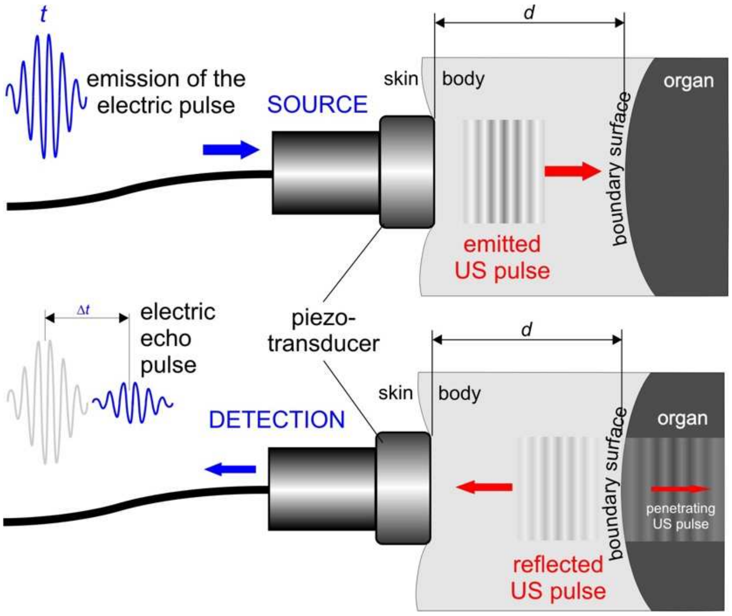


Fig. 4. *Pulse-echo principle.*

The time delay and the amplitude decay of the echo signal compared to the emission pulse contain all the information about the location of the organs examined in the body (Fig. 5.). **Wave-packet release time** (transmission) and **detection time** (reception) changes periodically in the transducer. The main frequency of the applied ultrasound is around several MHz, thus in the emitted wave-packet there are only a few sine-wave periods in 1 µs (the approximate duration of one pulse). The repetition frequency of the emission-detection cycle is around 1 kHz (Fig. 6.).

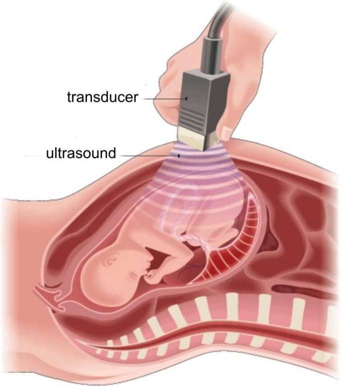


Fig. 5. *In this typical application the ultrasound transducer provides spatial information about the fetus.*

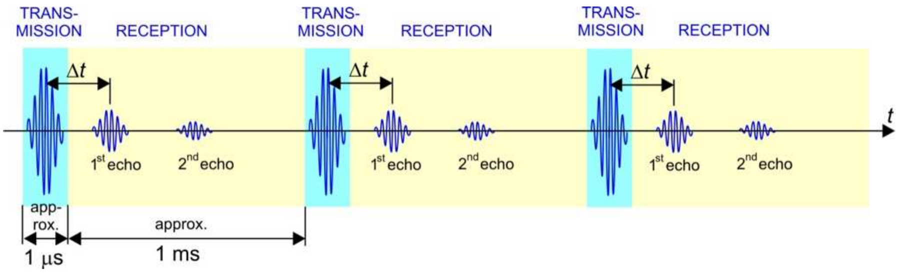


Fig. 6. *Temporal sequence of the emission and detection of the ultrasound.*

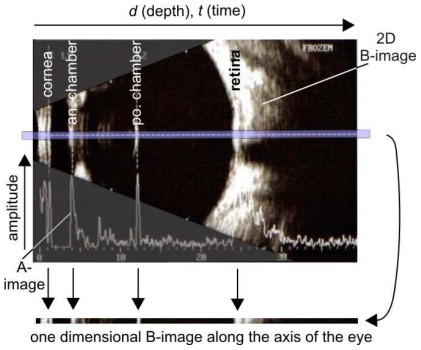


Fig. 7. *The eye of a goat according to ultrasound A-image along the optical axis (in the middle), 2D B-image (above) and a one-dimensional B-image along the axis of the eye (below). The main echo signals come from the cornea, the anterior chamber, the posterior chamber and the retina.*

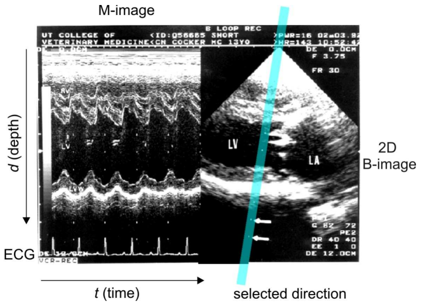


Fig. 8. *The M-image (left) represents the movement of the valve in the heart in time at the selected direction, which is indicated in the 2D B image (right).*

Fig. 9. *The reconstructed 3D ultrasound image of the fetus compared with the photograph of the newborn.*

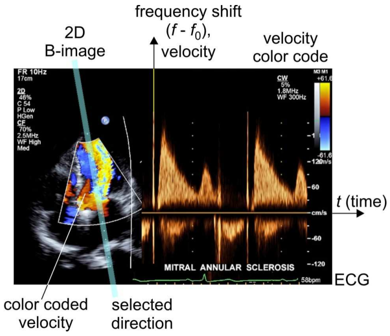


Fig. 11. *Colored Doppler-image of the mitral cardiac valve combined with a 2D B-image (left). The frequency shift (velocity) as the function of time (right) is shown in the selected direction (indicated by the blue line).*

Diagnostic ultrasound imaging methods

One-dimensional A-image (amplitude modulation): a single transducer produces one ultrasound beam that propagates in a straight line. In the image the horizontal axis represents time or the corresponding distance, and the vertical axis denotes the intensity of the reflected echo signal (Fig. 7., center).

One-dimensional B-image (brightness modulation): a single transducer produces one ultrasound beam that propagates in a straight line. The **brightness of pixels** on the horizontal time scale **is proportional to the amplitude of the reflected ultrasound signal**. Brightness is encoded usually on a gray scale (Fig. 7., bottom, brightness changes along the blue line).

Two-dimensional B-image (2D, brightness modulated): an array of several transducers are specially synchronized in a way that the direction of the wavefront can be changed, and a plane (of fan shape) is scanned. **A series of one-dimensional B-images at different angles** appears on the screen (curved array, Fig. 8., right). Real image is reconstructed of one section of the scanned region of the biological sample.

M-image (motion): In the 2D B-image one direction is chosen, and a sequence of one-dimensional B-images is plotted vertically as a function of time (horizontal time scale) (Fig. 8., on the left). We obtain information about the **position of the given surface as a function of time**.

Reconstructed 3D-image (tomography): Three-dimensional image of the biological object can be reconstructed from the 2D B-images of a large number of parallel planes scanned (Fig. 9.), that can be processed further by a computer. The 3D-rendered dataset can be manipulated orientationally (i.e., turned around arbitrary axes), or different image sections can be calculated.

Reconstructed 4D-image: Sequence of several reconstructed 3D images, where time is the 4th dimension. In this method an ultrasound movie is created.

Doppler methods

The Doppler effect: The Doppler effect is a change in the frequency (and wavelength) of the wave as a result of the relative motion of the source and the observer (Fig. 9).

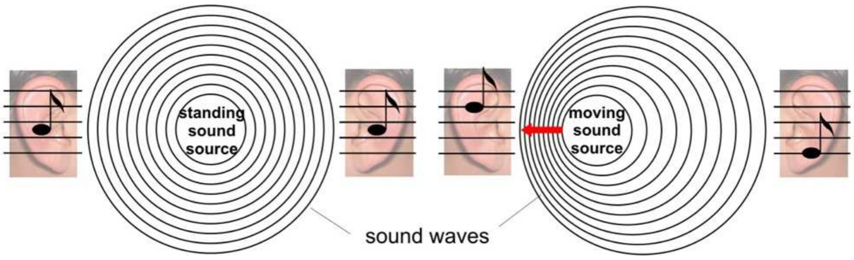


Fig. 9. *Doppler-effect: sound of an approaching source appears of higher pitch (shorter wavelength), while sound of departing source appears lower-pitch (longer wavelength) for the observer.*

Similarly to the phenomenon described above, the frequency of the ultrasound reflected from a **moving boundary surface** (considered as a sound source) differs from the original frequency as follows:

$$f \cong f_0\left(1 \pm 2\frac{v}{c}\right), \tag{6}$$

where f and f_0 are the frequencies of the reflected and incident ultrasound waves, respectively, c is the velocity of the ultrasound in the medium and v is the velocity component of the reflecting surface in the direction of the ultrasound propagation. The positive sign is used if the source and the observer moving towards each other, while the negative sign is applied if the source and the observer are moving away from each other. Frequency of the ultrasound reflected from a still surface does not change. The **Doppler shift** ($f - f_0$) is proportional to the relative velocity (v/c) and the incident frequency. The latter is adjusted so that the Doppler shift falls in the audible frequency range (several kHz), thus it can be observed directly with a loudspeaker.

Doppler time-velocity image: At the selected section of the indicated direction in the 2D B-image, Doppler-frequency-shift that corresponds to the velocity of the observed surfaces is plotted as a function of time (Fig. 11, right).

Color-coded Doppler image: The 2D B-mode image (grayscale) of the biological sample and the velocity information of the moving structures (color-coded) are displayed on the same image (Fig. 11, left). By convention, **blue** represents structures moving **away** from the transducer, while **red** indicates structures moving **toward** the transducer. (“**BART**”: Blue Away, Red Toward)

Doppler flow meter: allows the measurement of the velocity of blood flow in larger blood vessels according to:

$$v = \frac{c(f - f_0)}{2f_0 \cos \Theta}, \tag{7}$$

where v is the velocity of blood flow, c is the ultrasound velocity in the medium, $f - f_0$ is the Doppler shift and Θ is the angle between the ultrasound beam and the axis of the blood flow (Fig. 12.)

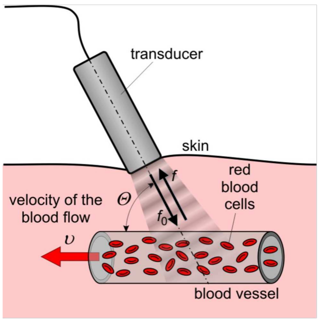


Fig. 12. Doppler flow meter.

PLAN OF THE EXPERIMENT

Measuring the Speed of Ultrasound Propagation in Air

The measurement setup consists of a microcomputer with a display, which controls an ultrasonic transducer module operating at a frequency of 40 kHz (Fig. 13).

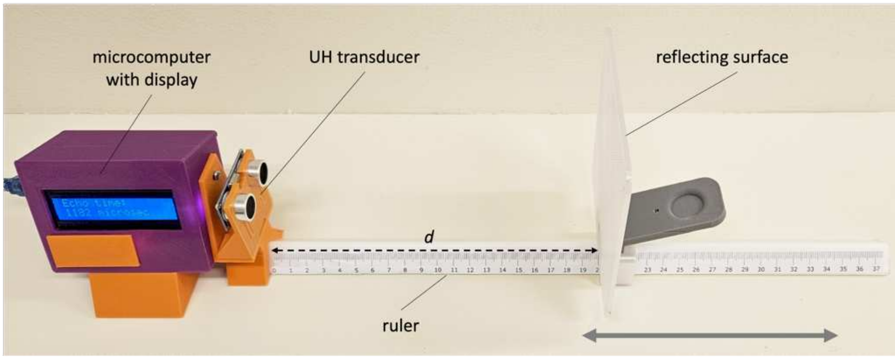


Fig. 13. Measurement system for determining the speed of ultrasound propagation in air.

1. A reflective surface is placed at a given distance (min. 15 cm, max. 45 cm) from the transducer. The distance d is accurately read using a ruler. The microcomputer measures the echo time of the ultrasonic pulses with microsecond precision, which is displayed on the screen. Based on the echo time (Δt) and the known distance d between the transducer and the reflective surface, the speed of sound in air can be determined using the formula: $c = 2d/\Delta t$.
2. For a more accurate result, a calibration line is created from the echo times corresponding to different known distances d, and the slope of this line is determined.
3. Finally, the measurement partner places the reflective surface at a distance d unknown to us and provides the echo time. Our task is to calculate the distance d to the reflective surface using the known speed of sound.

Measurements using a water-filled phantom (model)

1. Submerge a water-filled rubber glove into the phantom (Fig. 14). By moving it vertically, we can observe cross-sectional images of different layers.
2. Submerge an air-filled rubber glove into the phantom and observe the shadowing effect.
3. Submerge a rubber glove filled with glycerin, and then one filled with alcohol, into the phantom. Observe the shape distortions of the middle finger on the screen (Fig. 15). Provide an explanation for the phenomenon. Measure the variation in diameters depending on the medium and estimate the speed of sound in each medium using the formula:

$$c_{medium} = c_{water} \frac{d_{water}}{d_{medium}}, \tag{8}$$

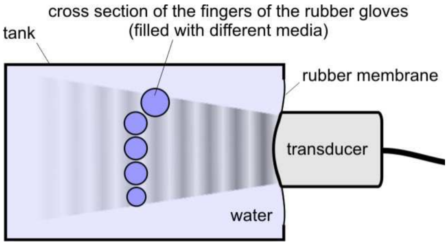


Fig. 14. Top view of the water-filled phantom.

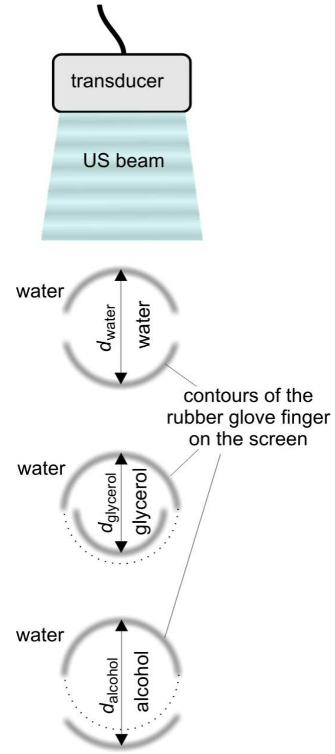


Fig. 15. *The image of the back-wall reflection appears at different distances depending on the material in the finger of the rubber glove.*

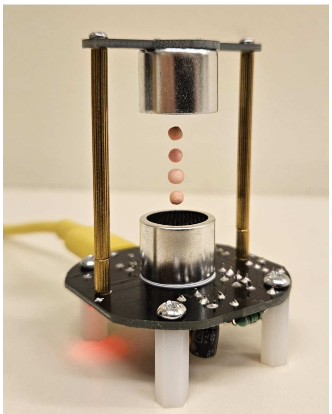


Fig. 17 *Levitation with ultrasound.*

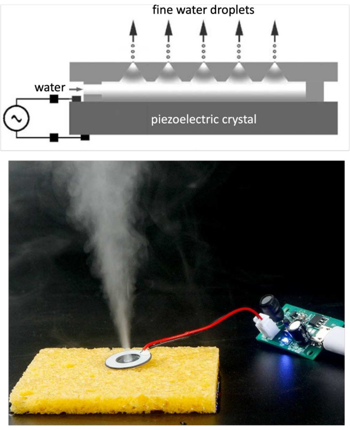


Fig. 18 *Vaporization with ultrasound*

Measurements on the human body

1. Observe the **common carotid artery** of a volunteer using a medical diagnostic ultrasound device. After freezing the image at the appropriate moment, use the cursor to measure the inner diameter of the vessel.
2. Switch the device to **M-mode** and study the time-dependent pulsation of the artery.
3. Switch the device to Doppler mode. By changing the tilt angle of the transducer, study how the **blood flow velocity** in the artery varies over time, as well as the changes in **color-coded blood flow representation** (the pulsation can also be made audible using the speaker).

DEMONSTRATION

The radar principle – distance measurement by ultrasound – US-A-image

Using a special ultrasound-head, short ultrasound pulses are emitted in air towards a reflecting surface, and the same ultrasound head detects the echo signal. Both the signal of the emitted ultrasound and the reflected echo signal are visualized on the screen of the oscilloscope (Fig. 14.).

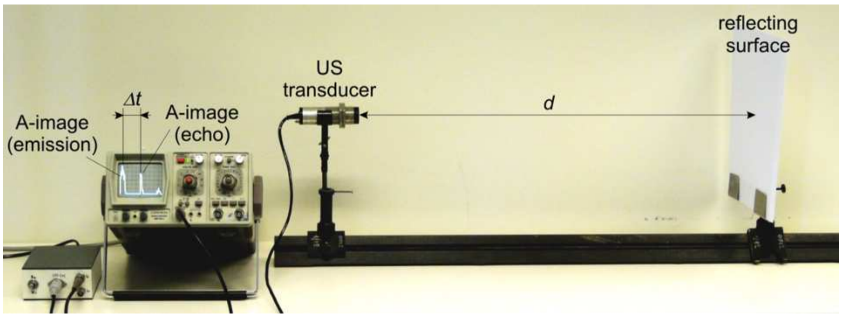


Fig. 16. *Distance measurement using ultrasound in the air.*

Measure the time between the two signals (Δt), and using the known sound velocity in air ($c = 340$ m/s), calculate the distance of the reflecting surface from the transducer ($d = c \cdot \Delta t / 2$). Measure the transducer-to-reflecting surface distance by a measuring tape as well and compare it with the calculated value.

Detection of blood flow based on the Doppler-effect

The ultrasound transducer (probe) producing a continuous wave at 8 MHz frequency is placed above the artery of the lower arm or the neck in a proper angle. The ultrasound, reflected from the corpuscular elements of blood is converted to the electric signal in the second transducer (detector). The difference between the **frequency** of the original and the reflected ultrasound signal is proportional to the flow **velocity** of blood (Doppler effect). After amplification, this difference signal is audible by use of a loudspeaker.

Demonstrating the Mechanical Effect of Ultrasound — Levitation

By operating two 40 kHz ultrasonic transducers facing each other at a proper distance and in the same phase, a longitudinal standing wave can be created in air. At the spatial points corresponding to the wave crests, light, sound-reflective objects (e.g., polystyrene beads) can be trapped using acoustic pressure (Fig. 17).

Demonstrating the Mechanical Effect of Ultrasound — Vaporization

A piezoelectric crystal operating at a frequency of 113 kHz sets a perforated metal plate into vibration through a thin layer of water between them. As a result of the vibrations, the water layer begins to ripple, and tiny liquid droplets—a few micrometers in diameter—are ejected from the surface. The droplet size depends on the frequency of the vibration (Fig. 18).

Therapeutic Application of Ultrasound

The relevant section can be found in 19. SINE WAVE OSCILLATOR.