OPTO-ACOUSTICAL CHARACTERIZATION OF PHANTOMS

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To guarantee the safe and correct operation of medical ultrasonic imaging instruments, the use of phantoms is essential during testing and evaluation. Phantoms mimic the acoustic properties of living tissue, allowing for performance tests and quality control of medical ultrasonic devices. Industry standards specify that tissue-mimicking materials used in quality control of ultrasonic devices should have specific acoustic properties. Acoustical and optical properties of two distinct tissue-mimicking materials, Zerdine and Agar, were studied and characterized in this research. Acoustical properties such as density, sound velocity, and acoustic attenuation coefficient were measured using the Pulse-Echo method and transmission technique. Optical properties were studied using a single integrating sphere system and the Kubelka-Munk function approach. The results of these studies may provide a foundation for future research on the opto-acoustical characterization of various phantoms.

Keywords. Medical Ultrasonics, Phantoms, Tissue-Mimicking Materials, Zerdine, Agar, Acoustical and Optical Properties.

INTRODUCTION

Materials can be characterized and evaluated based on how they will be used, such as their optical, thermal, mechanical, acoustical, and electrical properties. One specific type of material is called a phantom, which is used as a reference point in medical testing before a procedure is done on a living patient. Phantoms have the benefit of being able to imitate the properties of living tissue and be reused multiple times. Additionally, the use of materials that mimic biological tissue is also very common in the field of biophotonics.

It is crucial to test and evaluate the devices used in ultrasonic imaging and treatment systems to ensure they work safely and correctly. To do this, special materials called phantoms are used. These phantoms are designed to mimic the acoustic properties of the tissue being studied. This allows for performance tests and quality control of medical ultrasonic devices. In order for the measurements to be accurate and reliable, the phantom should have similar acoustic properties as human tissue. Some important physical properties that are measured when characterizing these phantoms include the speed of sound, density, characteristic acoustic impedance, and attenuation coefficient. The most important aspect of developing a phantom for use in ultrasonic imaging device testing is that it meets the standards for acoustic properties as specified in the industry standards [1,2].

Phantoms are essential for testing and evaluating medical ultrasonic imaging devices. According to industry standards such as IEC TS 62791:2015 and IEC 1390, the tissue-mimicking materials used in quality control of ultrasonic devices should have specific acoustic properties, including an ultrasonic sound velocity of (1540 ± 10) m/s and an attenuation coefficient of (0.50 ± 0.04) dB/(cm·MHz) for low attenuation coefficient echo targets and (0.70 ± 0.04) dB/(cm·MHz) for "background" materials [3,4]. These standards ensure that the tests are performed correctly and give accurate results.

When testing and evaluating phantoms, different parameters are examined depending on the type of characterization being performed. Acoustical characterization looks at parameters such as sound velocity, characteristic acoustic impedance, acoustic attenuation coefficient, and acoustic backscatter coefficient. In contrast, optical characterization examines parameters like absorption coefficient, scattering coefficient, and anisotropy factor [5]. While there is a well-established system for acoustical characterization, studies in optical characterization are still relatively new and developing.

The Kubelka-Munk model is a theoretical reflection model that is commonly used in optics. This model assumes that when light passes through a homogeneous sample, some of it is scattered and absorbed in different directions, causing the light to be weakened. The Kubelka-Munk model is a two-stream approach to general radiation transfer theory and it characterizes the spread of upstream and downstream fluxes by scattering and absorption coefficients known as S and K respectively.

This model is widely used for describing the optical properties of luminescent materials. It is one of the simplest and most successful models for predicting the optical properties of particulate films under dispersed illumination from the material's effective absorption and scattering coefficients. It has a wide range of applications in different materials such as paints, pigmented plastics or polymers, decorative and protective coatings, solar-absorbing pigments and paints, human tissue, biological systems, and optical properties. The model assumes that the optical properties of a coating can be described by two constants, the absorption and scattering coefficients [6-9].

In this study, the acoustical and optical properties of two types of phantoms, Zerdine and Agar phantoms,

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were analyzed separately. The acoustical characterization study measured the density, sound velocities, and acoustic attenuation coefficients of the phantoms. The optical characterization study used a single integrating sphere system to measure parameters such as absorbance, transmittance, and reflectance. Additionally, the refractive index and optical linear attenuation coefficient were calculated as macroscopic optical parameters. Microscopic optical properties, such as the absorption coefficient, scattering coefficient, anisotropy factor, reduced scattering coefficient, and penetration depth were determined using the Kubelka-Munk Function approach.

METHODOLOGY

In this study, Zerdine and Agar phantoms are characterized in terms of optical and acoustical methods. In optical characterization, the Pulse-Echo method and transmission technique were utilized while a single integrating sphere system and the Kubelka-Munk function approach were used in the optical characterization. All experiments were performed under controlled laboratory ambient conditions.

PREPARATION OF ZERDINE AND AGAR PHANTOMS

Tissue-Mimicking Materials (TMMs) are materials that are often used in medical research because they are able to mimic the properties of biological soft tissues. In this study, two types of TMMs were used, named Zerdine and Agar. Zerdine phantoms are commonly used as reference materials in quality control of ultrasonic imaging systems, while Agar phantoms are typically used in ultrasonic research. The Zerdine phantom was prepared in a rectangular container using a specific formulation, as specified in a patent by Zerhouni and Rachedine [10]. The Agar phantom was created by mixing 2% Agar and 0.4 M $ZnCl_2$ by weight of the starting water in a cylindrical container [11]. A picture of the Zerdine and Agar phantoms that were tested can be seen in Figure 1.

Fig. 1. A picture of the Zerdine (left) and Agar (right) phantoms under test.

SOUND VELOCITY MEASUREMENT SET-UP

The Puls-Echo method was used to measure sound velocities in this study [1,2]. The experimental setup and equipment connections used for these measurements are illustrated in Figure 2.

The Pulse-Echo method is a technique in which an ultrasonic probe, also called a transducer, is used to both transmit and receive signals. In this method, the probe is placed in contact with the phantom using an impedance matching gel and the signals sent and received by the Pulser/Receiver device are displayed on an oscilloscope screen. The period value between the observed signal peaks is recorded on the oscilloscope screen and the sound velocity is calculated using formulas (1, 2 and 3) as illustrated in Figure 4. It is important to ensure that the thickness of the sample being tested is accurately determined for the method to work correctly.

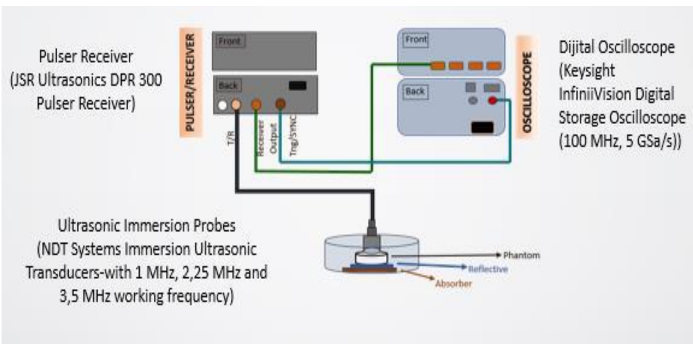

Fig. 2. Experimental setup used to determine ultrasonic sound velocity by using Pulse-Echo method.

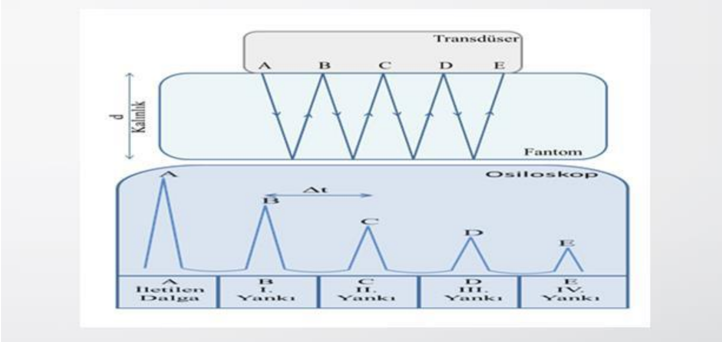

Fig. 3. Echo patterns observed in determining the speed of sound with Pulse-Echo method.

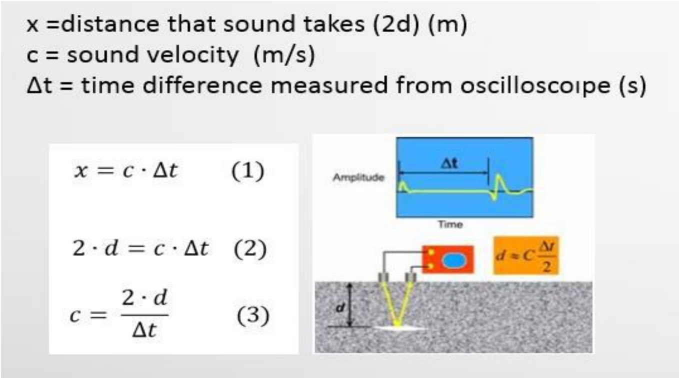

Fig. 4. Sound veocity calculation formulas.

ATTENUATION COEFFICIENT MEASUREMENTS AND SET-UP

The attenuation coefficient is determined using the "transmission" technique [1,2]. In this method, two transducers operating at the same frequency are used to generate and detect the ultrasound signal. The transducers are placed parallel to both surfaces of the sample. The amplitude of the signal that reaches the receiver transducer decreases exponentially, and the attenuation coefficient is calculated by using a specific formula.

$$A = A_0 e^{-\mu x} \qquad (4)$$

The attenuation coefficient is represented by the Greek letter, μ and is measured in units of dB / cm · MHz. It is calculated using the distance (x) in centimeters, the formula is given with the Greek letter μ, and x. The experimental setup used for measuring the attenuation coefficient is illustrated in Figure 5. Every tissue has a unique attenuation coefficient, which is a representation of the decrease in ultrasonic wave amplitude after it reaches the tissue due to absorption, scattering, and conversion of mode.

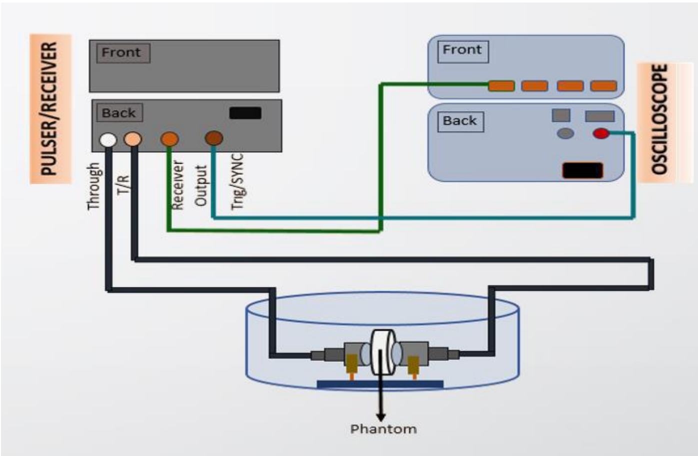

Fig. 5. Experimental setup used for attenuation coefficient measurements.

DENSITY MEASUREMENTS

Density is a measure of how much mass is contained within a certain volume of matter, and it is determined by the equation:

$$\rho = \frac{m}{V} \quad (5)$$

Where; "m" (kg) is the mass and "V" (m^3) is the volume. To determine the density of the phantom samples, the volume and mass were measured, then the density was calculated using the equation above.

ACOUSTIC IMPEDANCE CALCULATIONS

Acoustic impedance is a property of a material that describes how well it transmits sound waves and is denoted by the letter "Z" and calculated by the following equation:

$$Z=\rho \cdot c \quad (6)$$

Where; "ρ" (kg/m^3) is the density, "c" (m/s) is the sound velocity, and "Z" ($(kg/m^2) \cdot s$) is the acoustic impedance. Another unit used for acoustic impedance is Rayl.

OPTICAL MEASUREMENT EQUIPMENTS

A red colored solid-state diode laser with a wavelength of 635 nm, made by Optotronics and model VA-I-400-635, was used as the optical source for the measurements. The maximum working power of the laser was 400 mW. For the measurement of optical power, an Ophir StarBright model optical power meter and an Ophir 3A type thermal sensor were used. The Thorlabs IS200 model 2” integrating sphere was used to measure optical properties such as absorbance, transmittance, reflectance, refractive index and optical linear attenuation coefficient. All the optical measurement equipment used in the experiment are shown in Figure 6.

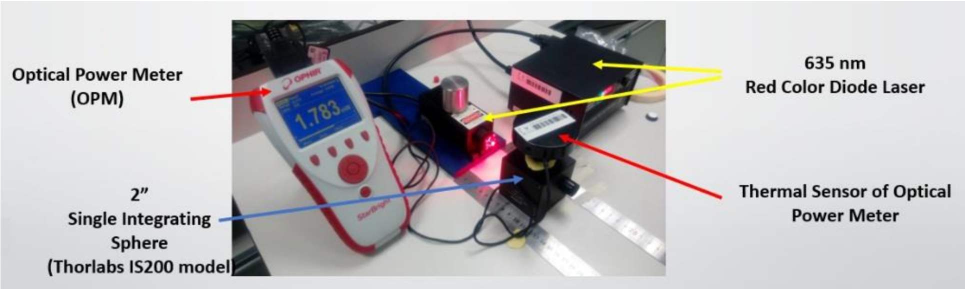

Fig. 6. Optical measurement equipment used in the experiment.

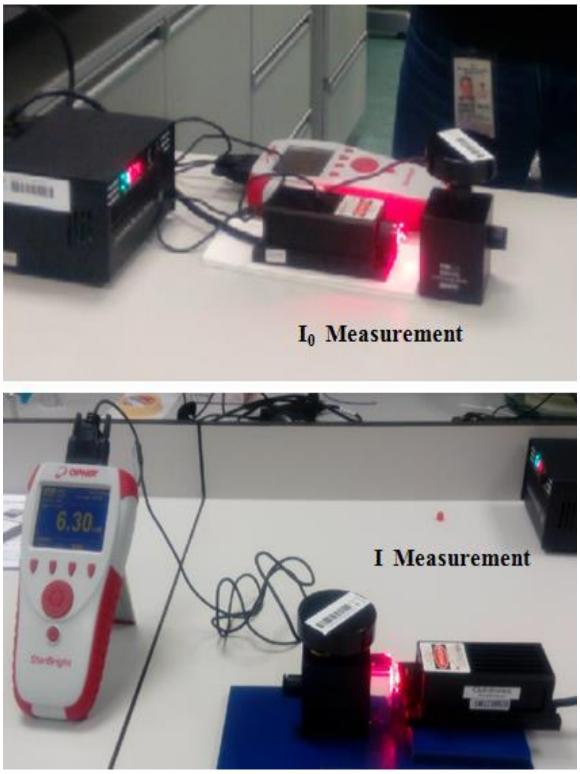

Fig. 7. Optical measurement equipment used in the experiment.

In this study, the single integrating sphere measurement method was used. Figure 7 illustrates the setup of the single integrating sphere experiment used for measuring both optical power and optical properties. The setup involves two measurements, I_o and I measurement. In the I_o measurement, there is no phantom in the system, while in the I measurement, there is a phantom in the system.

CALCULATION OF MACROSCOPIC OPTICAL PROPERTIES

The relevant formulas for macroscopic calculations of absorbance, transmittance, reflectance, refractive index, and optical linear attenuation coefficient can be seen as follows.

$$R+T+A=1 \text{ or } \%R+\%T+\%A=\%100 \quad [12] \qquad (7)$$

Absorbance,

$$A;\ A=-\log(I/I_0)=-\log(T)=2-\log(\%T) \quad [13] \qquad (8)$$

$$\text{Transmittance, } T;\ T=I/I_0 \quad [13] \qquad (9)$$

$$\text{Reflectance, } R;\ R=1-(A+T) \quad [12] \qquad (10)$$

$$\text{Reflectance, } R=\frac{(n-1)^2}{(n+1)^2},\ [12] \qquad (11)$$

where n is the Refractive Index.

$$I=I_0e^{-\mu x},\ \mu=-\frac{\ln\frac{I}{I_0}}{x} \quad [14] \qquad (12)$$

where μ is the Linear Total Attenuation Coefficient.

CALCULATION OF MICROSCOPIC OPTICAL PROPERTIES

The relevant formulas for microscopic calculations of absorption coefficient, scattering coefficient, reduced scattering coefficient, total attenuation coefficient and effective penetration depth are as follows.

The Kubelka-Munk Function is given by

$$F(R)=\frac{(1-R)^2}{2R}=\frac{k}{s},\ [15] \qquad (13)$$

where R = Reflectance, k= Absorption Coefficient, s=Scattering Coefficient.

The total attenuation coefficient is described by

$$\mu=\mu_t=\mu_a+\mu_s\,, \quad [16] \qquad (14)$$

Where μ_a is Absorption Coefficient, and μ_s is Scattering Coefficient.

That is, k=μ_a and s=μ_s can be matched by using (13) and (14) formulas.

The reduced scattering coefficient (μ_s') is defined by the following equation;

$$\mu_s'=(1-g)\mu_s\,, \quad [17] \qquad (15)$$

Where g is the anisotropy factor. The g value of the phantom was fixed at 0.9, which is the anisotropy factor of human tissue in the UV and Near-Infrared spectra.

The effective penetration depth, D_{eff}, is described by the following formula;

$$D_{eff}=\frac{1}{\sqrt{3\mu_a[\mu_a+\mu_s(1-g)}}\,, \quad [18] \qquad (16)$$

RESULTS AND DISCUSSION

Acoustical Characterization Results

The acoustical properties of the tissue-mimicking materials made from Agar and Zerdine ® materials were determined as follows:

Sound Velocity Measurement Results

The Pulse-Eco method was utilized to measure the speed of ultrasonic waves in the materials. The results of the sound velocity measurements, obtained from this method, are presented in Figure 8.

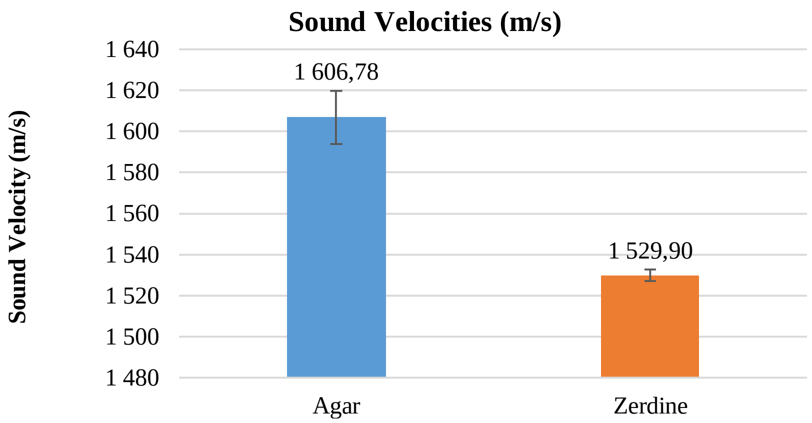

Fig. 8. Sound Velocities of Agar and Zerdine Phantoms.

Attenuation Coefficient Measurement Results

The Transmission technique was employed to measure the attenuation coefficient, which is a measure of how much ultrasonic waves will diminish as they pass through the tissue. The results of the attenuation coefficient measurements, obtained from this method, are shown in Figure 9.

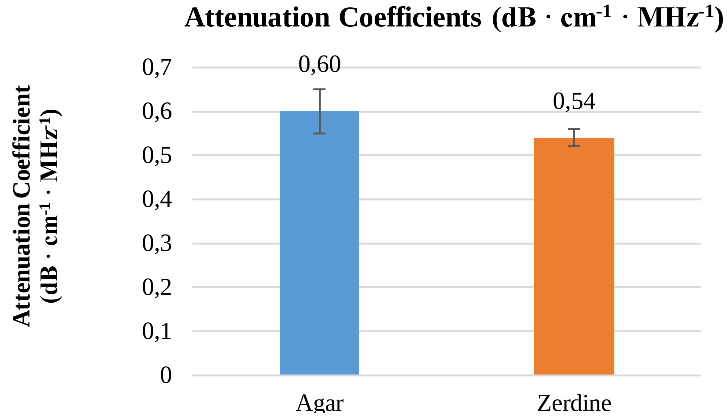

Fig. 9. Attenuation Coefficients of Agar and Zerdine Phantoms.

Density Measurement Results

The densities of the produced phantoms were calculated and are displayed in Figure 10.

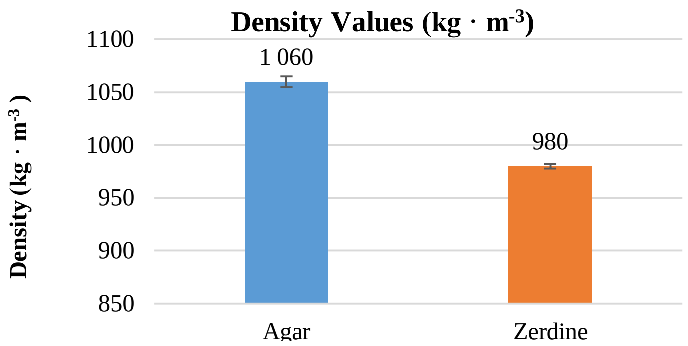

Fig. 10. Densities of Agar and Zerdine Phantoms.

Calculated Acoustic Impedance Values

The densities of the produced phantoms and the acoustic impedance values calculated using the sound velocity measurements are presented in Figure 11. The standard deviations for the acoustic impedance values were found to be very small and thus, are not included in the graph.

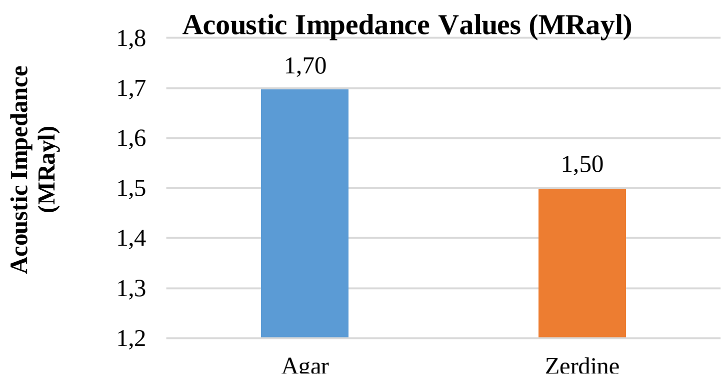

Fig. 11. Calculated Acoustic Impedances of Agar and Zerdine Phantoms

A summary of all the acoustical parameters obtained for the Agar and Zerdine phantoms through this study are presented in Table I.

Table I

Acoustic parameters determined for two different tissue-mimicking materials

TMM	Agar	Zerdine®
Sound Velocity ($m \cdot s^{-1}$)	1606.78 ± 13.00	1529.90 ± 2.86
Attenuation Coefficient ($dB \cdot cm^{-1} \cdot MHz^{-1}$)	0.6 ± 0.05	0.54 ± 0.02
Density ($kg \cdot m^{-3}$)	1060 ± 5	980 ± 2
Acoustic Impedance* (MRayl)	1.696	1.499

* Since the standard deviations calculated for acoustic impedance are very small, they are not given in the table.

Measurement Results of Macroscopic Optical Properties

The macroscopic optical properties, such as absorbance, transmittance, reflectance, refractive index, and attenuation coefficient, of the soft tissue phantoms were measured and calculated using the single integrating sphere test setup as reported in Table II and Table III in a previous study.

Table II

The measured macroscopic optical properties of the Zerdine and Agar phantom as average with the single integrating sphere measurement method

Phantom	Transmittance, T	Absorbance, A	Reflectance, R
Zerdine	0.91 ± 0.03	0.04 ± 0.01	0.05 ± 0.01
Agar	0.44 ± 0.21	0.41 ± 0.27	0.15 ± 0.09

Table III

The calculated macroscopic optical properties of the Zerdine and Agar phantom as average with the single integrating sphere measurement method

Phantom	Refractive Index	Total Attenuation Coefficient (cm^{-1})
Zerdine	1.58 ± 0.08	0.03 ± 0.01
Agar	2.26 ± 0.64	0.91 ± 0.10

Calculations of Microscopic Optical Properties

The microscopic optical properties of the soft tissue phantoms, including the absorption coefficient, scattering coefficient, reduced scattering coefficient, total attenuation coefficient, and effective penetration depth, were determined using the results from the single integrating sphere test setup. The calculated values for these properties are presented in Table IV and Table V.

Table IV

The calculated microscopic optical properties of the Zerdine and Agar phantom as average.

Phantom	Absorption Coefficient, μ_a, cm^{-1}	Scattering Coefficient, μ_s, cm^{-1}	Reduced Scattering Coefficient, μ_s', cm^{-1}
Zerdine	0.025 ± 0.011	0.003 ± 0.001	0.001 ± 0.0004
Agar	0.642 ± 0.074	0.266 ± 0.031	0.053 ± 0.006

Table V
The calculated total attenuation coefficient and effective penetration depth of the Zerdine and Agar phantom as average.

Phantom	Total Attenuation Coefficient, μ_t, cm^{-1}	Effective Penetration Depth, D_{eff}, cm
Zerdine	0.028 ± 0.012	22.655 ± 12.253
Agar	0.908 ± 0.104	0.865 ± 0.101

CONCLUSION

In this research, the acoustical and optical properties of two distinct tissue-mimicking materials, Zerdine and Agar, were studied and characterized. Acoustical properties such as density, sound velocity, and acoustic attenuation coefficient were measured using the Pulse-Echo method and transmission technique. Optical properties were studied using a single integrating sphere system and the Kubelka-Munk function approach. Macroscopic properties such as absorbance, transmittance, reflectance, refractive index, and attenuation coefficient were measured and calculated. Microscopic properties such as absorption coefficient, scattering coefficient, the reduced scattering coefficient, total attenuation coefficient, and effective penetration depth were calculated. The results of these studies provide a foundation for future research on the characterization of various phantoms.

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