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Metrological evaluation of ultrasonic velocity in oils for commercial phantom development

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Abstract. This study focuses on the metrological evaluation of ultrasonic velocity in materials to develop Tissue Mimicking Materials (TMM). TMMs are essential for assessing ultrasound equipment performance, safety, technical assessment, and studying the biological effects of ultrasound. Agar-based TMMs are commonly used but have limited durability, necessitating the development of commercially viable alternatives. Oil-based TMMs, such as mineral and lubricating, show promise due to their stability and favourable characteristics. The study aims to characterize the ultrasonic properties of oil-based materials, aiming to produce a stable TMM suitable for the transportation and evaluation of ultrasound diagnostic equipment. The results for each material were as follows: ethylene glycol (1727.0 + 4.6) m s^{-1}, mineral oil (1397.0 + 5.7) m s^{-1}, and lubricating oil (1472.0 + 4.7) m s^{-1}. Thus, mineral oil and lubricating oil are the most suitable materials.

1. Introduction

Tissue Mimicking Materials (TMM) play an essential role in performance evaluation, safety and calibration of ultrasonic diagnostic and therapy equipment, as well as in studies of biological effects caused by ultrasound [1]. They are used to simulate ultrasonic properties of soft tissue such as velocity, attenuation coefficient, backscattering coefficient, and nonlinearity parameter [2]. There are several materials that mimic soft tissues, such as those based on agarose, gelatin, phytagel, and zerdine [3], among others. Soft tissues comprise muscles, tendons, ligaments, fascia, fat, fibrous tissue, synovial membranes, nerves, and blood vessels [4][5].

The technical standard IEC 60601-2-37 [6] describes the specific basic safety and essential performance requirements for ultrasonic diagnostic equipment. The recommended ultrasonic speed for the TMM is 1,540 m s^{-1} estimated at a single frequency of 3 MHz [6].

Agar-based TMM is widely used and is mainly composed of glycerin, deionized water, benzalkonium chloride, silicon carbide, aluminium oxide, and agar [6][7]. According to [4], when stored properly, its properties remain stable for up to two and a half years. However, when used routinely in the laboratory without the necessary care, its durability is limited to less than a month due to bacteria proliferation or damage to its structure. Therefore, TMM made of that, or similar materials are unsuitable for long-term use and frequent moves.

Considering this, the need arises to produce TMM that can be commercialized. There are commercially available TMMs, such as Zerdine, which is hydrogel-based (CIRS Inc., Norfolk, CT, USA), condensed milk-based gel (Gammex RMI, Middleton, WI, USA) and a urethane rubber-based simulator (ATS Labs, St. Paul, MN, USA). Browne et al. [8] conducted a study on the acoustic properties of these materials, such as velocity and attenuation coefficient, over a frequency range of 2.25 to 15 MHz and at different ambient temperatures, from 10 to 35 °C. The study found that the agar-based material showed a linear increase in attenuation, indicating its sensitivity to frequency and temperature variation.

Oil-based tissue-mimicking materials (TMMs) have been used for this type of evaluation. Kondo et al. [9] evaluated an ethylene glycol-based TMM. They found that oils are favourable because bacteria do not propagate in them, and their organic liquids tend to remain stable without evaporating over time. Pavan et al. [10] investigated different ultrasound TMM materials, such as SEBS polymer mixed with mineral oil, gel paraffin, wax gel, and ballistic gel, which exhibited superior temporal stability compared to commonly used hydrogels. These materials are being explored as tissue substitutes for ultrasound imaging in various applications and complex anatomical structures due to their similar physical characteristics, including thermoplasticity, optical translucency, elasticity, and acoustic properties.

This study aims to characterize the ultrasonic properties of oil-based materials, such as mineral oil, lubricating oil, and ethylene glycol, to produce a tissue mimetic material (TMM) that maintains its properties stable over time and is suitable for transportation and evaluation of ultrasound diagnostic equipment.

2. Materials and Methods

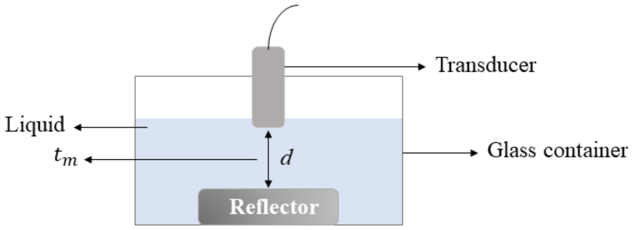
2.1. Mathematical model of the ultrasonic velocity in the analyzed materials

The ultrasonic velocity of the liquid (v_l) is determined by Equation 1:

$$v_m = \frac{2.d}{t_m} \tag{1}$$

Where t_m is the time of flight (ToF) in the material, and d is the distance between the transducer surface and the reflecting target. Figure 1 shows the measurement scheme:

Figure 1. Experimental setup (adapted from [14]).



The distance d is previously determined using the same measurement scheme, with deionized water as the reference medium.

$$d = v_w.\frac{t_w}{2} \tag{2}$$

Where, t_w is the ToF in water and v_w is the US propagation velocity in the water. Equation 3 reveals the Speed of Sound (SoS) as a function of the water temperature (T) [11]:

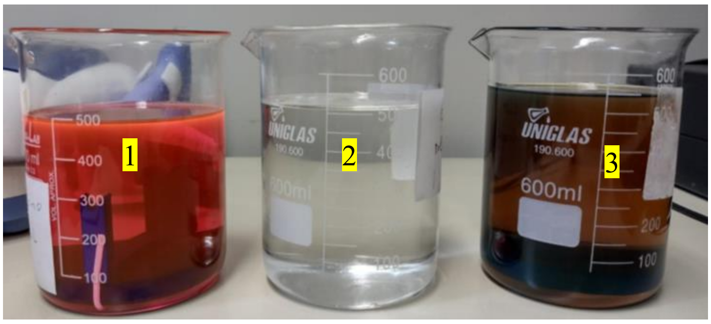
$$v_w = 1405.03 + 4.624 \cdot T - 3.83 \cdot 10^{-2} \cdot T^2 \tag{3}$$

The maximal error of Equation 3, reported by [11], was considered in the present study as an uncertainty source (0.18 m s^{-1}).

2.2. *Samples used*

Ethylene glycol, mineral oil, and lubricating oil samples were used, as shown in Figure 2. The samples were stored in 600 mL beakers.

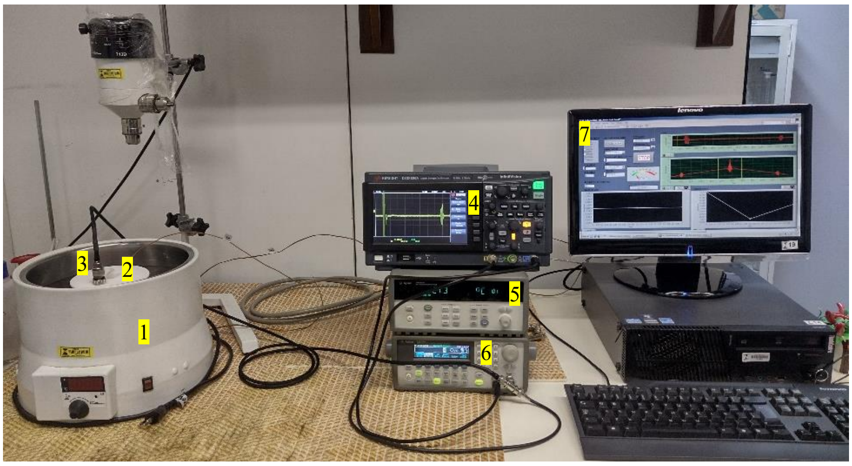
Figure 2. Samples used. (1) Ethylene glycol, (2) mineral oil, and (3) lubricating oil.



2.3. *Measurement procedure*

The pulse-echo measurement technique [12] was used. The measurement system is composed of a thermal bath model 557 (Fisatom, Brazil) filled with deionized water at room temperature, a glass container with the sample, a 5 MHz centre frequency transducer (Olympus - USA, model V309), oscilloscope (Keysight - USA, Model DSOX 1202A), a thermocouple type K and temperature measurement system (Agilent Technologies - USA, Model 34970A), a signal generator (Agilent Technologies - USA, Model 33250A) and the software for data acquisition developed in LabView™ (National Instruments, Austin, TX, USA) (Figure 3).

Figure 3. Characterization of the ultrasonic velocity of the analyzed materials. 1: thermal controlled water-bath; 2: sample; 3: transducer; 4: oscilloscope; 5: temperature measurement system; 6: signal generator; 7: software.



2.4. *Measurement uncertainty*

Measurement uncertainty is defined as a non-negative parameter that is associated with the measurement result and characterizes the dispersion of values that can be reasonably attributed to a measurand. Here, it is calculated according to the Guide of the Expression of Uncertainty in Measurements [13]. Ten repetitions of three readings of flight time and temperature were taken. The statistical analysis was performed from the average of ten repetitions of each measured and calculated quantity.

The uncertainty analysis includes consideration of Type A and Type B uncertainty components. The Type A evaluation consists of the number of times of flight, temperature, and velocity measurements. The Type B evaluation includes the measurement uncertainty of the oscilloscope for measuring the time of flight in liquid (0.024 %), the uncertainty stated in the temperature measurement system certificate (U = 0.09 °C, p = 0.95, k = 2), the measurement uncertainty of the distance between the transducer surface and the reflecting target surface (2.7396×10^{-5} m) and the measurement uncertainty of the velocity equation as a function of temperature (0.18 $\mathrm{m.s^{-1}}$).

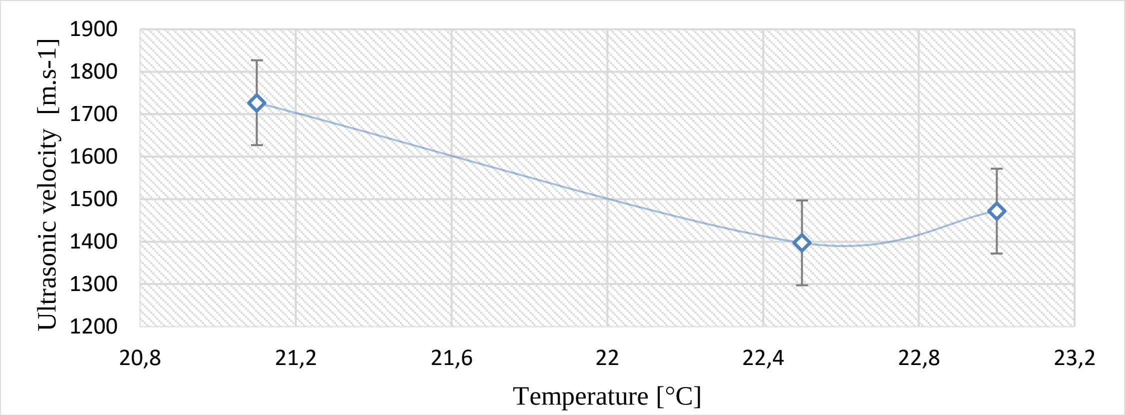
3. Results

The measurement results of the speed of sound in materials, with their respective uncertainties, are shown in Table 1.

Table 1. Ultrasonic velocity results for each material with their respective expanded uncertainties (p = 0.95).

Material	Temperature [°C]	SoS [m s^{-1}]	Combined Uncertainty [m s^{-1}]	Coverage Factor (k)	Expanded uncertainty [m s^{-1}]
Ethylene glycol	21.1	1,727.0	2.35	1.96	4.6
Mineral oil	22.5	1,397.1	2.89	1.96	5.7
Lubricating oil	23.0	1,471.8	2.39	1.96	4.7

Graphic 1. The ultrasonic velocity of each material as a function of temperature. The bars indicate expanded uncertainty.



4. Discussion and Conclusion

This study revealed which materials have an ultrasonic velocity closest to the reference value established by the standard IEC 60601-2-37 [6]. The standout materials in this regard were mineral oil and lubricant, with respective velocities of (1,397.1 + 5.7) m s^{-1} and (1,471.8 + 4.7) m s^{-1}, which are close to the value defined by the standard [6].

This finding is significant as it contributes to advancing research and developing more efficient Tissue Mimicking Materials (TMM). An improved TMM will have an extended lifespan and can be commercially utilized by ultrasound diagnostic equipment evaluation companies.

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