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The influence of temperature on the speed of sound of cortical bone phantom: a metrological view

Rebeca Monteiro Souza [1], Rodrigo P. B. Costa-Félix [1], André Victor Alvarenga[1]

[1] Laboratory of Ultrasound, Directory of Scientific and Industrial Metrology, National Institute of Metrology, Quality and Technology - Inmetro.

E-mails: rebecasouzam@gmail.com; rpfelix@inmetro.gov.br; avalvarenga@inmetro.gov.br

Abstract: This paper presents an experimental study to estimate the group velocity of ultrasound longitudinal propagation in a cortical bone phantom for the temperature range of 19 ºC to 37 ºC, and respective measurement uncertainty estimates. The group velocity was measured using the pulse/echo method. The uncertainty model was proposed based on the BIPM JCGM:100 – Guide of the Expression of Uncertainty in Measurements. The velocity results show a tendency to decrease linearly as the temperature increases, considering the uncertainty estimated.

Keywords: ultrasound, group velocity, cortical bone phantom, temperature variation.

1. INTRODUCTION

The characterization of cortical bone by ultrasound, based on parameters such as attenuation and longitudinal propagation velocity, can reflect the structure and elastic properties of the propagation medium [1][2]. Studying cortical bone properties *in vitro* has the advantage of working under controlled experimental conditions, while *in vivo* studies are influenced by the bone geometry and body movements, as well as temperature variations [2].

Bone phantoms are largely used to mimic real bone properties in estimating acoustic parameters (speed of sound, backscattering, and attenuation coefficient), as well as in assessing their heating distribution in thermal phenomena studies [3]. Hence, it is important to know and consider how their acoustic properties vary with different temperatures. This work assesses the group velocity variation of a cortical bone phantom for temperature ranging from 19 ºC to 37 ºC, and respective measurement uncertainty.

2. MATERIALS AND METHODS

2.1. Experimental setup

For this study, a 10 mm-thick epoxy block with short fibers (Sawbones™, USA) that simulates the mechanical properties of the cortical bone was used. The experimental setup consists on a 5 MHz-nominal frequency, 12.7-mm-diameter single-crystal circular unfocused ultrasonic transducers acting as transmitter and receiver (model V303, Olympus, USA); an arbitrary waveform generator (model 33250A, Agilent Technologies, USA) to excite the transducer with a sine burst of 3 cycles, 20 V peak-to-peak amplitude at 5 MHz; an oscilloscope (model DSO 5012A, Agilent Technologies, USA) to acquire the echo-signals; a water bath (Fisatom, Brazil) to heat the cortical bone phantom (Sawbones®, USA); a thermometer (ThermoSchneider, Germany) to measure temperature throughout the measurement process.

2.2. Measurement procedure

After the system alignment and thermal equilibrium, different times of flight are measured as showed in figure 1. First, the time of flight in the water ($\boldsymbol{t_w}$), without the sample, is measured. Then, the sample is inserted, and the times of flight on the sample surface ($\boldsymbol{t_1}$) and on the reflector ($\boldsymbol{t_2}$), with the sample inserted, are measured. The values of $\boldsymbol{t_w}$, $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$ are measured to six different temperature values between 19 ºC and 37 ºC. At each step of temperature, four repetitions are carried out.

Between repetitions, the phantom is removed from the system and the alignment procedure is repeated. After the temperature is increased for a next step, a new thermal equilibrium is allowed by at least 30 min.

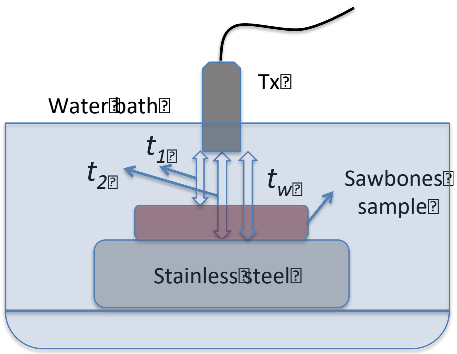

Figure 1. Experimental setup.

2.3. Group velocity and phantom thickness

The phantom thickness ($\boldsymbol{x}$) is determined as:

$$\boldsymbol{x = v_w} . \left(\frac{\boldsymbol{t_w - t_1}}{\boldsymbol{2}}\right) \tag{1}$$

in which $\boldsymbol{v_w}$ is the speed of sound in water as a function of temperature ($\boldsymbol{T}$ in ºC) as [5]:

$$\boldsymbol{v_w = 1405{,}03 + 4{,}624\,.\,T - 3{,}83.\,10^{-2}.\,T^2} \tag{2}$$

The group velocity within the phantom is calculated as:

$$\boldsymbol{v = 2 \cdot x \cdot\ (t_2 -\ t_1)^{-1}} \tag{3}$$

2.4. Measurement uncertainty

The entire procedure is repeated three times and uncertainties are estimated based on the Guide to the expression of uncertainty in measurement [6].

The following sources of uncertainty were considered: an uncertainty component obtained by a Type A evaluation (estimated as the experimental standard deviation of the mean), the standard uncertainty of the temperature obtained from the calibration certificate of the thermometer ($\boldsymbol{\mu_T} =$ 0.015 ºC), the uncertainty of the determination of the ultrasound propagation velocity in water ($\boldsymbol{\mu_{eq}} =$ 0.18 m s^{-1}) [5] and the uncertainty of the time base (0.04%) obtained from the calibration certificate of the oscilloscope.

Based on the expressions for thickness of the specimen (1) and for the speed of sound in water as a function of temperature (2), the following sensitivity coefficients are determined:

$$c_{v_w} = \frac{\partial x}{\partial_{v_w}} = \frac{t_w - t_1}{2} \tag{4}$$

$$c_{t_w} = \frac{\partial x}{\partial_{t_w}} = \frac{v_w}{2} \tag{5}$$

$$c_{t_1} = \frac{\partial x}{\partial_{t_1}} = -\frac{v_w}{2} \tag{6}$$

$$c_{v_w}^T = \frac{\partial v_w}{\partial T} = 4{,}624 - 7{,}66\,.\,10^{-2}.\,T \tag{7}$$

The combined uncertainty of speed of sound in the water is given by:

$$\mu_{vw}^2 = \mu_{eq}^2 + \left(c_{v_w}^T\right)^2 . \mu_T^2 \tag{8}$$

The combined uncertainty for x (μ_x) (in meters) is thus expressed as:

$$\mu_x = \sqrt{c^2{}_{vw}.\mu^2{}_{vw} + c^2{}_{tw}.\mu^2{}_{tw} + c^2{}_{t_1}.\mu^2{}_{t_1}} \tag{9}$$

Based on the model for the group velocity (3), the following sensitivity coefficients are determined:

$$c_x = \frac{\partial v}{\partial x} = 2 \cdot (t_2 - t_1)^{-1} \quad (10)$$

$$c_{t_1} = \frac{\partial v}{\partial t_1} = -2x \,.\, (t_2 - t_1)^{-2} \quad (11)$$

$$c_{t_2} = \frac{\partial v}{\partial t_2} = 2x \,.\, (t_2 - t_1)^{-2} \quad (12)$$

The combined uncertainty of v (u_v) (m/s) is thus expressed as:

$$u_v = \sqrt{{c^2}_x . {\mu^2}_x + {c^2}_{t_1} . {\mu^2}_{t_1} + {c^2}_{t_2} . {\mu^2}_{t_2}} \quad (13)$$

3. RESULTS

The phantom thickness is estimated by the pulse/echo technique as 10.302 mm (U = 0.018 mm; p = 0.95). Tables 1, 2 and 3 present the results of group velocity measured at each temperature, their respective expanded uncertainties (U) and coverage factors (k), from three repetitions of the complete measurement procedure carried out in three different days.

Figure 2 presents the group velocity results from the three repetitions of the measurement procedure all together. One can observe that group velocity tends to decrease linearly as temperature increase in the range of 19 ºC to 37 ºC.

4. DISCUSSIONS AND CONCLUSION

Many works have been assessing the velocity on bone phantoms and samples, but rarely they mention the temperature observed during the experiments [3][8][9][9]. Moreover, the measurement uncertainties of the published results are never declared.

Litniewski et al. [8] proposed a method for simultaneous assessment of thickness and longitudinal velocity of cortical bone phantoms and samples. The ultrasonic data were obtained at the frequency of 1.0 MHz using a single element focusing transducer. For bone phantoms, the authors mention relative errors for thickness of 5.9%, and 6.8% for the ultrasonic wave velocity.

Table 1. Results of group velocity measured at each temperature, their respective expanded uncertainties (U) and coverage factors (k) for the first repetition of the measurement procedure.

Temperature [ºC]	Group Velocity [m/s]	U [m/s]	*k*
19.1	2967	11	2.02
23.0	2948	10	1.97
26.9	2926.1	8.9	1.96
31.6	2909	10	1.96
33.8	2894.6	9.2	1.97
37.2	2875.3	8.8	1.96

Table 2. Results of group velocity measured at each temperature, their respective expanded uncertainties (U) and coverage factors (k) for the second repetition of the measurement procedure.

Temperature [ºC]	Group Velocity [m/s]	U [m/s]	*k*
20.9	2958	10	1.96
23.9	2944	10	1.96
27.0	2929	10	1.96
31.0	2909	10	1.96
34.0	2893	10	1.96
37.0	2873	10	1.96

Table 3. Results of group velocity measured at each temperature, their respective expanded uncertainties (U) and coverage factors (k) for the third repetition of the measurement procedure.

Temperature [ºC]	Group Velocity [m/s]	U [m/s]	*k*
19.5	2959.6	6.2	1.96
23.0	2948.5	6.1	1.96
26.9	2931.1	5.9	1.96
30.8	2908.7	6.5	2.0
33.9	2891.9	5.9	1.97
37.0	2877.4	5.8	1.97

McCarthy et al. [9] assessed the longitudinal velocity of bone samples from the mid-site of the third metacarpus of 20 horses. The ultrasonic data were obtained at the frequency of 2.25 MHz. The authors observed that over the temperature range of 4 ºC to 42 ºC, velocity varied inversely to temperature. Standard deviation of 3.5% is declared for the velocity measured.

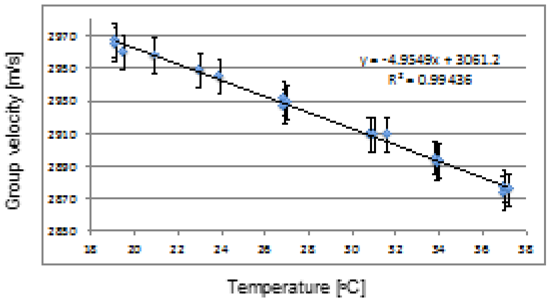

Figure 2. The group velocity results from the three repetitions of the measurement procedure together. Vertical bars indicate the expanded uncertainties.

El-Sariti et al. [9] measured the longitudinal velocity (@ 750kHz) in bovine bone marrow as a function of temperature between 17 °C and 44 °C. The authors pointed out a difference of 74 m s^{-1} in velocity between 20 °C, temperature normally used *in vitro* experiments, and 37 °C, temperature in which clinical measurements are carried out.

Sellani et al. [3] assessed the therapeutic ultrasound (TUS) heating distribution on commercial bone phantoms and *in vitro* femur and tibia human samples using thermographic images. An infrared camera captured images after 5 min of TUS stimulation (@ 1 MHz). The authors pointed out that temperature increased up to 8.2 °C and 9.8 °C for the femur and tibia, respectively. Moreover, they declared minor differences in mean and standard deviation temperatures between bone phantoms and samples. The authors concluded the commercial bone phantoms could be applied on thermal effects of ultrasound research.

In this work, we observe that group velocity on a cortical bone phantom tends to decrease as temperature increase. Moreover, an uncertainty model was presented to help assessing the differences in velocity for different temperatures. Finally, we conclude that different values of group velocity should be considered when temperature varies in simulations or experimental procedures, and this has obvious implications for the research results carried out in bone samples and phantoms.

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