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Metrological evaluation of speed of sound in oils for commercial phantom development

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ABSTRACT
This study presents a metrological evaluation of speed of sound in oil-based materials, aiming to support the development of Tissue Mimicking Materials (TMM) for the performance assessment of diagnostic ultrasonic equipment. While traditional agar-based TMMs are commonly used, their limited durability and stability highlight the need for alternative materials with improved transportability and long-term consistency. In this context, mineral oil, lubricating oil, and ethylene glycol were characterized for their ultrasonic properties. Measurements were carried out using a pulse-echo ultrasonic setup with submerged transducers, under controlled temperature conditions. The speed of sound was determined based on time-of-flight data, and the associated measurement uncertainties were evaluated following the Guide to the Expression of Uncertainty in Measurement (GUM). The measured ultrasonic velocities for each material were as follows: ethylene glycol at (1727.0 ± 4.6) m s^{-1}, mineral oil at (1397.0 ± 5.7) m s^{-1}, and lubricating oil at (1472.0 ± 4.7) m s^{-1}. Among the tested materials, mineral and lubricating oils demonstrated the most suitable acoustic behaviour and are therefore strong candidates for use in the development of stable and transportable oil-based phantoms.

Section: RESEARCH PAPER

Keywords: Metrological assessment; oil-based phantoms; tissue-mimicking materials; ultrasonic properties; ultrasound diagnostic equipment

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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]. These materials are used to simulate ultrasonic properties of soft tissue, such as velocity, attenuation coefficient, backscattering coefficient, and nonlinearity parameter [2]. Several materials mimic soft tissues, such as those based on agarose, gelatine, phytagel, and Zerdine [2], among others. Soft tissues comprise muscles, tendons, ligaments, fascia, fat, fibrous tissue, synovial membranes, nerves, and blood vessels [4], [5]

The international standards IEC 60602-3-5 [6] and IEC 60601-2-37 [7] describe specific requirements and tests for the safety and performance of ultrasonic physiotherapy equipment and ultrasonic diagnostic equipment, respectively. Both standards recommend the use of TMMs that mimic the thermal and acoustic properties of human soft tissues. The recommended ultrasonic speed for the TMM is 1,540 m s^{-1}, estimated at a single frequency of 3 MHz [6], [7].

Agar-based TMMs are commonly used in ultrasonic applications and are typically composed of 11.21 % glycerine, 82.95 % deionized water, 0.47 % benzalkonium chloride, 0.53 % silicon carbide, 0.88 % aluminium oxide (0.3 µm), 0.94 % aluminium oxide (3 µm), and 3.08 % agar [7], [8]. According to [4], when stored properly, these materials remain stable for up to two and a half years. However, when used routinely in the laboratory without the adequate care, their durability decreases to less than a month due to bacteria proliferation or structural damage. Therefore, TMMs made from these or similar materials are unsuitable for long-term use and frequent moves.

Considering this, there is a need to produce TMMs that are suitable for commercialization. Some commercially available TMMs included Zerdine, a hydrogel-based material (CIRS Inc., Norfolk, CT, USA), a condensed milk-based gel (Gammex RMI, Middleton, WI, USA), and a urethane rubber-based simulator (ATS Labs, St. Paul, MN, USA). Browne et al. [9] 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.

In response to these challenges, oil-based materials have emerged as promising candidates for more robust and durable TMMs. Kondo et al. [10] evaluated a TMM formulation based on ethylene glycol and reported that oils offer intrinsic advantages, such as resistance to bacterial growth and high chemical stability, minimizing evaporation over time. Subsequent studies, such as that by Cabrelli et al. [11], validated the use of SEBS copolymers dispersed in mineral oil, showing controllable acoustic properties and compatibility with soft tissue characteristics, including speed of sound between 1423 m s^{-1} and 1502 m s^{-1}. Recent reviews support these findings; Pavan et al. [12] and Jawli et al. [13] identified a growing trend in the use of polymeric and oil-based materials – such as SEBS, paraffin gel, and PVA due to their thermal stability, acoustic compatibility, and suitability for medium- and long-term applications.

In this context, the present study seeks to characterize the speed of sound of oil-based materials, such as mineral oil, lubricating oil, and ethylene glycol, with the objective of assessing their feasibility for use in the fabrication of tissue-mimicking materials that combine long-term stability, ease of transport, and acoustic fidelity suitable for the evaluation and calibration of ultrasonic diagnostic systems.

2. MATERIALS AND METHODS

2.1. Modelling speed of sound: Mathematical approach for the selected materials

The speed of sound of the liquid (v_l) is determined by equation (1):

$$v_\mathrm{l} = \frac{2 \cdot d}{t_\mathrm{m}}, \tag{1}$$

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.

The distance d is previously determined by equation (2) using the same measurement scheme, with deionized water as the reference medium.

$$d = v_\mathrm{w} \cdot \frac{t_\mathrm{w}}{2}, \tag{2}$$

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) [14]:

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

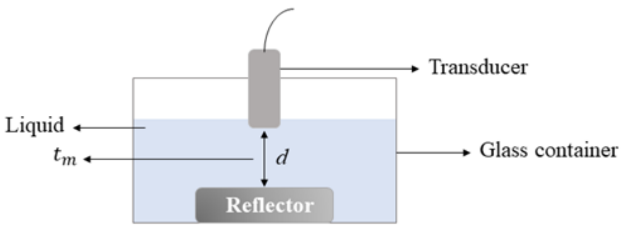

Figure 1. Experimental setup (adapted from [17]).

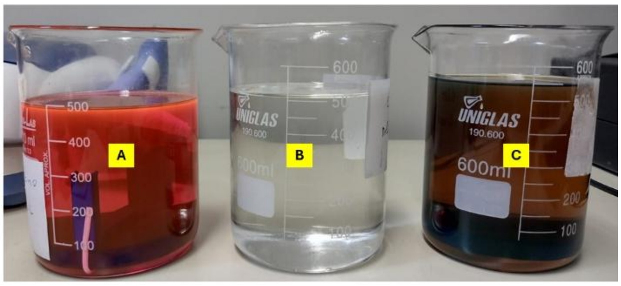

Figure 2. Samples used: A) Ethylene glycol, B) mineral oil, and C) lubricating oil.

The maximum deviation of Equation (3) from experimental data, reported by [14] as $\pm$ 0.18 m s^{-1}, was considered in this study as a type B standard uncertainty component associated with the propagation model. This value was included in the combined uncertainty budget for the calculation of the speed of sound in the test materials, following the principles of uncertainty propagation outlined in the GUM.

2.2. Samples used

Samples of ethylene glycol (Probil, Nova Iguaçu, Brazil), mineral oil (Isofar, Duque de Caxias, Brazil), and lubricating oil (Lubrax, Rio de Janeiro, Brazil) were used, as illustrated in Figure 2. Each substance was stored in an individual glass beaker with an approximate capacity of 600 mL. No additional purification steps were performed prior to their experimental use.

2.3. Measurement procedure

The pulse-echo measurement technique [15] was used. The measurement system consists 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), an oscilloscope (Keysight - USA, model DSOX 1202A), a type K thermocouple and temperature measurement system (Agilent Technologies - USA, model 34970A), a signal generator (Agilent Technologies - USA, model 33250A), and data acquisition software developed in LabView™ (National Instruments, Austin, TX, USA) (Figure 3).

2.4. Measurement uncertainty

Measurement uncertainty is defined as a non-negative parameter that is associated with the result of a measurement that characterizes the dispersion of values that can reasonably be attributed to a measurand. In this study, the combined standard

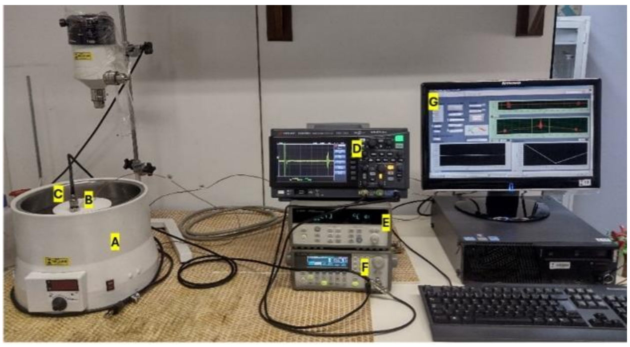

Figure 3. Characterization of the speed of sound of the analysed materials. A: thermal-controlled water bath; B: sample; C: transducer; D: oscilloscope; E: temperature measurement system; F: signal generator; G: software

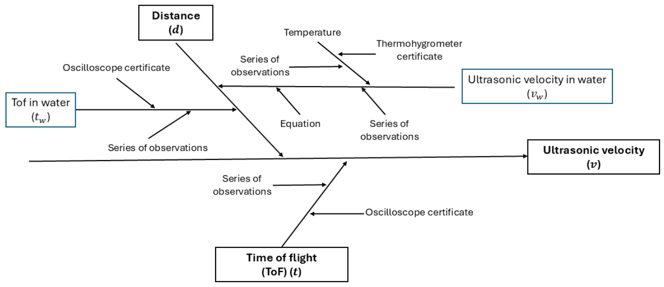

Figure 4. Ishikawa's diagram: contributors to uncertainty in ultrasound group velocity measurements.

uncertainty was evaluated in accordance with the principles established in the Guide to the Expression of Uncertainty in Measurement (GUM) [16]. A total of ten repetitions were performed for each of the three sets of measurements, including time of flight and temperature. The statistical treatment was based on the mean values obtained from these repeated measurements, and the associated standard deviations were used to quantify the variability of each quantity.

The uncertainty evaluation considered both Type A and Type B components. Type A uncertainties were determined through statistical analysis of repeated measurements of time of flight, temperature, and speed of sound. Type B uncertainties, on the other hand, were estimated from information external to the measurement series, including: the measurement uncertainty of the oscilloscope for measuring the time of flight in liquid (0.024 %), the expanded uncertainty reported in the calibration certificate of the temperature (U = 0.09 °C, p = 0.95, k = 2), the uncertainty in the distance measurement between the transducer surface and the reflecting target surface ($2.7396 \cdot 10^{-5}$ m), and the uncertainty related to the mathematical model used to estimate speed of sound in water as a function of temperature (0.18 m s^{-1}). The contribution of each source of uncertainty is illustrated using an Ishikawa's diagram, shown in Figure 4.

3. RESULTS

3.1. Speed of Sound (SoS)

The measurement results of the speed of sound in materials, with their respective uncertainties, are shown in Table 1 and Figure 5.

4. DISCUSSIONS

The development of stable and reliable Tissue Mimicking Materials (TMMs) is critical for the accurate evaluation of ultrasound diagnostic equipment. Agar-based TMMs, although widely used, suffer from limited durability, prompting the exploration of alternative materials with superior stability. This study investigated oil-based materials, including mineral oil, lubricating oil, and ethylene glycol, to assess their potential as long-lasting TMMs.

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

Material	Temperature in °C	SoS in $m \cdot s^{-1}$	Combined Uncertainty in $m \cdot s^{-1}$	Coverage factor k	Expanded uncertainty in $m \cdot s^{-1}$
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

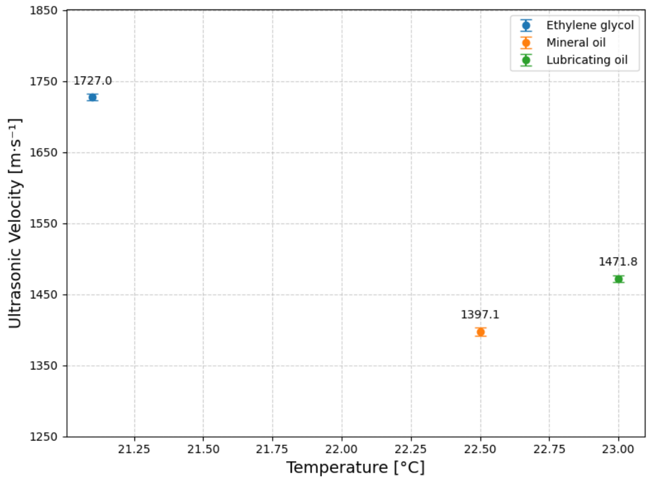

Figure 5. Ultrasonic velocity results for each material with their respective expanded uncertainties (p = 0.95).

Ethylene glycol exhibited the highest SoS, followed by lubricating oil, while mineral oil presented the lowest value. These differences reflect intrinsic variations in the acoustic properties of each fluid, which may be associated with their molecular composition and physical structure. Notably, mineral and lubricating oils showed SoS values within the typical range for soft tissues, supporting their potential as base components in tissue-mimicking formulations.

The temperature of each fluid was recorded at the time of measurement using a calibrated thermometer. Although all experiments were performed under controlled laboratory conditions, slight temperature variations (within approximately 2 °C) were observed among the samples. These variations are attributed to the different thermal properties and stabilization times of each material. Despite these small differences, they were considered metrologically acceptable and were incorporated into the uncertainty analysis of the speed of sound measurements, ensuring the reliability of the results.

The low combined and expanded uncertainties across all materials support the consistency and reproducibility of the measurement method used. This level of precision is crucial when selecting TMMs for standardization or reference purposes. The relatively narrow uncertainty ranges suggest that the materials tested can provide stable acoustic performance over time and under controlled conditions.

These findings suggest that both mineral and lubricating oils are suitable candidates for developing stable TMMs, as their SoS values fall within the typical range required for mimicking soft tissue. Furthermore, their moderate uncertainties indicate consistent performance across measurements, reinforcing their potential as reliable alternatives to traditional agar-based phantoms. Ethylene glycol, while having the highest SoS, may offer different applications, such as in specialized phantoms where higher acoustic velocities are necessary.

5. CONCLUSIONS

Based on the results, mineral oil and lubricating oil emerged as the most suitable candidates for developing TMMs due to their stable ultrasonic properties and low uncertainty values. The measurement process followed the principles of the Guide to the

Expression of Uncertainty in Measurement (GUM), ensuring traceability and methodological rigor. Their acoustic behaviour aligns well with the requirements for mimicking soft tissue, making them viable options for phantoms designed for the transport and evaluation of ultrasound diagnostic equipment.

Although ethylene glycol exhibited the highest SoS among the materials tested, its properties may be more appropriate for applications where higher acoustic velocities are necessary. Therefore, further studies could explore its potential in specialized phantom designs. Overall, the oil-based materials demonstrated superior durability and stability compared to traditional agar-based TMMs, reinforcing their suitability for long-term use in ultrasound applications.

AUTHORS' CONTRIBUTION

M. K. Assis, the first author and a master's student, conducted the experimental measurements, analysed the data, and wrote the manuscript. R. P. B. Costa-Félix, the second author, is the academic advisor and research project coordinator. He supervised all activities, assisted with the tasks performed by M. K. Assis, and reviewed the manuscript.

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