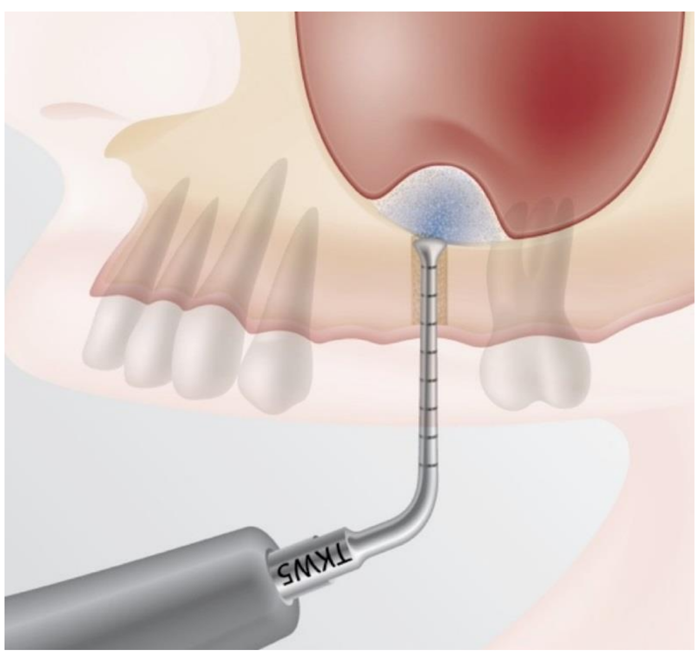
Department of Medical Physics , Tabriz School of Medicine

Tabriz University
of Medical Sciences

Experiment N0. 9

Investigation of Physical, Chemical, and Therapeutic Properties of Medical Ultrasound Waves



9-1 Experiment Objective

The purpose of this experiment is to:

- ✓ Investigate the effect of changes in intensity and pulse on the movement of water particles, Study the cavitation producing property of ultrasound waves in water
- ✓ Examine the thermal property of ultrasound waves in both water and glycerin, and explore the chemical characteristics of ultrasound waves
- ✓ The diagnostic capability of ultrasound waves

9-2 Required Equipment

Speaker, generator, small Beaker, water, gel, ultrasound device, experimental tube, glycerin, thermometer, carbon tetrachloride, potassium iodide, and pipette.

9-3 Experiment Theory

Sound is the displacement of particles in a substance through compression and rarefaction and ultimately leading to mechanical vibrations and sound production. Sound waves are pressure or mechanical waves that cause the movement of particles within a medium, leading to variations in their average positions. This movement is illustrated in Figure 1, depicting regions of compression and rarefaction.

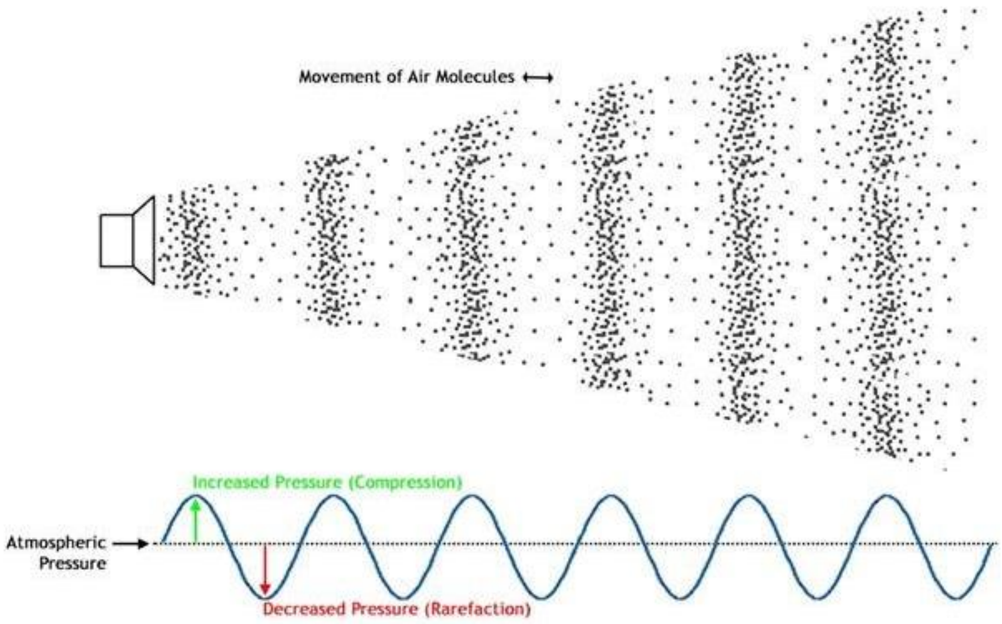


Figure 1. Sound propagation with compression and expansion regions

A source generating sound waves oscillates or vibrates at a certain sound frequency. Air molecules in front of the source immediately compress, creating a high-density air region described by a small high-pressure region. As the source moves backward, a low-density molecular region forms, representing the expansion or low-pressure region. The density variation pattern over distance is represented by a wave pattern. The motion of sound molecules is determined by the wave equation:

$$A = A_0 * Sin\ (2\pi ft.) \quad (1)$$

Where A is the wave amplitude at time t, A_0 is the maximum amplitude, f is the frequency. Sound waves with frequencies beyond the human audible range are called ultrasonic waves, and objects capable of producing ultrasound are referred to as piezoelectric bodies. The human audible frequency range is between ~16 Hz and 20,000 Hz. Additionally, waves with frequencies below the human audible range are referred to as infrasound waves. Parameters such as wavelength, amplitude, frequency, period, velocity, impedance, intensity, and behavior in different surrounding will vary the practical applications of ultrasonic waves.

Ultrasound Wave Generator

The interaction between mechanical pressure and electric force in a medium is referred to as piezoelectric effect. Certain crystals generate electric force under mechanical pressure, and conversely, creating a potential difference across these crystals results in their compression and expansion, leading to oscillations and wave generation. Materials possessing this property are known as piezoelectric materials. The piezoelectric effect exists only in crystals that don't have central symmetry. Quartz crystal is one such material, utilized in a device called a transducer or probe to generate ultrasound waves.

Biophysical and Physiological Effects of Ultrasound (Ultrasound Bio effects)

Upon absorption of ultrasonic energy within tissues, particles around their approximate positions undergo oscillation. This oscillation or sound energy transforms into thermal energy, the magnitude of which correlates with the intensity of the ultrasound. If all of this heat is not dissipated by natural physiological mechanisms, localized heating increases and thermal effects become evident in the tissue. If the dissipated heat matches the generated heat, no net heat is produced in the tissue, and the observed effects are related to non-thermal effects of ultrasound. Non-thermal effects are achieved by using low intensities or by pulsing the ultrasound output.

1. Thermal Effects

For beneficial therapeutic effects, tissue heating should be maintained consistently between 40-45 degrees Celsius for a minimum of 5 minutes, and a drop in temperature should be prevented. The advantage of using ultrasound for generating thermal effects lies in gradually heating collagen tissue and effectively penetrating this energy into deep structures. However, structures capable of absorbing ultrasound, located along the path of sound waves, may hinder these waves from reaching deeper tissues. The degree of absorption depends on the material, tissue perfusion, and frequency of the waves.

2. Non-Thermal Effects

One of the non-thermal effects of ultrasound is the phenomenon of cavitation. The various gases in the blood can form extremely small bubbles, as small as one micron, due to ultrasonic waves. These tiny bubbles, if they possess minimal energy, can be beneficial and alter the permeability of adjacent cell membranes. However, bubbles with high-energy pressure can generate significant heat, leading to the production of free radicals in the blood, which can be hazardous. Avoiding the creation of steady-state waves through motion of the applicator on the skin and using low-intensity or pulsed waves we can reduce the formation of these bubbles and their side effects.

Steady-State Waves: When an ultrasound wave passes between two tissues with different acoustic impedances, such as bone and muscle, a portion of it is reflected, and upon encountering the main waves, it creates a field of steady-state waves with high-pressure peaks (antinodes). These peaks are separated by half a wavelength, with nodes, areas without pressure, in between. In regions where the composite wave amplitude is significantly high, localized heating is possible. However, continuous motion of the ultrasound applicator prevents the formation of steady-state waves.

Mechanical Micro-Massage: During tissue compression and expansion, longitudinal ultrasound waves impact the tissue, displacing water between tissues and consequently reducing edema (accumulation of fluid within tissues due to localized impact).

Pulsed and Continuous Ultrasound: Ultrasound generators are equipped with circuits that deliver ultrasonic waves in short pulses, typically 2 milliseconds. The use of pulsed ultrasound reduces the average intensity over time and thus decreases the energy available for tissue heating. Therefore, therapists can confidently use pulsed ultrasound to harness its mechanical effects while eliminating its thermal effects solely. This allows for higher-intensity ultrasound to be applied to the tissue, as the average heat generated using this method is much lower. It's important to note that continuous ultrasound is recommended for musculoskeletal conditions like muscle spasms, joint stiffness, and pain reduction, while pulsed ultrasound is preferably used for soft tissue injuries. The number of times the crystal is excited or pulsed per second is called the Pulse Repetition Frequency (PRF).

Non-Medical Applications of Ultrasound Include:

1. Sonar technology used in underwater navigation or military sciences, such as tracking submarines, measuring water depth, fishing, and other purposes.
2. In laboratories, acoustic-optic microscopy and acoustic holography are employed to image deep body parts and areas where light penetration is limited, providing three-dimensional imaging. The interaction of ultrasound waves with tissue: When ultrasound waves are conducted into the body, they interact with the tissue based on their properties. The results of this interaction are recorded as reflected ultrasound waves. These interactions are similar to behaviors observed in light, including reflection, refraction, scattering, diffraction, interference, and absorption. All of these effects contribute to the attenuation of ultrasound intensity in the body, known as weakening.

Speed of Ultrasound Waves: It is the velocity at which a wave propagates through a medium and depends on the density and compressibility of the medium. In this relation, ρ is density, and K is the compressibility coefficient of the medium.

$$c = 1/\sqrt{\rho K} \tag{2}$$

Acoustic Impedance and its Calculation: The product of the density of a substance, ρ, and the speed of ultrasound waves, c, indicates the acoustic impedance of the material, represented by the following equation:

$$Z = \rho c \tag{3}$$

This quantity represents the resistance against ultrasound wave passage and is similar to electrical resistance against electron motion in a conductor. The unit of acoustic impedance is Rayl or kg/m^2/s. Materials with high density, have high sound velocity, and thus high acoustic impedance.

Reflection Coefficient: When sound enters a different medium from one environment to another, due to their differences in the impedances, a portion of wave will be reflected. The amount of reflection depends on the impedance of the two surroundings. The reflection coefficient is defined as follows:

$$\%R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \times 100 \tag{4}$$

%R = Reflection Coefficient, Z_1 and Z_2 are the acoustic impedance of the first and second surrounding, respectively.

Impedance Matching Layers: Impedance matching at ultrasonic frequencies with scanned or irradiated bodies is a factor that affects sensitivity. The ultrasonic impedance of crystal 30×10^5 is much larger than that of soft tissue 1.6×10^5, leading to significant reflection at the transducer-tissue interface according to the above equation. Only a small portion derived from the following equation enters the tissue.

(5) $$\%T = 100 - \%R$$

Introducing front materials or impedance matching layers between the transducer and tissue using gel largely alleviates this issue.

Ultrasonic Intensity: The amount of energy flowing through a unit area of a material's cross-section per second. In ultrasonic, an increase in intensity corresponds to increased particle compression in regions of compression, increased sound pressure, and increased amplitude of particle oscillations. These units W/cm^2, mW/cm^2 or $\mu W/cm^2$ are used for the intensity of ultrasound waves. Ultrasonic intensity is proportional to the square of pressure amplitude, particle displacement amplitude, or particle velocity amplitude. For instantaneous intensity, it can be calculated as:

(6) $$I = (P_i^2)/(\rho c)$$

Where P_i is the instantaneous sound pressure, ρ is the density, and c is the speed of sound.

Methods of Applying Ultrasound:

1. **Direct Contact Method:**

   In this method, which is the most common way of applying ultrasound, the therapeutic head is placed on the skin with the help of a coupling medium. As ultrasound waves do not pass through the air, there should be no air between the transducer and the skin. Additionally, to prevent the transducer from heating up and reducing the crystal's lifespan due to wave reflection from the air, an intermediate coupling medium allowing the passage of sound waves is necessary.

2. **Underwater Treatment:**

   If the treatment area has an irregular shape, making direct contact between the skin and the therapeutic head difficult, underwater treatment is used. The treatment area is placed in a container filled with water. The therapeutic head is submerged in the water and held at a desired distance from the treatment area. Care should be taken to eliminate air bubbles between the skin and the therapeutic head and the water's surface.

3. **Water Pillow Method:**

   Another approach for irregular surfaces that cannot be immersed in water is using a plastic bag filled with water as a water pillow placed between the transducer and the skin. Before tying the bag, all visible air bubbles should be removed by pressing the bag. The coupling medium must be well applied to the bag's surface, the skin, and the transducer head. Some researchers suggest that the output intensity should be around 50% higher than that needed for direct contact treatment.

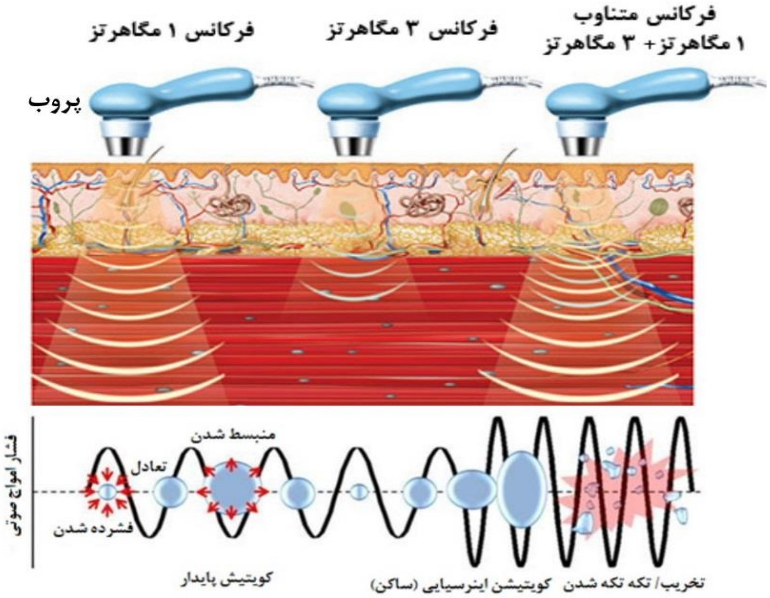


Figure 2: Propagation of Ultrasound Waves in Tissue and Their Effects on Tissue

Ultrasound Device Specifications in the Medical Physics Laboratory

The ultrasound device, known as BTL-4000, is a therapeutic device used in the laboratory. The device utilizes ultrasound wave generation and operates with a city power supply of 220 volts and a frequency of 50-60 Hz. However, the frequency of the generated ultrasound in this device is 1.3 MHz The device is capable of producing single-pulse and multi-pulse ultrasound with intensities ranging from 1 to 3 watts per square centimeter. It has programmable features for treating various diseases as well as manual programming. The pulse duration for all programs is set at 3 minutes.

1. Intensity of 1 watt per square centimeter and 10 pulses are stored under the code 8006.
2. Intensity of 1 watt per square centimeter and 50 pulses are stored under the code 8007.
3. Intensity of 2 watts per square centimeter and 10 pulses are stored under the code 8008.
4. Intensity of 2 watts per square centimeter and 50 pulses are stored under the code 8009.

Figure 3: Ultrasound Device for Therapeutic Applications

Diagnostic Ultrasound Device

The DP-6600 available in the laboratory is a portable digital diagnostic ultrasound system with black and white imaging.

Figure 4: Diagnostic Ultrasound Device in the Medical Physics Laboratory

Part One of the Experiment:

Investigating the Effect of Intensity and Pulse Variations on Water Particle Movements

Method: A small amount of water is poured into a container (ensuring it doesn't overflow), and the probe is placed on top. The movements of water particles are observed under two conditions: 10-pulse and 50-pulse waves with intensities of 1 and 2 watts per square centimeter. The pulse duration is set to 3 minutes.

Part Two of the Experiment:

Studying the Cavitation Property of Ultrasound Waves in Water

Method: A certain amount of water is poured into a tube, and the formation of bubbles is observed as they rise from the bottom of the tube to the water's surface. Changes in size, number, and speed of bubbles are observed under intensities of 2 w/cm^2, 10 and 50 pulses. Results are noted.

Part Three of the Experiment:

Studying the Thermal Property of Ultrasound Waves in Water and Glycerin

Method: Two separate tubes of equal size, material, and environmental conditions are filled with equal amounts of water and glycerin. The experiment is conducted with an intensity of 2 w/cm^2 and a constant time of 3 minutes. Results are noted according to the provided table for 10 and 50 pulses.

Experiment Materials	10-pulse	50-pulse
water		
glycerin		

Changes in temperature (ºC) after receiving ultrasound waves with the same intensity and different number of pulses.

Part Four of the Experiment:

Studying the Chemical Property of Ultrasound Waves

Method: A certain amount of water is poured into a tube (up to 2 cm), and a small amount of potassium iodide is added, mixing until fully dissolved. A few drops of carbon tetrachloride are added using a pipette, forming a separate phase at the bottom of the tube. Changes are noted before and after ultrasound exposure under 2 w/cm^2 and 10 pulses. The dissolution formula is provided.

Part Five of the Experiment:

Diagnostic Application of Ultrasound Waves

Method: In this section, the instructor demonstrates the diagnostic properties of ultrasound waves using the DP-6600 device on a phantom containing several sample materials. Observations are recorded.

Figure 5: Image of Materials inside the Water Phantom

Questions:

1. What is the reason for the differences in ultrasound images obtained from different materials? Explain.
2. Based on the ultrasound images of the phantom, which tissues are the best and worst for imaging different body parts?
3. How is the effect of ultrasound on carbon tetrachloride observed?
4. How does the dissolution of carbon tetrachloride and potassium iodide change visually?
5. Mention the application of this property of ultrasound.
6. Is the difference in temperature noticeable in the 2 w/cm^2 intensity of water?
7. Is there a difference in thermal changes between 10-pulse and 50-pulse waves?
8. How would you compare the thermal difference between water and glycerin?
9. How do you evaluate the changes in 10-pulse and 50-pulse waves?
10. Does the presence of cavitation property make the use of ultrasound waves dangerous?
11. How does the motion of waves differ between 10-pulse and 50-pulse waves with increasing intensity?
12. What is the difference in motion between 10-pulse and 50-pulse waves?