Ultrasound Tissue Mimicking Materials
Using 2% Agar based phantom

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Abstract

We propose and demonstrate experimentally the possibility of reproducing the attenuation coefficients, Young's Modulus, the acoustic reflection coefficients, and the thermal conductivity of a real biological tissue which using 2% Agar based phantom (2g Agar for 100ml degassed water).The design of 2% Agar based phantom fabrication is discussed. The attenuation coefficient is measured using measurements of the acoustic properties and Young's modulus is measured using the mechanical compression test by applying the relation between the Nominal Stress and the Nominal Strain. Phantom is a material that simulates some properties of body tissues. It is important for helping the development of Hand-Eye coordinate necessary for ultrasound guided intervention and also allowing the performance of the simulated interventions without having to do it as the first time in the patient. Acoustic properties were measured for the frequency of 4.8M Hz at a range of ambient temperatures (10 – 35 °C). The acoustic velocity of the TMMs remained relatively constant with increasing frequency.

Keywords: Young's Modulus; thermal conductivity; phantom; intervention; acoustic

1. Introduction

The most important usage of TMMs is assessing the performance of ultrasound diagnostic. Although there are significant variations of the properties of US of different tissues, it is possible to choose appropriate standard TM properties, depending on the application used.

1.1. Ultrasound imaging

Medical ultrasonic (US) imaging depends on the transmission of a high-frequency (MHz range) acoustic pulse into tissue through a transducer that is capable of both transmitting and receiving high-frequency sound. The sound is then scattered due to the mismatching between the acoustic impedances in the propagation which the transmitted pulse propagates through tissue and the backscattered portion of this energy can be received by the aforementioned transducer, which oppose the direction of the pulse propagation and the signal amplitude of this received echo is related to specific tissue structure [1].

1.2. Tissue mimicking phantom

Ultrasound Phantom is that any material that mimic body tissues when it interacts with ultrasound and can be used to perform simulated interventions and provide a more clinically realistic imaging environment. Ultrasound test Phantom incorporating tissue mimicking materials TMMs play an essential role in the quality control and performance testing on ultrasound devices [2][3]. The basic acoustic properties of human tissue are sound speed, density and the coefficient of attenuation which should be presented by the Phantom. To approach equivalence with tissue, Phantoms should have similar acoustic properties to the tissue being represented across the range of frequencies used diagnostically. In soft tissues, the average of acoustic speed is 1540 m/s, and the range of attenuation coefficients is from approximately 0.5 to 3.3 dB /cm MHz^{-1}; while they are low 0.18 dB/cm MHz^{-1} for blood [3]. The important properties of TMMs are the attenuation Coefficient, back-scattering Coefficient and sound speed, although other parameters, such as non-linearity parameter may be specified [4]. Non linearity has become important as an acoustic parameter, due to the development of tissue harmonic imaging. Also, with the development of new techniques such as elastography and strain imaging, future TMMs may need to simulate the mechanical properties of tissue. Moreover, there is an important factor that depends on the attenuation coefficient is, thermal distribution which is used to develop the medical ultrasonic systems. Hence, the development of the Phantom for the purpose in various applications is strongly required [5].

1.3. Study and motivation

The main purpose of this paper to understand what is the meaning of the Tissue mimicking Materials TMMs or Phantoms and gives the tools to construct realistic one. In this study, 2% Agar and degassed water were used as the phantom base. Firstly, we can know the attenuation coefficient (α) and the acoustic velocity from the acoustic properties. Secondly, measurement we can know the mechanical properties of the Phantom through the test of mechanical compression, so we can calculate Young's Modulus which determines its elasticity, mechanical response .Finally, using labVIEW and MATLAB program; we can calculate the thermal coefficient (k) throughout measuring the temperature rise and non-linear curve fitting to understand the thermal property of the phantom.

2. Material and methods

2% Agar based phantom fabrication

Initially, phantoms were prepared by combining agar and degassed water. The ratio of agar to degassed water is 2% (it means 2g of agar for 100ml of degassed water).Firstly, we poured the 100ml of degassed water into the beaker and heated it on the hotplate and then, added the 2g agar into the beaker. To minimize the vapour loss we were stirring the solution continuously at the same time of adding the agar. Secondly, we heated it over 95°C for about 20 minutes to improve the long term of stability and enhance cross-linking of the phantom [6]. When we noticed that the solution became uniform and clear, we stopped stirring. Finally, the final hot solution was poured into the container and once cooled to the room temperature mould with the phantom and it should be put into a refrigerator to set overnight.

1. Acoustic properties measurement

For measuring the attenuation coefficient, the acoustic impedance and the acoustic velocity of the phantom, we setup and connect these instruments by using two transducers (transmitter and receiver), signal generator as the output of the signal (provide the voltage) and 2 channels oscilloscope for measuring the signal properties as shown in "Fig.1".We used the sine wave signal with frequency=4.8M Hz, amplitude=5Vpp and 3 circles burst. The maximum signal was received by adjusting the position of the transducer.

Exercises and data analysis:

Firstly, we measured the distance between the two transducer (D) and the thickness of the sample (h) .By knowing times from channel 1(reference signal) and from channel 2 (receiver signal), t1 and t2 respectively, it was easy to measure the acoustic velocity of the water from the formula:

$$v(water) = \frac{D}{|t1-t2|} \qquad (1)$$

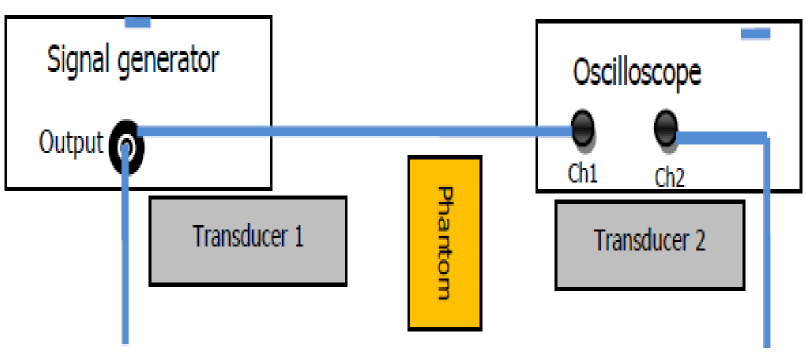

Figure1 Schematic diagram of acoustic properties measurement

Then, place the sample in the middle of two transducers and ensure the surface of the sample is normal to the axis of the transducer, hence calculate t3 from channel 2(t3=38 µs).Therefore, the acoustic velocity for the sample (Vs) can be calculated from the formula as shown in "Fig.1".

$$\frac{h}{Vs} + \frac{D-h}{V(w)} = t3 \qquad (2)$$

Since we know the densities for water and the sample so it is easy to measure the acoustic impedances for them. So, from the formula

$$Z = \rho . v \qquad (3) \quad [2]$$

Hence, the acoustic reflection coefficient (R) at the water /sample interface:

$$R = \frac{Z(s)-Z(w)}{Z(s)+Z(w)} \qquad (4) \quad [2]$$

Finally, we could calculate the attenuation coefficient using the following formula

$$\alpha(\text{phantom}) \left(\frac{\text{dB}}{\text{cm}}\right) = \alpha(\text{w}) - \frac{[\ln \text{A(s)} - \ln \text{A(w)} - 2\ln(1-\text{R})]}{\text{h}} \qquad (5) \quad [3]$$

Since A(s) and A (w) are the amplitudes of the received ultrasound pulse of sample and water, respectively

2. Mechanical Compression test on Phantoms

This test is used mainly to calculate the Young's modulus from the mechanical response of the phantom which is a significant factor used to characterize the mechanical interaction between medical instruments and Phantoms. For the 50.45 mm length, 33.4 mm width and 38.5 mm thickness sample of the tissue mimicking materials TMMs (phantom), dynamic measurements of complex Young's moduli were made using "mechanical Compression Test System"(Tinius Olsen H5KS device, two contact plates, Bubble level). Firstly, we should assemble the contact plate onto load block, and adjust their horizon with bubble level as shown in "Fig.2".

Exercises and data analysis:

It is easy to set up the test, just set the test speed as 5 mm/min and the compression depth as 5 mm and put the phantom sample on the lower contacting plate. Then, manually lower the above contacting plate until the full contact to the surface of the phantom is happened but make sure it does not squeeze it hardly as it is soft so it can distort. Finally, we made measurements for 3 times in Qmat software and calculated the averaged of those measurements from the force-extension curve and using calculations to transform it to nominal stress, nominal strain, true stress and true strain. Since the ***nominal stress*** uses the 'original cross' sectional area to calculate the stress which is quite easy to do however the ***true stress*** which is more difficult to determine as it uses the cross sectional area at the 'time of measurement'.

Nominal stress= $\frac{F}{S}$ Nominal strain (ε) = $\frac{\Delta L}{L}$ (6) [4]

Where F is the average force, S is the surface area of the sample and ΔL is the extension of the phantom.

Finally, it is easy to calculate the Young's modulus from the formula of

Young's modulus = $\frac{\text{nstress}}{\text{nstrain}}$ (7) [4]

Figure 2 Set up for mechanical compression test

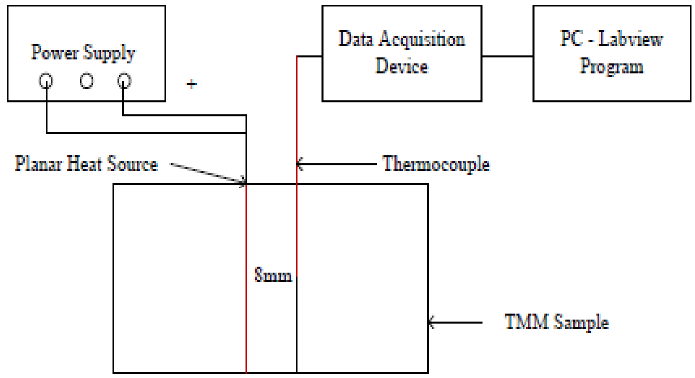

Figure 3 schematic diagram of the exprimental setup

3. Thermal property measurement

The purpose of this test to measure the temperature distribution when using high power in ultrasound phantom treatment. This measurement is very important for safety in medical devices. Also, there is another important factor for developing those devices is the thermal conductivity which is depending on the attenuation coefficient (α)[5].The another aim of this test to make tissue mimicking material (phantom) for appropriate acoustic properties for visualization thermal distribution[2]. "Fig.3" shows that the phantom is divided into three sections where the planar heat source is located between section 1 and 2 and connected to the power supply. Then, the thermocouple is placed into sections 1 and 2 which should be aligned making it straight with the center of the heater, with a distance∼ **8 mm** and connected to the data acquisition device.

Exercises and data analysis:

Firstly, we used the LabVIEW program for measure temperature rise and non-linear curve fitting; we set and save the parameters of heating on the front panel which Driving current: 0.1A, Density of the phantom: 1011kg.m^{-3}, Effective are of the heater: 0.0022m^2, Resistance of the heater: 418Ω, Thickness between the heater and thermocouple: 8mm and the whole measurement time is **600** sec. Run the LabVIEW program and on the same time turn on the power supply for the heater which the output of the supply: **40v, 0.1A**.After10 minutes, measurements is finished so turn the power supply off and wait until the red fitted curve shown in the lower curve through the non-linear curve fitting procedure. As shown in the front panel there is rise of temperature by 8.2℃ measured by the thermocouple, therefore the temperature will be 33.34℃ inside the phantom since it was 25.14℃ in the beginning of the program. Finally, we can know the thermal diffusivity , $\boldsymbol{\alpha}$ and the specific heat capacity, **c**. Then, it is easy to calculate the "thermal conductivity", **k** from the formula

$$k=\rho\alpha c \qquad (8) \qquad [5]$$

Secondly, we imported the data of temperature and time from the labVIEW for plotting the non-linear curve fitting in MATLAB program and after calculations it also is easy to calculate the "thermal conductivity", **k** from its formula.

3. Results

This discussion shows the properties of the phantom through three tests:

1- <u>Acoustic properties measurements</u>

We can easily calculate the acoustic properties from the data analysis we described before since the values of D=5.7 cm, h=38.5 mm, t1=32 ns and t2=37.998 μs.Hence the acoustic velocity of the phantom is Vs=1499.356m/s. So the acoustic impedance of the phantom is Z(s) =1.8158M kgm^{-2}/s, since its density =1011kg/cm^3.Also the reflection coefficient(R) =0.00481.Finally, we could calculate the attenuation coefficient of the phantom, is $\alpha(TMM) = 0.14\ dB/cm$.

2- Mechanical Compression Test

After we made the measurements for 3 times in Qmat software and calculated the averaged of those measurements from the force-extension curves as shown in “Fig. 4” and transform it to nominal stress, nominal strain, true stress and true strain. The measurements were F1= 16.5N, F2= 16.35N, F3= 16.35, So F (avg) = 16.4N and $\Delta L = 5\ mm$. So, we can import the data of the forces and the extensions and draw the two curves as stress-strain curves using MATLAB as shown in “Fig.5”.Nstress= 9.73276KN, nstrain= 0.099108, Tstress= 10.697kN, Tstrain= 0.0944. So, Young’s modulus= 98.2 k Pa.

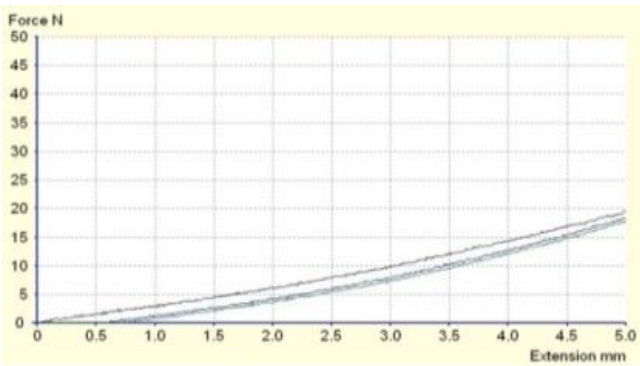

Figure 4 Force-Extension curves

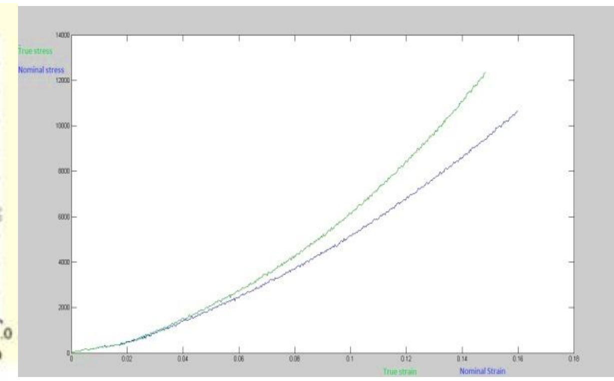

Figure 5 Stress strain curves since the green curve for true ones and the blue curve for nominal ones using MATLAB program

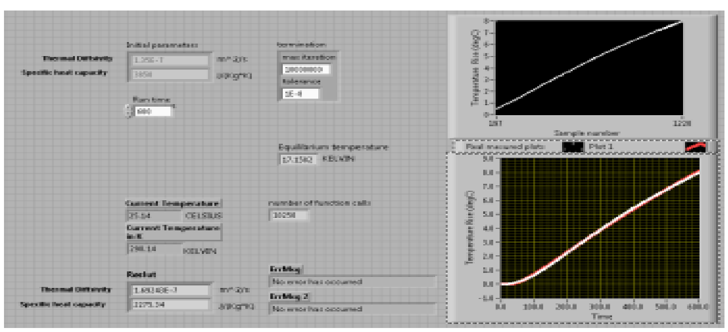

Figure 6 Front panel of labVIEW program

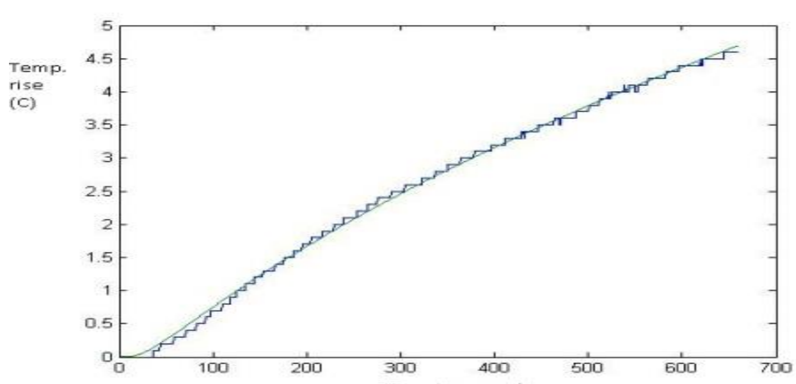

Figure7 Temperature rise(C) vs. time (t) for non-linear curve fitting

3- Thermal property measurement:

Firstly, After 600 seconds, the labVIEW program stops, and we can the values of the thermal diffusivity *, $\boldsymbol{\alpha}$* and the specific heat capacity, **c** from the front panel of the program as shown in "Fig.6", then it is easy to calculate the "thermal conductivity",**k:** Since $\alpha = 1.6924 * 10^{-7} m^2 s^{-1}$, C=2275.34J/ (Kg*K),$\rho(s) = 1011\, Kg.\mathrm{m}^{-3}$ So, k=0.3893 J/ (k.m.s). Secondly, we are also using the data of temperatures and time for plotting the non-linear curve fitting curve using the MATLAB program as shown in "Fig 7". When we compare the theoretical value (green curve) of the temperature to the measured one (blue curve),it noticed that they were not the same that due to wrongs at the time of the procedure ,for example, voltage variations, the thermocouple was not in the correct place,… etc. Again, calculating the thermal diffusivity $\boldsymbol{\alpha}$ and the specific heat capacity, **c** so we can measure the thermal conductivity, k, since $\alpha = 4.0345 * 10^{-7} m^2 s^{-1}$, C=2000.8541 J/ (Kg*K),$\rho(s) = 1011\, Kg.\mathrm{m}^{-3}$So, k=1.164 J/ (k.m.s) comparing to the value calculated from the LabVIEW it showed that the thermal conductivity, k is better from the labVIEW with comparing both to the standard k=0.34374 J/ (k.m.s) since the standard values for $\alpha = 10^{-7} m^2 s^{-1}$and for C=3400 J/ (Kg*K)[7].

4. Discussion

1- **Acoustic properties measurements:** The results of attenuation coefficient, the acoustic impedance and acoustic speed of the measured phantom were **0.015dB/cm,1.5158M$\boldsymbol{kgm^{-2}/s}$** and **1499.356m/s** respectively which those results are in range of the standard range values according to the table (1), [7] [8], so it is satisfied and it is near also to the values of human body since the coefficient of human body is (**0.4~2dB/cm**) [9], [10].

2- **Mechanical Compression Test**: The mechanical properties of the phantom are depending on an important factor to show its elasticity and this factor is used to characterize the mechanical interaction between the medical devices and phantom-representing soft tissue. From the test we measured Young's modulus=98.2kPa which also in the range according to "Elastic properties of soft tissue-mimicking phantoms assessed by combined use of laser ultrasonic and low coherence interferometer "Young's modulus=93$\pm$8.28 kPa [11].This value showed the elasticity of the phantom which means that need less load to do an extension 5 mm of the phantom.

Table 1 Sound velocities, impedances, acoustic attenuation coefficients and thermal conductivity of 2% agar.

	Velocity, Cs (k m/s)	Impedance (M $kg\ m^{-2}/s$)	Attenuation coefficient (dB/cm)	F (MHz)	Thermal Cond. (K) J/ (k.m.s)
Agar 2%	1.50 ± 0.03c	1.57 ± 0.08c	0.4 ± 0.1	5	0.4($\pm$)0.02

3- **Thermal property measurement**: As mentioned before, the thermal distribution of the phantom is very important to medical ultrasound systems to be safe. The thermal distribution is depending on the attenuation coefficient which is important to improve the medical ultrasound devices. Then we calculated the thermal conductivity which is 0.3893 J/ (k.m.s) which is satisfied, [7].

5. Conclusion

Tissue mimicking materials TMMs (phantoms) are usually adopted due to its linearity, homogeneity and repeatability. The 2% agar based phantom investigated in this paper is suitable for simulating the human body tissues and according to the results approved, the values of attenuation coefficient, sound speed and the mechanical response(Young's modulus) were quite similar to those of tissues of human bodies. Therefore, for approaching equivalence with tissue, phantoms should have similar acoustic properties to the tissue being represented across the range of frequencies used diagnostically.

6. References

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