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Precisely evaluation of temperature influence on artificial blood phantom properties made of polymers using ultrasound signals

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ABSTRACT

Purpose: The study aims to evaluate precisely influence of temperature on the acoustical and physical properties of blood mimicking fluid (BMF) phantom made of polymer material.

Materials & methods: Propylene glycol (PG) and polyethylene glycol (PEG) were fabricated to create artificial blood phantom. Acoustic (speed and attenuation) and physical properties (density and viscosity) of BMF were tested at specific temperatures of range 22 °C, 25 °C, 35 °C, 36 °C, and 37 °C using ultrasound signals.

Results: At center frequency of 5 MHz, pulse-echo allows to acoustical (speed and attenuation) and physical (density and viscosity) values to be linearly decreased with increasing of temperature. The difference in values of speed, attenuation, density, and viscosity was nuance (±0.01, ±0.001, ±0.005, and ±0.151), respectively.

Conclusions: Temperature test of range 22C°-37C° have nuance influence (±0.01, ±0.001, ±0.005, and ±0.151) on acoustical and physical properties when BMF phantom of special material of PG and PEG was used. This nuance influence may be taken in account in quality assurance of ultrasound imaging system.

Keywords: temperature, acoustical, physical, propylene glycol, polyethylene glycol, ultrasound

INTRODUCTION

Blood is known to be one of the connective tissues in the human body, as the blood connects every single cell, tissue, and organ in the body together. Blood is a vital fluid that transports oxygen, carbon dioxide, nutrients, and waste to the body's cells. The heart's performance as a pump is efficient in transporting blood into the vasculature throughout the body. The efficient flow of blood is required for the elasticity of blood vessels and the prevention of cardiovascular disease. Previous research demonstrated that blood and its properties could be studied using computer simulations or in vitro studies [1].

Applying Doppler ultrasound mechanism for measuring the blood in vessels relies on the variation of ultrasound frequency waves, which are reflected from movable scattered particles of blood [2, 3]. The frequency shift or Doppler shift increased with increasing the speed of blood [4]. The implementation of Doppler medical ultrasound equipment can be estimated with various test object [5, 6]. Tissue-mimicking material (TMM) and artificial blood should have similar acoustic and physical properties to human tissue and blood to make the examination more meaningful [7]. In this study, blood mimicking fluid (BMF) was created in order to precisely determine the effect of temperature on the acoustical and physical properties of BMF.

The acoustic and physical properties values of artificial blood must equal the constant values defined in the International Electrotechnical Commission (IEC) standards [8]. The properties of human blood vary from normal to abnormal [9]. The values of acoustical and physical properties are necessary to specify the compatibility and validation of examined items as artificial blood. Artificial blood is a mixture of items that simulate the acoustical and physical properties of human blood [10-16]. The liquid glycols are the most commonly used items as a mixed fluid of artificial blood [13].

Phantoms can be fabricated from any material that simulates human tissues with relevant physical properties. A phantom must have a similar mass density to those of simulated human tissues [10]. Because of their varying electron densities, effective atomic numbers, and mass densities, polymers are ideal materials for phantom device fabrication [13]. Particle phantom material density should be as close to human blood density as possible, which is between 1.01 g/cm^3 and 1.09 g/cm^3 for IEC values [11]. Because it is critical to remain neutrally buoyant, even at low speeds, particle materials used in BMF preparation must be able to remain suspended (not float or precipitate) inside a mixture fluid (liquid) [17, 18]. To avoid refraction artifacts, the acoustic speed in BMF should be identical or within the same ranges as in the tubes and TMM [19]. The refraction artifacts can be noticed when using tubes with a high velocity of sound [20].

MATERIALS & METHODS

Sample Preparation

Speed, attenuation, viscosity, and density of a mixture fluid were measured at different temperatures using an ultrasonic German Society for Applied Medical Physics and Technology (GAMPT) technique, a viscometer, and a density meter (DM). For speed of sound, pulse-echo (PE) method was used. PE method can determine the time between two maximum peaks of the transmitted sound wave through the depth of the mixture. All measurements for the acoustical and physical properties are repeated three times. The achieved results were compared with IEC standard values to emphasize their compatibility and validation. Synthetic blood formation is useful vital for several studies' such as, physical blood properties including velocity, viscosity, bleeding, and clotting. Hence, artificial blood phantom was fabricated. The phantom of polymer was created to test its own acoustical and physical properties under different temperature conditions.

Seven samples made of a mixture solution contain of propylene glycol (PG) and polyethylene glycol (PEG). BMF was prepared by mixing the required amount of mixture components-based of weight (%): pure water 85.5%, PG 4.5%, PEG 10.0%. These samples were continually stirred on a magnetic stirrer until the mixture becomes homogenous. This mixture was removed from the beaker from the magnetic stirrer and poured into a rectangular and circular acrylic shaped mold [8]. Plastic beaker with double size of the mixture was used to avoid overflow of the components during stirring. This plastic beaker was cleaned with plenty of distilled water. A magnetic stirrer rod was placed in the cleaned plastic beaker. The diameter of a plastic beaker is seven cm and magnetic stirrer rod of two cm. The mixture components in each sample were weighted. PG and PEG with a fume hood poured into the plastic beaker. At temperature of 37±0.7 °C, the beaker was placed on the stirrer plate to allow the components stirring long 15 minutes, whereby the stirrer plate rotates 700 rounds per minute. A vacuum pump device was used to degas the fluid mixture long 30 minutes. At temperature of (22 °C, 25 °C, 35 °C, and 36 °C), each sample was examined in order to determine influence of the temperature on the acoustical and physical properties.

The acoustical and physical properties values for materials components were 99.0% pure supplied by Sigma-Aldrich. In addition, PG and PEG were also supplied with suitable densities and molecular weight by Sigma-Aldrich.

Experimental Setup

The acoustical and physical properties measurement system utilizes the ultrasonic GAMPT technique. The echoscope was switched on after being connected with the PC. The front panel of the device (function generator) was controlled and examined. The function generator supplied the electrical signal to send and receive ultrasound echo pulses.

In this study, PE (A-scan) mode, in the same probe, sends concise ultrasound pulses as an echo signal. The amplification of the transmission signal can be set. Thus, a low value of transmitter power until 80.0% of the highest amplitude of the signal peak was selected, as shown in **Figure 1** [19].

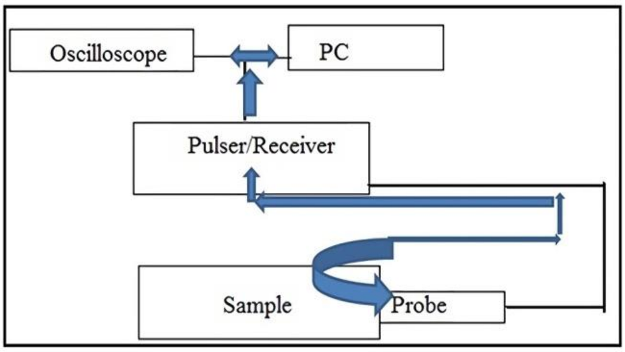

Figure 1. Schematic diagram of acoustic properties measurement system (Source: Authors' own elaboration)

Numerous samples were prepared and characterized, but only the optimum samples were chosen. These samples made from special polymer of PG and PEG. The samples tested using specific temperatures of range 22 °C-37 °C then adjusted in order to evaluate influence of the temperature on the acoustical and physical properties. The measurements in the experiment for the speed, attenuation, density, and viscosity.

Acoustic Features

The typical formula for determining the speed of ultrasound using PE method was displayed in Eq. (1):

$$SS = \frac{2l}{t}, \quad (1)$$

where *SS* is speed of the sound, *l* is the thickness of the mixture, and *t* is the time of flight (ToF).

GAMPT technique and PE method were used for determining ultrasonic signal. Ultrasonic signal waves can be determined when ToF measured between two identical peaks of signals pulses, as shown in **Figure 2**.

For attenuation measurements, the frequency-based attenuation of the individual signal was measured by preceding a fast fourier transform. The value of PE techniques (A-scan system) in dB unit was determined to calculate the attenuation coefficient (α) of the mixture. This attenuation can be calculated by the natural (*ln*) difference in amplitude of transmitted signal waves, as shown in Eq. (2):

$$\alpha = \frac{1}{x1-x2} \ln \frac{A2}{A1}, \quad (2)$$

where *x1-x2* is the depth of sample in *mm* unit. *A1* is the power signal amplitude at frequency (*f*) and (*x, y*) position of reference signal with no presence sample (amplitude of transmitted signal wave). *A2* is the amplitude of received signal wave at *f* and (*x, y*) position through the sample.

Physical Features

The density g/ml of the mixture at different temperature was measured by an electronic instrument called DM (DMA35). DMA35 accurately can measure density of mixture with uncertainty ±0.01 g/ml. Electronic rotational viscometer was used to determine the dynamic viscosity (mPa.s) of mixture.

RESULTS

The results obtained under influences of temperatures, as shown in **Table 1**. The density, speed, viscosity, and attenuation were changed with specific temperature degree.

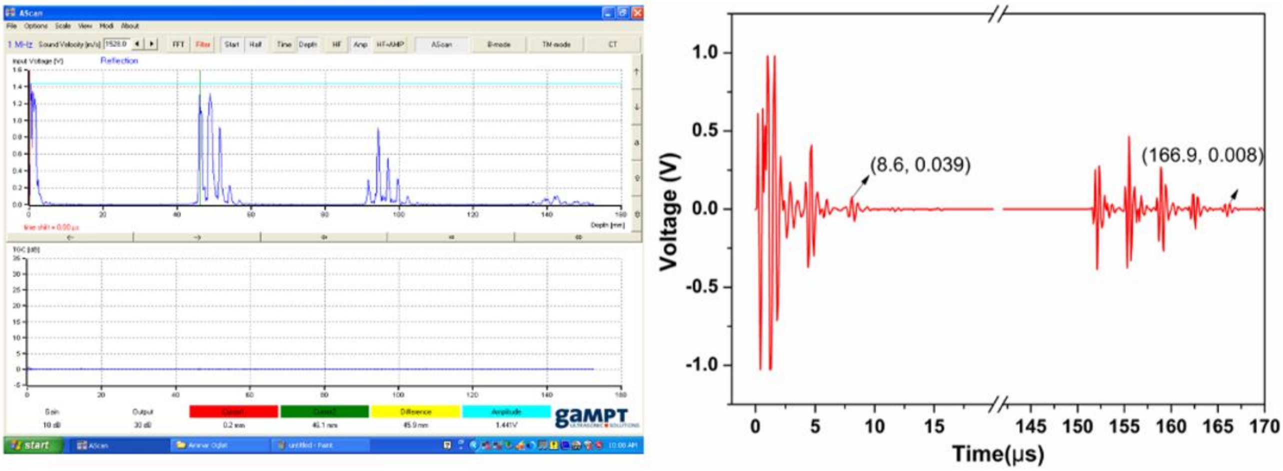

Figure 2. Ultrasonic signals used GAMPT ultrasonic technique (Source: Authors' own elaboration)

Table 1. Physical & acoustic properties values of BMF* at different temperatures

Temperature (°C)	Density (g/ml)	Speed (cm/s)	Viscosity (mPa.s)	Attenuation coefficient (Db/MHz)	Standard deviation
22	1.039	15.83	7.435	0.059	0.047
25	1.039	15.83	7.435	0.059	0.047
35	1.036	15.82	7.435	0.058	0.046
36	1.035	15.82	7.335	0.058	0.046
37	1.034	15.81	7.284	0.058	0.046

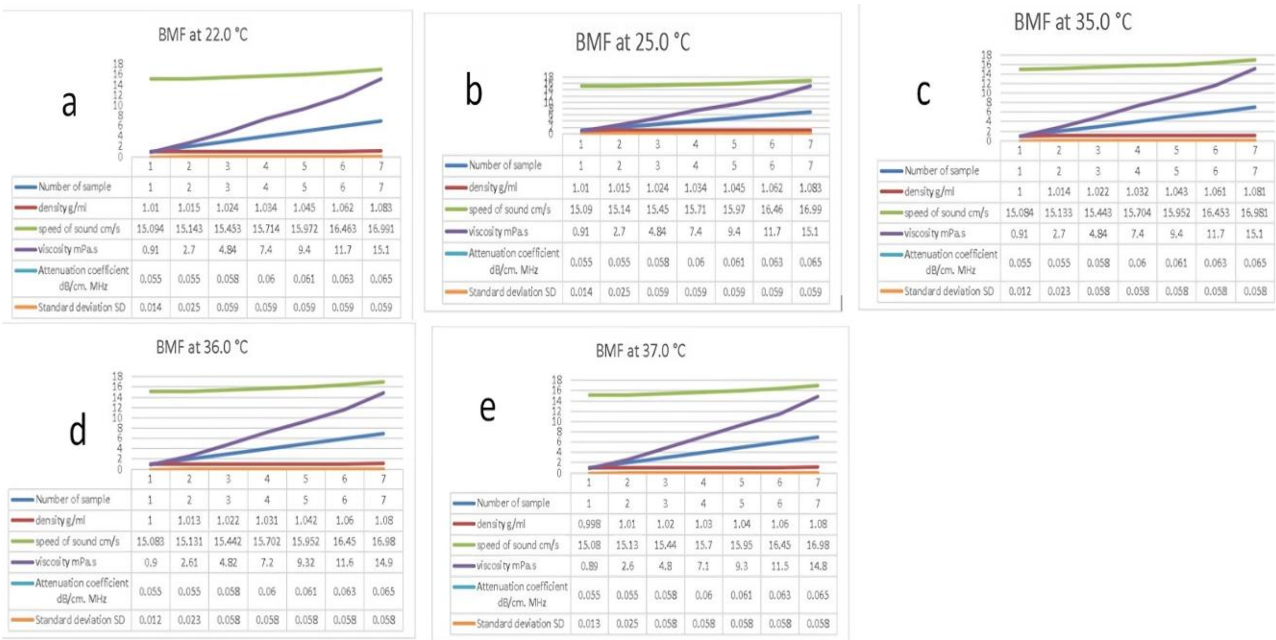

Figure 3. Acoustic & physical values of BMF mixture at 22 °C, 25 °C , 35 °C , 36 °C , & 37°C (Source: Authors' own elaboration)

Acquired results showed relationship of influences of temperatures on acoustical and physical properties in terms density, speed of sound, viscosity, and attenuation coefficient, as shown in (**Figure 3**). The mean value for density, sound speed, viscosity, and attenuation coefficient were calculated using samples of mixture and relationship between acoustical and temperature.

Investigations are made on the connections between the temperatures, densities, speeds, viscosities, and attenuation. The specified BMF, IEC requirements, and human blood all exhibit great correspondence and similar acoustical and physical qualities to BMF* mixture (**Table 2**). It was observed that the outcomes resemble human blood remarkably well and that a nylon-based perfect BMF is produced [11]. Viscosity of real blood was seen of 3.000 mPa.s whereas 4.100 mPa.s and 7.284 mPa.s for BMF of nylon and BMF*, respectively. This contrast in values related to Newton Law of viscosity, which described viscosity as a simple linear relation between shear stress [mPa] and shear rate [1/s].

Viscosity of human blood is non-Newtonian fluid in-vivo, but BMF is considered Newtonian fluid in-vitro [21]. Newtonian fluids are fluids that show a fixed viscosity and do not depend on the flow rate compared to non-Newtonian fluids. Also, the viscosities of fluid types relied on their molecular weight [14].

Figure 4, **Figure 5**, **Figure 6**, and **Figure 7** showed correlations of temperature influence to mean value of density,

Table 2. Physical & acoustic properties values of recommended BMF & human blood compared to BMF*

	Density (g/ml)	Speed (cm/sec)	Viscosity (mPa.s)	Attenuation coefficient (Db/MH₂) (g/cm³)
IEC1685 specification	1.050	15.70	4	<0.100
Human blood at 37 °C	1.053	15.83	3	0.150
BMF of nylon at 22 °C	1.037	15.48	4.100	0.050
BMF* at 22 °C	1.034	15.83	7.435	0.059
BMF* at 37 °C	1.034	15.81	7.284	0.058

Note. BMF*: Mixture of propylene glycol & polyethylene glycol

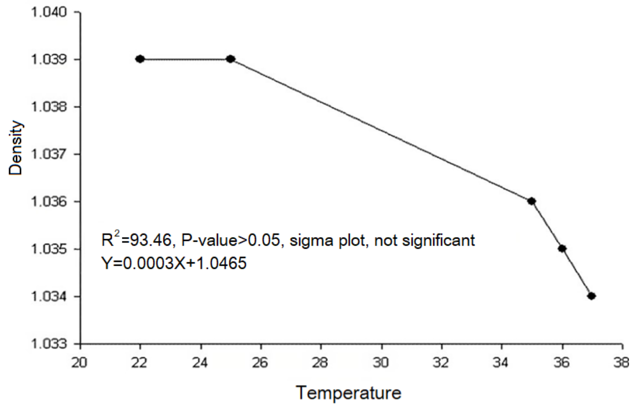

Figure 4. Relationship between density of mixture & temperature (Source: Authors' own elaboration)

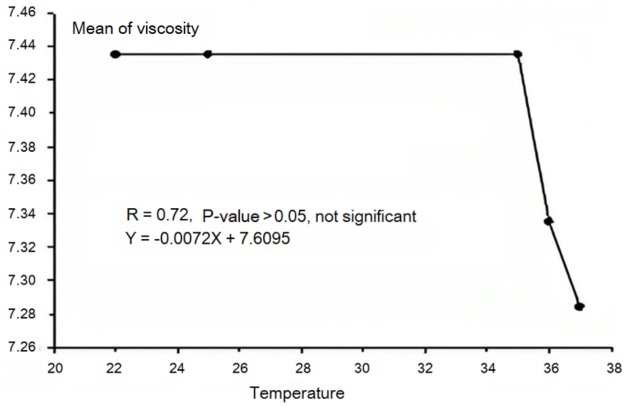

Figure 6. Relationship between viscosity of mixture & temperature (Source: Authors' own elaboration)

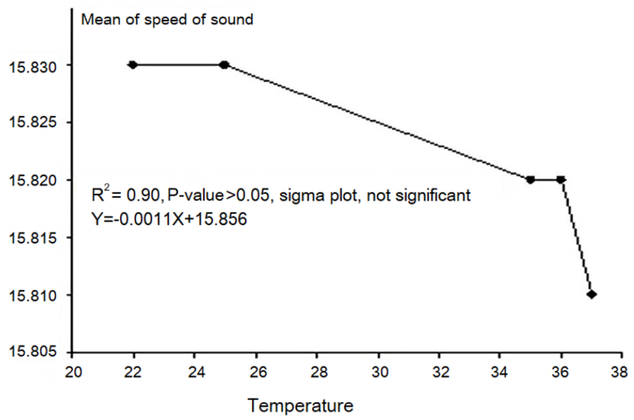

Figure 5. Relationship between speed of sound of mixture & temperature (Source: Authors' own elaboration)

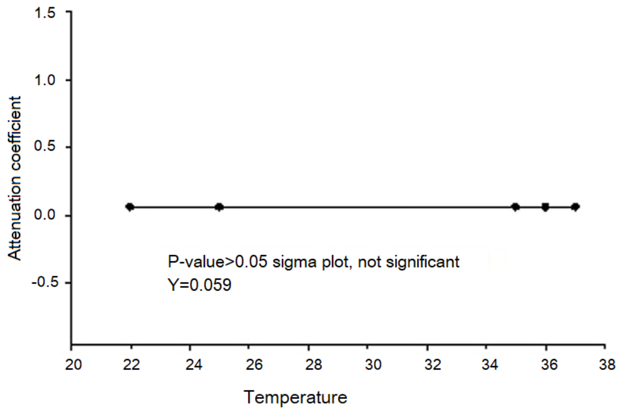

Figure 7. Relationship between attenuation of mixture & temperature (Source: Authors' own elaboration)

speed of sound, viscosity, and attenuation coefficient, respectively. These correlations showed the following R^2: $R^2_{22\,°C}$=0.93, $R^2_{35\,°C}$=90, $R^2_{36\,°C}$=0.72, and $R^2_{37\,°C}$=0.00 when the mixture was influenced at different temperature degrees of 22 °C, 25 °C, 35 °C, 36 °C, and 37 °C, respectively.

Figure 4, **Figure 5**, **Figure 6**, and **Figure 7** show separately relationships between temperature and density, speed, viscosity, and attenuation coefficient of the mixture, respectively. **Figure 4**, **Figure 5**, and **Figure 6** show that when temperature rises, density, speed, and viscosity all decrease.

The values of the acoustical and physical parameters show that there is no significant temperature change (p>0.05, sigma plot). The temperature (22+3 °C) had the least impact on these values, whereas 37 °C had the most.

Furthermore, it was found that changing the temperature had little effect on the attenuation coefficient. This fact is well illustrated in **Figure 7** since attenuation characteristics depend on both the material's properties and the frequency and amplitude of the signal wave [20]. But, as the temperature rises, the ultrasonic energy of the molecules in the mixture may weaken to a greater extent. Therefore, it can be said that ultrasonic absorption via material is the principal cause of ultrasonic attenuation under the influence of temperature. Since the attenuation in a genuine blood study is negligible (0.9 dB cm1 at 3.5 MHz), the attenuation is not significant in blood analogue [17].

Findings revealed subtle differences in the mean values for density, sound speed, viscosity, and temperature-dependent attenuation. the attenuation of BMF is directly proportional to the density of the mixture and this density become decreased (1.039 to 1.034) when the temperature increase from range 22 °C-25 °C to 35 °C-37 °C. in similarity, the speed of the sound decreased with increasing of the temperature matching with results that high-density of the medium attenuate the sound more than low-density of the tissues [22].

Since the average kinetic energy of the molecules is directly related to temperature, this nuance grew as the temperature rose from 22 °C to 37 °C, being 0.005, 0.010, 0.151, and 0.001, respectively. This kinetic energy causes the mixture's molecules to vibrate more as a result of an increase in atom amplitude. The findings demonstrated that as temperature rose, molecules' densities decreased, and their sizes expanded in accordance with their energy (**Figure 4**). The findings agree with the idea that blood flow will become more turbulent if speed, diameter, density, or viscosity change [23]. It was shown that when temperature dropped from 37 °C to 22 °C, the viscosity of the results produced fell by 2.0% (7.284-7.435). Even though the data indicated that there had been no appreciable change in the values of the acoustical and physical qualities, they were inversely proportional to temperature.

Phantoms are used for QA and specific anatomical likeness. To accurately reflect real clinical attenuation conditions, this phantom needs to be constructed as tissue-equivalent materials. Due to the lack of attenuation media, motion blur, and a physiological assessment that was not approximated, BMF phantom could not be extended to genuine clinical research.

CONCLUSIONS

The nuance influence of the temperature of range 22 °C-37 °C on physical and acoustical BMF-polymer phantom was precisely evaluated. This precise evaluation is novel and important in ultrasound examination for BMF-phantom made of PG and PEG.

Author contributions: MAS: preparation & writing initial draft of manuscript, editing, proofreading, arrange data as a scientific article, response to reviewers, corrections in whole manuscript, & proof correction; **AAO:** ideas, conceptualization, methodology, resources, software, validation, & visualization; **MZJ:** supervision & project administration; **AAK:** editing, proofreading, & application of statistical mathematics; & **MA:** synthesizing study data & revision. All authors have agreed with the results and conclusions.

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Ethical statement: The authors stated that the study does not require any ethical approval since the research used vitro experiment/phantom not vivo experiment/patients or animals. Informed consents were obtained from the participants.

Declaration of interest: No conflict of interest is declared by authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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