Ultrasonic Attenuation and Speed in Phantoms Made of PVCP and Evaluation of Acoustic and Thermal Properties of Ultrasonic Phantoms Made of polyvinyl chloride-plastisol (PVCP)

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Abstract. Biological phantoms are commonly used on biomedical ultrasound research, but they have some limitation. We have been studying the acoustic and thermal properties of polyvinyl chloride-plastisol (PVCP) that have longer time stability. We estimated thermal conductivity in steady-state methods and specific heat with Method of Mixture. PVCP blocks were made with different graphite and PVC powders concentrations. US speed and attenuation presented the expected behavior as a function of powder concentration, that is, they tend to have growing values. US speed values are between 1400 and 1470 m/s, while attenuation is in the range 0.14 –1.16 dB/cm. Specific heat values ranged from 1.16 - 2.65 J/(kg°C) and thermal conductivity values range from 0.0603 – 0.1243 J (s ºC m)$^{-1}$. The thermal conductivity and acoustic attenuation values are similar to fat tissue and can be adjusted to other types of tissue by mixing, for instance, graphite or PVC powder.

1 Introduction

Plastisol or PVCP is a suspension of PVC (Polyvinyl chloride) particles in a plasticizer that when heated to around 170ºC dissolves and becomes a translucent and viscous liquid. The cooling below 60ºC results in a flexible plasticized material. In this research, it was used the PVCP from the M-F Manufacturing Co., Fort Worth, TX, USA. It is a white opaque solution of monomers that polymerizes in a non-toxic plastic, commonly used to produce tissue mimicking materials (TMM) known as phantoms[1]. Only optical and acoustic properties have been obtained to several TMM at room temperature[1,2], but no thermal properties have been reported so far. Those properties can be changed when some substances are added into the PVCP solution. In our particular case, PVC and graphite powders were used.

In this work, the procedure for constructing phantoms is described and their acoustic and thermal properties analyzed at 20–50ºC temperature range. Furthermore, the uncertainty of parameters is presented.

2 Materials and Methods

2.1 Phantoms

To prepare a phantom, liquid PVCP, pure or mixed with powder, is placed in a chamber linked to a vacuum pump to eliminate air bubbles. After that, the liquid is poured in a mold and heated in a oven (Stuart Scientific) with controlled time and temperature according to Table 1. Two types of PVCP (Plastic and Super Soft Plastic) were used at two temperatures (130 and 170 C). Upon cooling in room temperature, the PVCP solution solidifies and can easily be removed from a mold of any convenient shape.

Table 1. Material type, code name and temperature of the phantom in furnace (cook time, 2 hours).

PVCP type	Name	Material	Temperature
Plastic	PH 2	PVCP pure	130
Plastic	PH 6	PVCP+graphite 5%	130
Plastic	PH 7	PVCP+PVC 8%	130
Plastic	PH 9	PVCP+PVC8%+graphite2%	130
Super-Soft	PH 10	PVCP pure	130
Super-Soft	PH 11	PVCP pure	170

2.2 Acoustic Technique

A US-Key Single Channel Ultrasound Device (Lecoeur electronique, France), was used to generate and detect longitudinal wave with 30V excitation voltage, 80 MHz sampling rate, 4000 points and 0dB gain in two 1-MHz ultrasonic transducers (Harsonic 13-0108-S) immersed in a thermal bath with distilled water (reference medium). The transducers parameters are described in Table 2. Measurements in the thermal bath (WiseCircu WCB-22) were made at around each 0.2 °C of temperature increase. The signals were acquired by a microcomputer through a USB interface with a program developed in Matlab®. The temperature was measured by a T-type thermocouple, using high a speed multiplexer NI 9213 (National Instruments; Austin, Texas, EUA) (Fig. 1). The transmission–reception technique was employed to measurement ultrasonic attenuation coefficient and longitudinal velocity of the phantom. The RF's signals were acquired between 20 and 50ºC with the phantom between transducers. Then, the procedure was repeated without the phantom to collect the reference signal at the same temperature range.

Table 2. Experimental parameters settings.

Parameters	Value
Temperature	~20 to ~50ºC
transducer Separation	30.0 mm
Ultrasonic central Frequency	1.0 MHz
Transducer diameter	12.7mm

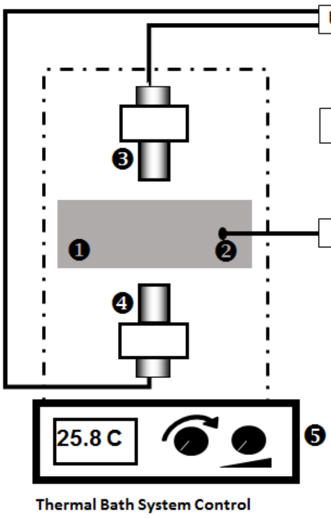

Fig. 1. Experimental System Diagram to measure acoustic properties during heating. 1 - Phantom, 2 - thermocouple, 3 - Transmitter Transducer, 4 - Receiver Transducer, 5 - controlled thermal bath, MUX - temperature multiplexer, US-ND - ultrasonic wave generator / receiver, PC - computer. Dashed lines indicate elements immersed in water.

A program in Labview® 2009 was developed to treat the signals and estimate the longitudinal velocity and attenuation coefficient in the temperature range. The technique to estimate the longitudinal velocity consists in detecting the greaters peaks of the Reference (Sr) and Phantom (Sp) signals and then calculate time difference (t) between them. The thickness phantom (x) was measured by caliper and velocity in reference medium (v_{ref}) was estimated using the equation 2[3] that use the temperature T, measured by thermocouple. The longitudinal velocity is estimated from equation 1:

$$v_p = \left(\frac{x v_{ref}}{x - t v_{ref}} \right). \tag{1}$$

$$v_{ref} = 1402{,}38 + 5{,}03T - 0{,}05T^2 + 3{,}34 \cdot 10^{-4} T^3 - 1{,}47 \cdot 10^{-6} T^4 + 3{,}14 \cdot 10^{-9} T^5 \tag{2}$$

Equation (3) was used to estimate the attenuation coefficient α (dB/cm).

$$\alpha = 10\frac{\log\left(\frac{A}{A_o}\right)}{x} \quad (3)$$

where A_o is the peak of the amplitude spectrum (obtained through a Fast Fourier Transform – FFT) of the reference signal and A is the peak amplitude spectrum of phantom signal at the same frequency of the reference signal.

2.3 Thermal Technique

Thermal Conductivity

The thermal conductivity (k) is an important property in the design of any thermal process. It is a coefficient which measures the rate of heat transfer (dQ / dt) along the direction of a temperature gradient in the stationary state (dT / dx), governed by Fourier's law in equation 4 (A is the sample thickness):

$$\frac{dQ}{dt} = -k.A\frac{dT}{dx} \quad (4)$$

In steady-state methods, two sides of a flat object are maintained at two different constant temperatures and the heat flux through the sample is measured. The most common technique is the longitudinal heat flow method. In this method, the plate heating source, the sample and the heating sink are placed in contact one with other. The thermal plates (source and sink) keep a constant temperature once reached the steady state, preventing the loss of heat within the limits of the source. However, the achievement of equilibrium conditions can take several hours. It is assumed that all the heat input is transferred through the sample. The thermal conductivity was calculated by measuring the amount of heat input required to maintain the steady state temperature profile through the unidirectional test sample. The measurement method is to place a thin layer of the phantom material (thickness of 2.01 ± 0.01mm, averaged over 6 measurements taken with a caliper) in contact with a heat source and in an environment with constant temperature. Metal blades of negligible thicknesses (<0.01mm) were used to equalize the faces temperatures of the phantom and the other faces of the phantom were coated with polyurethane-expanded (40kg/m^3 density, thermal conductivity 0.029 W / (mK) and specific heat of 1674 J / (kg K)). The heat source used was a flat electrical resistance with 10W of maximum power. The temperature was measured by T-type thermocouples, one on the font face and three on the other side (Fig. 2). The conductivity was measured as soon as steady-state is reached (around 60 minutes, in the present case). The determination of thermal conductivity does not include the effect of evaporation–condensation phenomena. It is assumed to be negligible, or not occurring, in the working temperature range.

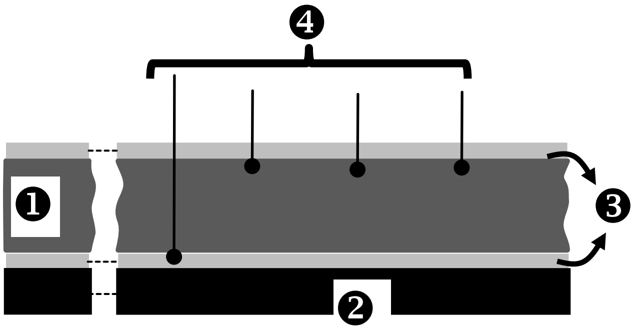

Fig. 2. Schematic of thermal conductivity measurements (sagittal cut). 1-phantom, 2-heating source, 3- two metal sheets, 4-thermocouples set.

The time necessary to reach steady-state is very long and has not been reached, as can be seen in curves of Fig. 3.

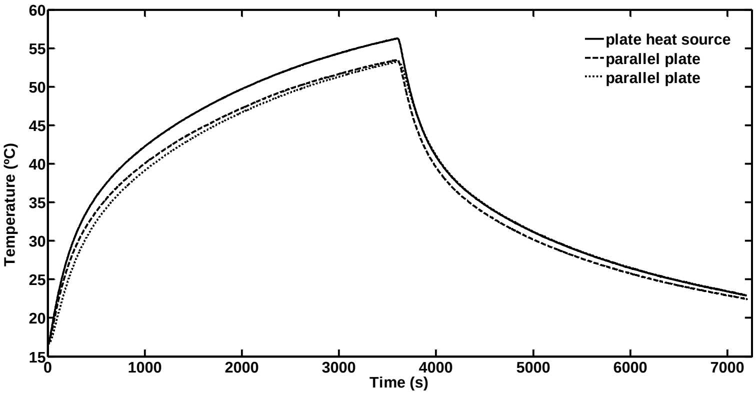

Fig. 3. Temperature curves of heating (transient) and cooling of Phantom 10, using Longitudinal Heat Flow Method. Continuous line corresponds to the hot plate (heat source), dotted lines correspond to the two parallel sheets (see Fig.2) **.**

Specific Heat - Method of Mixture

The estimation of specific heat is based on the so called method of mixture, in which the sample changes heat with water in a reservoir. The phantom at a certain temperature T_1 is put into a calorimeter (with heat capacity Γ_{Kal}) that contains water. Both calorimeter and water are at temperature T_2 ($T_1 > T_2$). Thermal equilibrium is reached in a certain temperature T_M. The amount of heat that left the sample $\Delta Q_1(m_p, c_p, T_1, T_M)$ is equal to the amount received by water+reservoir ΔQ_2 (Γ_{Kal}, m_w, c_w, T_2, T_M). c_w is the specific heat of water (4.187×10^3 Jkg^{-1} K^{-1}), m_w is the water mass, m_p, is the phantom mass. The specific heat c_p, of the phantom is, then, given by:

$$\mathrm{c}_P = \frac{\left(m_w c_w + \Gamma_{kal}\right)\left(T_M - T_2\right)}{m_P\left(T_M - T_1\right)} \tag{5}$$

We worked below 50°Celsius to avoid loss of heat from evaporation and convection. The masses were measured in a balance with precision of 0.10 g (OHAUS MOD. SCOUT SP-6001). The heating capacity of the calorimeter Γ_{Kal} (reservoir) is not negligible and was determined by mixing two masses of water at different temperatures. Then, by using the same principle, Γ_{Kal} can be estimated as:

$$\Gamma_{kal} = \frac{mc_w\left(T_2 - T_e\right) - mc_w\left(T_e - T_1\right)}{T_e - T_1} \tag{6}$$

And the associated uncertainty can be given by equation 7, with coverage factor k =2 and δX the uncertainty of the measuring X.

$$\frac{\delta(\Gamma_{kal})}{k} = \sqrt{\left|\frac{\partial\Gamma_{kal}}{\partial m}\right|^2 (\delta m)^2 + \left|\frac{\partial\Gamma_{kal}}{\partial c_w}\right|^2 (\delta c_w)^2 + \left|\frac{\partial\Gamma_{kal}}{\partial T_e}\right|^2 (\delta T_e)^2 + \left|\frac{\partial\Gamma_{kal}}{\partial T_1}\right|^2 (\delta T_1)^2 + \left|\frac{\partial\Gamma_{kal}}{\partial T_2}\right|^2 (\delta T_2)^2} \tag{7}$$

The experimental setup is presented in Fig. 3. Temperatures are measured with T-type thermocouples connected to a multiplexer National Instruments NI9213, sample rate 100Hz and 50 samples by trigger), managed by a software in Matlab® (temperature sampling frequency 1Hz). The equilibrium condition is given by equation 8:

$$\frac{\left|T_w - T_P\right|}{2} \le \sigma_{T_w} \tag{8}$$

where T_w and T_p are temperatures of water and phantom, respectively, σ_{Tw}, is the standard deviation of T_w.

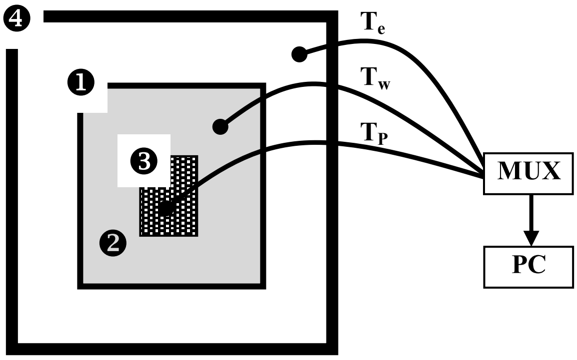

Fig. 3. Experimental setup for determining the specific heat: 1- adiabatic calorimeter, 2-water, 3- phantom, 4-adiabatic box, MUX-multiplexer, PC-Computer. Tp, T_w, T_e thermocouples in phantom, water and environment respectively.

3 Results and Discussions

It can be seen from the six different phantoms studied that acoustic and thermal properties can be altered according to the type of PVCP, material used in the mixture and cooking time (Table 1).

From the velocity *versus* temperature curves of Fig. 4, it can be seen three distinct groups:

- Group 1: pure super-soft PVCP has a lower US velocity (PH10 and PH11);
- Group 2: pure PVCP and PVCP+Graphite powder (PH2 and PH6) have medium velocities;
- Group 3: PVCP+PVC powder has a higher US velocity (PH7 and PH9).

Some indications can be obtained from these results: (*i*) the cooking temperature did not change the US velocity significantly (group 1); (*ii*) the addition of graphite powder did not change velocity significantly (compare PH2 to PH6 and PH7 to PH9); and; (*iii*) the addition of PVC powder increased the US velocity (group 3).

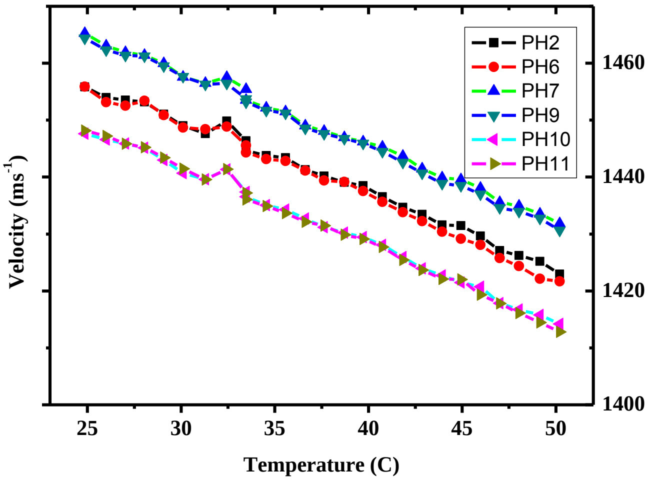

Fig.4. Velocity *vs* temperature of phantoms (see Table 1 for phantom composition).

Table 3. Estimated values of the linear velocity versus temperature

Phantom	Intercept		Slope		R-Square
	Value	Error	Value	Error	
PH2	1488.73	0.89	-1.291	0.023	0.99
PH6	1490.68	0.98	-1.366	0.026	0.99
PH7	1497.69	0.72	-1.305	0.019	0.99
PH9	1497.89	0.61	-1.329	0.016	0.99
PH10	1482.39	0.80	-1.354	0.021	0.99
PH11	1484.14	0.82	-1.407	0.021	0.99

Attenuation values (table 4) have not presented a clear tendency as the US velocity ones. Nevertheless it is still possible do observe a light tendency keeping the same group distribution: phantoms PH2 and PH6 have the smaller attenuation values; PH10 and PH11 have medium values and; PH7 and PH9 presented the higher attenuation values.

Specific heat (c) values ranged from 1.16 - 2.65 J/(kg°C) and thermal conductivity (k) values range from 0.0603 – 0.1243 J (s ºC m)-1. The specific heat and acoustic attenuation values are similar to fat tissue (PH6) and thermal conductive is lower than biological tissues although for PH11 it is near the fat value (Table 4). The thermal and acoustic properties can be adjusted to other types of tissue by mixing, for instance, graphite or aluminum oxide powders. Two different cooking temperatures (130 and 170 ºC) were tested for same type of PVCP (PH10 and PH11) only velocity did not change; the other properties seem to be significantly affected. This variable, cooking temperature, must be more investigated.

Table 4. Estimated values of acoustic (at 25ºC) and thermal properties (range 20 to 50ºC)

Name	*v* (ms^{-1})	α ($dB.cm^{-1}$)	*k* (J (s ºC m)$^{-1}$)	*c* (J (kg ºC)$^{-1}$)
PH 2	1440.4 ±9.9	0.14 ±0.06	0.0700± 0.0043	1.16±0.39
PH 6	1439±10	0.58±0.08	0.0757±0.0027	2.40±0.46
PH 7	1449±10	1.09±0.06	0.0652±0.0050	2.00±0.74
PH 9	1448±10	1.16±0.06	0.0709±0.0094	2.65±0.51
PH 10	1431±10	0.66±0.07	0.0603±0.0045	2.20±0.34
PH 11	1431±11	0.92±0.06	0.1243±0.019	1.79±0.25

5 Conclusion

In this work it could be determinate ultrasonic velocity, attenuation coefficient, specific heat and thermal conductivity by simple techniques in phantoms based PVCP. It could be found the linear dependence of velocity with temperature variation in range between 20 to 50 ºC. The attenuation coefficient phantoms are in the biological tissue ranges values. The acoustic and thermal parameters presented important changes with phantom cooking temperature. Further investigations are necessary to explore this dependency as it is important to have phantoms to mimic different biological tissue types.

References

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