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Assessment of the Acoustic Properties of Common Tissue-mimicking Test Phantoms

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Running title: Acoustic Properties of tissue-mimicking phantoms

ASSESSMENT OF THE ACOUSTIC PROPERTIES OF COMMON TISSUE-MIMICKING TEST PHANTOMS

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Abstract - Ultrasound test phantoms incorporating tissue-mimicking materials (TMMs) play an important role in the quality control (QC) and performance testing of ultrasound equipment. Three commercially-available TMMs (Zerdine^{TM} from CIRS Inc.; condensed milk based gel from Gammex RMI; urethane rubber based from ATS Labs) and a non commercial agar-based TMM, were investigated. Acoustic properties were measured over the frequency range 2.25 to 15 MHz at a range of ambient temperatures (10 – 35 °C). The acoustic velocity of the TMMs remained relatively constant with increasing frequency. Only the agar-based TMM had a linear increase of attenuation with frequency, with the other materials exhibiting non linear responses to varying degrees ($f^{1.08}$ to $f^{1.83}$). The acoustic velocity and attenuation coefficient of all the TMMs varied with temperature, with the urethane rubber TMM showing the greatest variation of ± 1.2 % for acoustic velocity and ± 12 % for attenuation coefficient. The data obtained in this study highlight the importance of greater knowledge of the acoustic behavior of TMMs to variations with both frequency and temperature, to ensure that accurate and precise measurements are obtained during QC and performance testing. (E-mail : 9911989batstudent.gla.ac.uk)

Key Words: Tissue-mimicking, Speed of sound, Attenuation, Backscatter, Temperature dependence and quality control.

INTRODUCTION

Ultrasound test phantoms play an important role in the quality control (QC) and performance testing of ultrasound equipment. Test phantoms should be tissue-mimicking so that their measurement results are consistent with clinical performance. In order for tissue mimicking materials (TMMs) to approach equivalence with tissue, they should have similar acoustic properties to the tissue being represented across the range of frequencies used diagnostically. Ideally, such materials should mimic soft tissue in terms of acoustic velocity, attenuation coefficient, scattering coefficient and non linearity parameter. Also, with the development of new techniques such as elastography and strain imaging, future TMMs may need to simulate the mechanical properties of tissue. The "IEC 1390" and "AIUM Standard 1990"standards for TMMs recommend an acoustic velocity of 1540 m s^{-1}, an attenuation coefficient of 0.5 dB cm^{-1} MHz^{-1} and 0.7 dB cm^{-1} MHz^{-1} for the frequency range 2 – 15 MHz with a linear response of attenuation to frequency, f^1. Non linearity has become important as an acoustic parameter, due to the development of tissue harmonic imaging; however, the different professional organisations have not yet recommended an appropriate value. Tissue is known to have a non linearity parameter of between 6 – 10, while fat has a higher value of between 10 - 11 (Law et al 1985).

There are a number of commercially-available tissue-mimicking phantoms, the more widely used being urethane rubber from ATS Labs (Bridgeport, CT, USA), condensed milk from Gammex-RMI (Middleton, WI, USA) and Zerdine^{TM} from CIRS Inc. (Norfolk, VA, USA). The data reported in the product literature for each of the tissue-mimicking phantoms is usually for only one frequency at room temperature, with the exception of the Gammex-RMI condensed-milk-based gel which has an attenuation coefficient of either 0.5 dB cm^{-1} MHz^{-1} (0.5) or 0.7 dB cm^{-1} MHz^{-1} (0.7). The data are insufficient, as TMMs are routinely used for testing ultrasound scanners between 2 -15 MHz. Also, the room temperature and the test phantom temperature may vary during the QC testing or from one QC test to another. Therefore, data for the effect of frequency and temperature on acoustic properties are important and should be available for TMMs. Any variations in TMMs' acoustic properties with temperature and frequency could result in inaccurate QC and performance testing results being obtained (Iball et al 2001). In this paper, the effect of variations in frequency and temperature on the acoustic properties of three commercially-available TMMs and an agar TMM developed as part of an European Commision project will be presented (Teirlinck et al 1998).

MATERIALS AND METHODOLOGY

Tissue-mimicking materials (TMMs)

The tissue-mimicking materials investigated were: a hydrogel-based material Zerdine™ (nominal specified attenuation 0.5 dB cm^{-1} MHz^{-1}) (CIRS Inc. Norfolk, USA); a urethane-rubber-based material (0.5 dB cm^{-1} MHz^{-1}) (ATS Labs; Bridgeport, USA), two condensed-milk-based gel materials (0.5 and 0.7 dB cm^{-1} MHz^{-1}) (Gammex RMI, Middleton, USA); and an agar material (0.5 dB cm^{-1} MHz^{-1}) developed through an EC funded project (Teirlinck et al 1998; Ramnarine et al 2001) (Table 1). These five TMMs were chosen because each represented the different types of material frequently used in test phantoms. All samples were obtained from the manufacturers, apart from the agar material, which was made in the Medical Physics Department in Edinburgh University, as described elsewhere (Ramnarine et al 2001). The Zerdine™ and the two condensed milk gel samples were contained within a test cylinder covered on both ends by 25 μm thick Saran Wrap® (Extol, Ohio, USA), while a machined cylinder of the urethane rubber without any test cylinder was used. The dimensions of the samples are presented in Table 2.

Measurements of acoustic velocity, attenuation coefficient and relative backscatter

The acoustic velocity, attenuation coefficient and relative backscatter coefficient of the TMM samples were determined using a scanning acoustic macroscope (SAM) system (Ultrasonic Sciences Limited, Fleet, UK) by the pulse echo substitution method (Schwan and Carstensen 1952). The scanning macroscope was used as it allows the collection and averaging of ultrasound data over a defined area of the sample. This allows spatial averaging and improves the signal-to-noise ratio. The experimental set-up is shown in Fig. 1. The SAM system consisted of a water tank, an 8-bit 100 MHz general purpose analog-to-digital input/output PC board, a 1-20 MHz pulser receiver and a stepper motor control system, all of which were controlled by a PC. The pulse-echo technique involved the use of one transducer acting as both the transmitter and receiver. For the acoustic velocity and attenuation coefficient, the driving voltage of the transducer was set at the relatively low value of 100 V in order to minimise non linearity effects. For backscatter measurements, the driving voltage was increased to 300 V to improve the signal-to-noise ratio. The pulse was reflected from a highly-polished flat steel plate back to the transducer through degassed water. An area of 16 mm x 16 mm was scanned in increments of 1 mm. At each position of the transducer, the reflected rf signal from the steel reflector was digitised at a sampling rate of 100 MHz and stored for offline analysis. Data were collected with and without the sample in place, to provide sample and reference data sets. The fast Fourier transform (FFT) of each of the signals was obtained using an in-house-developed program written in MATHLAB (MathWorks Inc., Natick, MA, USA). To improve the signal-to-noise ratio, averaging was performed on the 256 FFTs. The acoustic velocity (c), attenuation coefficient (α) and relative backscatter coefficient (μ) of each of the TMM samples were determined by comparing the resulting frequency spectra following measurements by the transducer with and without the sample in place. The acoustic velocity of the samples was determined by measuring the time shift Δt in the position of the rf pulse from the steel reflector with and without the tissue sample in the path, given by eqn 1:

$$\frac{1}{c_s} = \frac{1}{c_w} - \frac{\Delta T}{2d} \qquad \textbf{[1]}$$

where c_s = acoustic velocity in the sample, c_w = acoustic velocity in degassed water, d = sample thickness and Δt = time shift upon displacement of the water with the sample in place.

The reference acoustic velocity in degassed water as a function of temperature was set between 1447 m s^{-1} at 10° C to 1520 m s^{-1} at 35° C (Del Grosso and Mader 1972). The uncertainty in c was estimated to be ± 1 m s^{-1} due to a random error of ± 0.5 m s^{-1} and a systematic error of ± 0.8 m s^{-1} within frequency range 2.25 – 15 MHz. The systematic error was due to uncertainty in the measurement of the sample thickness, the uncertainty in the measurement of the difference between the time of arrival of the reference pulse and the pulse through the sample and, finally, the uncertainty of the acoustic velocity of the reference medium.

The attenuation as a function of frequency was calculated from the log difference between the two spectra obtained and given by eqn (2):

$$\alpha(x,y,f) = -\frac{20}{2d}\log_{10}\frac{A(x,y,f)}{A_o(x,y,f)} \quad [\mathrm{dB\ cm^{-1}}] \qquad \textbf{(2)}$$

where A(x,y,f) = magnitude of the spectrum with the sample in place; and A_o(x,y,f) = magnitude of the spectrum with no sample in place.

Corrections were made for the samples containing Saran Wrap® at both ends, taking into account attenuation of the beam by the two Saran Wrap® layers, by subtracting the attenuation of a cell containing degassed water bound by two Saran Wrap® layers. The accuracy of attenuation measurement was assessed using two standard silicone oil test cells calibrated by the National Physical Laboratory (Teddington, UK).

The uncertainty in attenuation was estimated to be ± 0.03 dB cm^{-1} due to a random error of ± 0.02 dB cm^{-1} and a systematic error of ± 5 % within frequency range 2.25 - 15 MHz. The systematic error was due to reflection, diffraction, alignment of the transducer and uncertainty in the measurement of the sample thickness.

Relative backscatter coefficients measurements of the TMMs were made in dB relative to the signal from a flat steel reflector at the transducer focus. A gate length of 4 μs was used and the gated rf signal at the focus was analysed. The relative backscatter was calculated in dB from the log difference between the spectra at the transducer focus, given by eqn (3):

$$\mu(x,y,f) = -\frac{20}{2d}\log_{10}\frac{A(x,y,f)}{A_0(x,y,f)} \quad [\mathrm{dB}] \qquad \mathbf{(3)}$$

The sample was positioned with the transducer focus just beyond the sample surface, in order to minimise attenuation loss through the sample and to gate out the sample /

water interface reflection. The repeatability of the measurements was found to be ±1 dB.

The effects of frequency on the acoustic velocity and attenuation of the samples at 20 °C ± 0.5 °C were measured using the SAM with four broadband transducers centered at 2.25 MHz (Ultrasonic Sciences Limited, Fleet, UK), 3.5 MHz (Panametrics, MA, USA), 7 MHz (Ultrasonic Sciences Limited, Fleet, UK) and 15 MHz (Panametrics, MA, USA). The details of each of the transducers are presented in Table 3.

The effects of temperature on acoustic velocity, attenuation and relative backscatter measurements of the samples were measured using the SAM system with 2.25 MHz, 7 MHz and 15 MHz broadband transducers. Each set of TMM measurements were made for the temperature range between 10 – 35 °C. The temperature was controlled to ± 0.5 °C. Sufficient time (about 1 h) was allowed for the test cylinders to reach thermal equilibrium with the water bath before the measurements were made.

RESULTS

Effect of frequency on the acoustic properties : acoustic velocity and attenuation

The effect of frequency on the acoustic velocity and attenuation of the different TMMs at 20 °C are presented in Figs. 2 to 4. The acoustic velocity of all the TMMs tested remained relatively constant (± 3 m s^{-1}) with increasing frequency. The attenuation coefficient of all of the TMMs increased with increasing frequency; the largest increase in the attenuation coefficient was observed for the urethane rubber from 0.43 dB cm^{-1} at 2.25 MHz to 2.53 dB cm^{-1} at 15 MHz. Urethane rubber and Zerdine™ exhibited highly non linear responses of attenuation to frequency of $f^{1.83}$ and $f^{1.3}$, respectively, while the condensed milk gel (0.5) and condensed milk gel (0.7) materials exhibited slightly non linear responses ($f^{1.1}$ and $f^{1.08}$). The agar TMM was the only material to exhibit a linear response of attenuation to frequency ($f^{1.01}$).

Effect of temperature on the acoustic properties : acoustic velocity, attenuation and relative backscatter value

The effect of temperature on acoustic velocity on the five TMMs can be seen in Fig. 5 for the 7 MHz transducer and Tables 4 and 5 for the 2.25 MHz and the 15 MHz transducers. The acoustic velocity of the agar, condensed milk gel (0.5) and condensed milk gel (0.7) TMMs all increased with increasing temperature, by a rate of approximately 1.5 m s^{-1} °C^{-1}. Whereas, the Zerdine™ increased by a rate of 2 m s^{-1} °C^{-1} and the ATS TMM decreased by a rate of approximately 2.5 m s^{-1} °C^{-1} with increasing temperature.

The effects of temperature on attenuation coefficient for the five TMMs can be seen in Fig. 6 for the 7 MHz transducer and Tables 6 and 7 for the 2.25 MHz and 15 MHz transducers. The attenuation coefficient of the urethane rubber, condensed milk gel (0.5) and condensed milk gel (0.7) TMMs decreased with increasing temperature by a rate of less than 0.02 dB cm^{-1} MHz^{-1} °C^{-1}, with the exception of the urethane rubber TMM at 15 MHz, which decreased by a rate of 0.08 dB cm^{-1} MHz^{-1} °C^{-1}. The change in the attenuation coefficient of 0.005 dB cm^{-1} MHz^{-1} °C^{-1} with temperature for the agar and Zerdine^{TM} TMMs was less than the experimental error, therefore both TMMs appeared to remain constant with increasing temperature.

The effect of temperature on the relative backscatter coefficient can be seen in Fig. 7. The relative backscatter coefficient of all of the TMMs remained relatively constant with increasing temperature.

DISCUSSION

The effects of frequency and temperature on the acoustic properties of the five TMMs were investigated. The effects of frequency on the acoustic velocity and attenuation of the TMMs are important, as TMMs are used routinely to evaluate ultrasound scanners with different frequency probes. The effect of frequency on acoustic velocity is important, due to the calibration velocity (1540 m s^{-1}) of ultrasound scanners. A large variation in the acoustic velocity of tissue-mimicking materials occurring for the different frequencies tested has been shown to result in distance measurement errors and defocusing of the beam, which would both result in deterioration of the lateral resolution measurements of the scanner (Goldstein 2000; Dudley et al 2000). The IEC

1390 standard recommends that the acoustic velocity of test phantom remains constant for the diagnostically-used frequency range of 2 - 15 MHz, which was found to be the case for the five TMMs tested (± 3 m s^{-1}).

The IEC 1390 standard also suggests, that the test object material should have a linear response of attenuation to frequency, f^1, and an attenuation coefficient of 0.5 or 0.7 dB cm^{-1} MHz^{-1}, as is the case for tissue in general. It was found that the agar and condensed milk gel (0.5) TMMs had responses of $f^{1.01}$ and $f^{1.08}$, respectively, to frequency, while the condensed milk gel (0.7) TMM had a response of $f^{1.1}$ to frequency. The urethane rubber and Zerdine^{TM} TMMs had highly non linear responses to frequency, $f^{1.83}$ and $f^{1.3}$, respectively. In a recent Medical Devices Agency report (MDA 1024), it was found, that for a variety of probes with frequencies greater than 8 MHz, the penetration depth measured in the model 550 test object (ATS) was less than in the model 404GS LE test object (Gammex-RMI). This result was reported as being unexpected, as the model 404GS LE test object was specified with a higher attenuation coefficient (0.7 dB cm^{-1} MHz^{-1}) than the model 550 test object, which has a reported attenuation coefficient of 0.5 dB cm^{-1} MHz^{-1}. The frequency response results obtained in this study for the urethane rubber ($f^{1.83}$) and condensed milk ($f^{1.08}$) TMMs should explain the unexpected result reported in the MDA 1024 report.

Tissue-mimicking materials, which exhibit a significant non linear response of attenuation to frequency potentially produce QC and performance results which are not representative of tissue, as the higher frequencies would be attenuated more than they would in tissue (O' Donnell and Miller 1979). Consequently, a deterioration in axial resolution and penetration depth measurement results at higher frequencies would be perceived (Zagzebski and Madsen 1995; Browne et al 2002).

It was found that changes in temperature resulted in change in acoustic velocity, the greatest change occurring in the urethane rubber TMM (± 2.5 m s^{-1} $°C^{-1}$). The IEC 1390 standard recommends that changes in acoustic velocity due to temperature changes should be less than 3 m s^{-1} $°C^{-1}$; all of the TMMs complied with this recommended value. However, if the temperature of any of the above test objects varied from 25 °C to 15 °C between two QC tests, this would result in a change of approximately 10 m s^{-1} of the TMMs' acoustic velocity, which would result in changes in the lateral resolution and slice thickness results. If the acoustic velocity of the TMM differs greatly from the calibrated acoustic velocity of the ultrasound scanner, then there will be an effect on the distance measurement accuracies and the lateral resolution and slice thickness of the QC and performance test results (Goldstein 2000; Dudley et al 2000). This effect may be more prominent in the urethane rubber TMM, as it has a significantly lower acoustic velocity (1460 m s^{-1}) compared with the ultrasound scanners' calibrated acoustic velocity (1540 m s^{-1}), a situation which is further compounded if temperatures lower than room temperature are experienced. The manufacturers have reported that the object placement within the phantom is such that the distance inaccuracies caused by the 1460 m s^{-1} acoustic velocity are taken into account at 22 °C.

The above results suggest that it is best to use test objects at or near room temperature, but that particular care should be taken when using the urethane rubber TMM. However, it has been suggested that the urethane rubber TMM should not be used for evaluating distance measurement inaccuracies or transducer focusing performance, due to both its low acoustic velocity and its highly non linear response of attenuation to frequency (Goldstein 2000).

The IEC 1390 standard recommends that changes in attenuation coefficient due to changes in temperature should be less than 0.02 dB cm^{-1} MHz^{-1} °C^{-1}; again, all of the TMMs complied with this recommended value apart from the urethane rubber TMM (0.08 dBcm^{-1}MHz^{-1}°C^{-1}) at 15 MHz. This change in the attenuation coefficient of the urethane rubber TMM with temperature at 15MHz means that any temperature change within or between QC tests would have a significant effect on the measured axial resolution and penetration depth for the U/S scanner, which would not be reflective of its actual performance (Goldstein 2000; Iball 2001).

The purpose of QC testing is to monitor changes in the performance of the different imaging parameters of the ultrasound scanner over time. There are set threshold values for each of these imaging parameters that are used to determine whether the ultrasound scanner needs corrective action to be taken, such as maintenance, or even to be removed from clinical use, in extreme changes. Therefore, the response of the TMM's acoustic parameters to changes in frequency and temperature should be taken into account when performing QC testing, or controlled in the case of temperature.

The effect of temperature on the relative backscatter was investigated and it was found that the relative backscatter of the five TMMs remained relatively constant (± 1 dB) with increasing temperature.

CONCLUSIONS

The effects of frequency and temperature on the acoustic properties of the five TMMs were investigated. It was found that acoustic velocity remained constant (± 3 m s^{-1}) with increasing frequency, while attenuation was found to increase with increasing frequency. In order for the TMMs to reflect the clinical situation, they should have a linear response of attenuation to frequency. The urethane rubber and Zerdine™ TMM were found to have non linear responses of attenuation to frequency ($f^{1.83}$ and $f^{1.3}$), which has been found in other studies to result in a deterioration in penetration depth results as well as axial resolution results at frequencies greater than 7 MHz (MDA 1024 2001; Goldstein 2000; Browne et al 2002).

It was found that the acoustic velocity of the agar, Zerdine™, condensed milk (0.5) and condensed milk (0.7) increased with increasing temperature by a rate of approximately 1.5 m s^{-1} $°C^{-1}$. Whereas, the acoustic velocity of the urethane rubber TMM decreased with increasing temperature, by a rate of 2.5 m s^{-1} $°C^{-1}$. All the changes found in acoustic velocity with temperature for each of the TMMs were within the IEC 1390 recommended value of 3 m s^{-1} $°C^{-1}$. Despite all the changes in acoustic velocity being with the recommended IEC 1390 value, all efforts should be made to use test objects at or near room temperature, in order for subtle changes in the scanners performance between QC tests to be detected with confidence; particular care should be taken when using the urethane rubber TMM.

Large changes in attenuation coefficient with temperature may significantly effect the QC and performance test results for the ultrasound scanners; however, the changes observed in attenuation coefficient with temperature for the agar, Zerdine^{TM}, condensed milk gel (0.5) and condensed milk gel (0.7) TMM samples should have a negligible effect. Whereas, the rate of change of the attenuation coefficient (0.08 dB cm^{-1} MHz^{-1} °C^{-1}) with temperature found for the urethane rubber TMM at 15 MHz would have a significant effect on the axial resolution and penetration depth results for QC tests of ultrasound scanner, measured at different temperatures.

This study has served to highlight the need for more extensive data on the acoustic properties of commercially-available TMMs with both frequency and environmental changes such as temperature, so that accurate and precise QC and performance test results may be obtained. Furthermore, with the introduction of tissue harmonic imaging in most commercial scanners, there is a growing need to determine the non linearity parameter of TMMs. There is clearly a need for more work to be carried out in order to determine the full acoustic properties of all commercial and research TMMs. With new techniques such as elastography imaging, stress/strain imaging and arterial compliance imaging being developed, there may be a need in the future to have TMMs which also mimic the elastic properties of tissue.

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Table 1. Manufacturer Reported Acoustic Data of Common TMMs.

TMM	Acoustic Velocity, c (m s^{-1}) at 22 °C	Attenuation Coefficient, α (db cm^{-1} MHz^{-1}) at 22 °C	Non linearity parameter, B/A at 22 °C
Urethane rubber (ATS Labs)	1460 at 3 MHz	0.5 and 0.7 at 3-4 MHz	unknown
Zerdine^{TM} (CIRS Inc.)	1540 at 3 - 4 MHz	0.5 and 0.7 at 3-4 MHz	unknown
Condensed milk gel (0.5) (Gammex RMI)	1540* at 2 - 18 MHz	0.5* at 2 - 18 MHz	6.6
Condensed milk gel (0.7) (Gammex RMI)	1540* at 2 - 18 MHz	0.7 * at 2 - 18 MHz	6.6
Agar (EC Project)	1540 at 2 - 10 MHz	0.5 at 2 - 10 MHz	unknown

* 10-30 °C

Table 2. Dimensions of the Tissue-Mimicking Samples Tested.

TMM	Agar	Urethane rubber	Zerdine^{TM}	Condensed milk (0.5)	Condensed milk (0.5)
Thickness	0.5 cm	3.96 cm 0.5 cm	2.5 cm 0.5 cm	3.51 cm 0.5 cm	3.52 cm 0.5 cm
Diameter	2 cm	5 cm	5 cm	7 cm	7 cm

Table 3. Transducer Characteristics.

Frequency	2.25 MHz	3.5 MHz	7 MHz	15 MHz
Crystal diameter (mm)	14.1	9.9	11.8	9.4
Focal length (mm)	43	57.9	54	36.9
Centre frequency (MHz)	2.25	3.89	7	15.1
- 6 dB bandwidth (%)	57.7	63.4	71	50

Table 4. Effect of temperature on acoustic velocity of the five TMMs at 2.25 MHz.

	Acoustic velocity [± 1 m s^{-1}]				
Temp (°C)	**Agar**	**Urethane rubber**	**Zerdine™**	**Condensed milk gel (0.5)**	**Condensed milk gel (0.7)**
10	1532	1490	1517	1516	1522
20	1546	1466	1538	1535	1545
30	1550	1448	1558	1544	1552

Table 5. Effect of temperature on acoustic velocity of the five TMMs at 15 MHz.

	Acoustic velocity [± 1 m s^{-1}]				
Temp (°C)	**Agar**	**Urethane rubber**	**Zerdine™**	**Condensed milk gel (0.5)**	**Condensed milk gel (0.7)**
10	1531	1496	1522	1523	1525
20	1547	1468	1536	1537	1542
30	1553	1447	1554	1548	1552

Table 6. Effect of Temperature on attenuation of the five TMMs at 2.25 MHz.

	Attenuation coefficient [± 0.03 dB cm^{-1} MHz^{-1}]				
Temp (°C)	**Agar**	**Urethane rubber**	**Zerdine^{TM}**	**Condensed milk gel (0.5)**	**Condensed milk gel (0.7)**
10	0.56	0.55	0.72	0.6	0.8
20	0.57	0.43	0.69	0.57	0.76
30	0.56	0.31	0.69	0.51	0.7

Table 7. Effect of Temperature on attenuation of the five TMMs at 15 MHz.

	Attenuation coefficient [± 0.03 dB cm^{-1} MHz^{-1}]				
Temp (°C)	**Agar**	**Urethane rubber**	**Zerdine^{TM}**	**Condensed milk gel (0.5)**	**Condensed milk gel (0.7)**
10	0.7	3.5	1.48	0.95	1.24
20	0.67	2.5	1.46	0.84	0.97
30	0.59	1.95	1.45	0.8	0.87

List of Figures

Figure 1 : Experimental Set-up for the Scanning Acoustic Macroscope.

Figure 2 : Effect of Frequency on Acoustic velocity (± 1 m s^{-1}) of the five TMMs at 20 ºC.

Figure 3 : Effect of Frequency on Attenuation Coefficient (± 0.03 dB cm^{-1} MHz^{-1}) of the five TMMs at 20 ºC.

Figure 4 : Effect of Frequency on Attenuation of the five TMMs at 20 ºC.

Figure 5 : Effect of Temperature on Acoustic velocity (± 1 m s^{-1}) of the five TMMs at 7 MHz.

Figure 6 : Effect of Temperature on Attenuation Coefficient (± 0.03 dB cm^{-1} MHz^{-1}) of the five TMMs at 7 MHz.

Figure 7 : Effect of Temperature on Relative Backscatter Value (± 1 dB) of the five TMMs at 7 MHz.

Figure 1

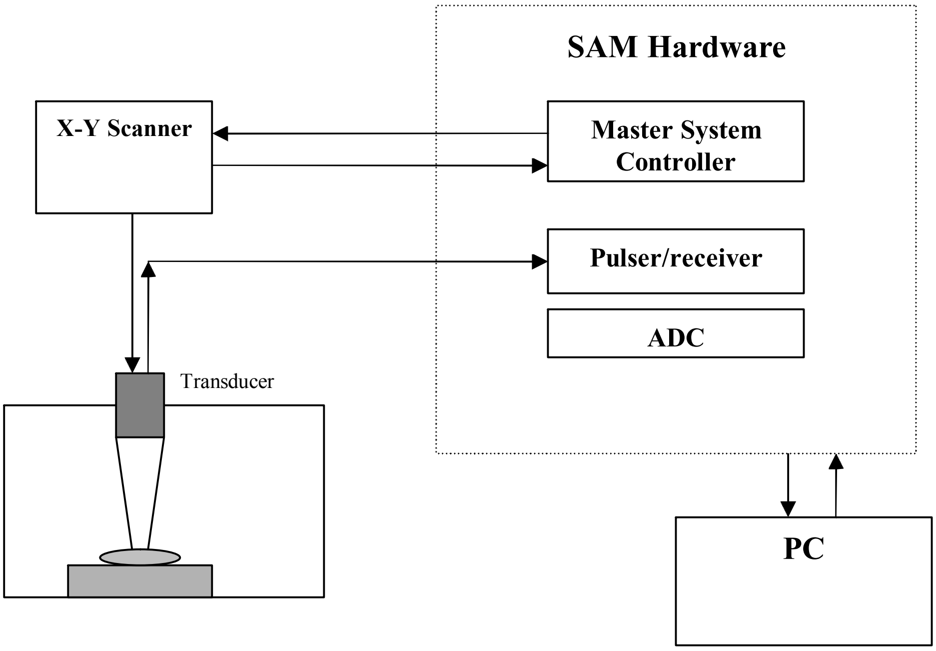

SAM Hardware
X-Y Scanner
Master System Controller
Pulser/receiver
ADC
Transducer
PC

Figure 2

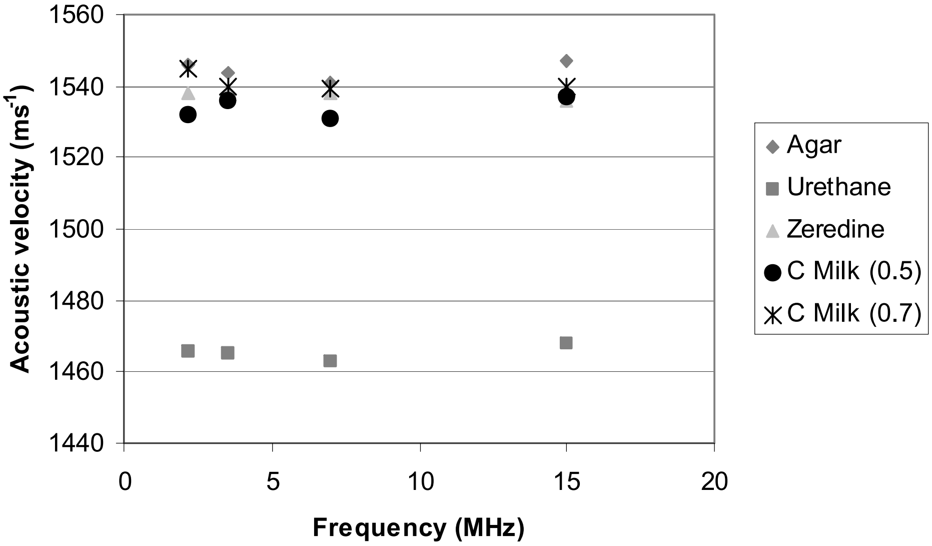
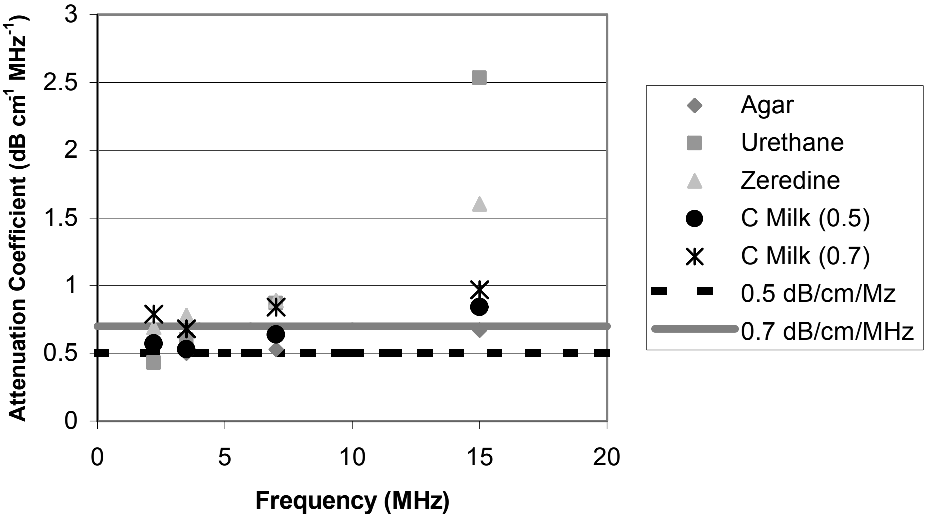

1560
1540
1520
1500
1480
1460
1440
Acoustic velocity (ms^{-1})
0
5
10
15
20
Frequency (MHz)
Agar
Urethane
Zeredine
C Milk (0.5)
C Milk (0.7)

Figure 3:



Attenuation Coefficient (dB cm^{-1} MHz^{-1})
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
Frequency (MHz)
Agar
Urethane
Zeredine
C Milk (0.5)
C Milk (0.7)
0.5 dB/cm/Mz
0.7 dB/cm/MHz

Figure 4

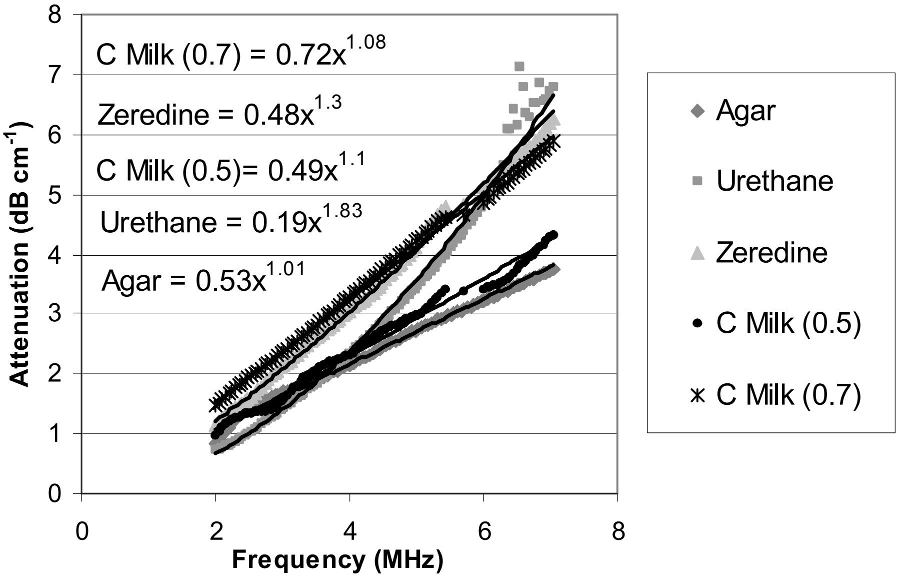
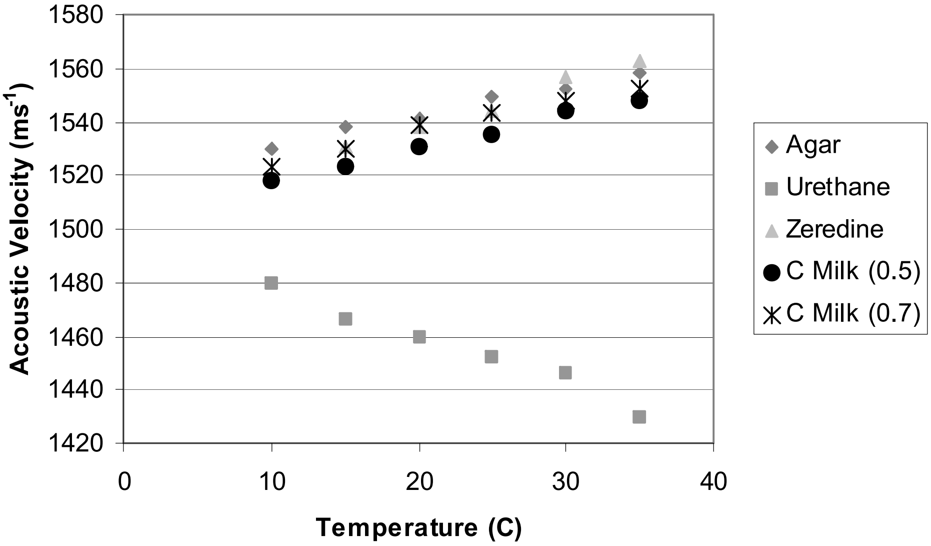
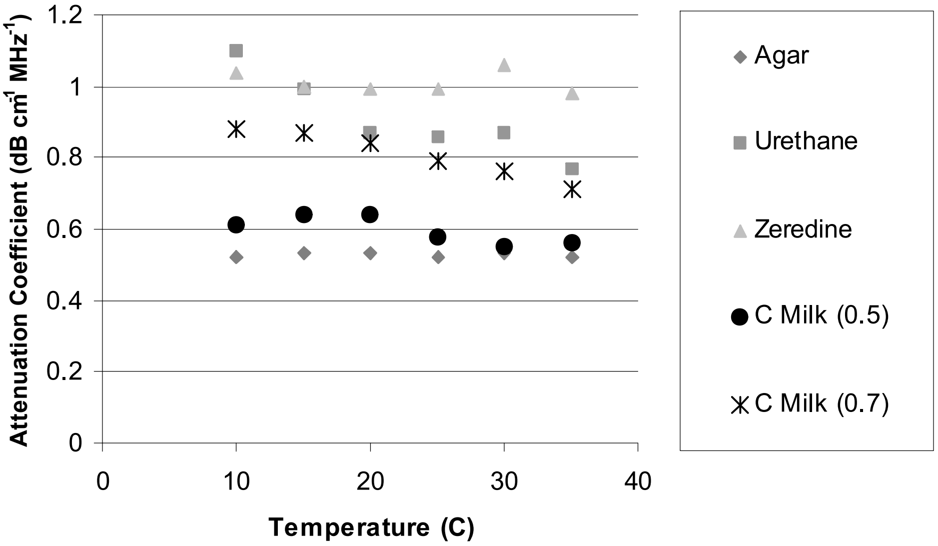

C Milk (0.7) = 0.72x^1.08
Zeredine = 0.48x^1.3
C Milk (0.5)= 0.49x^1.1
Urethane = 0.19x^1.83
Agar = 0.53x^1.01
Attenuation (dB cm^-1)
Frequency (MHz)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
◆ Agar
■ Urethane
▲ Zeredine
● C Milk (0.5)
⁎ C Milk (0.7)

Figure 5:


1580
1560
1540
1520
1500
1480
1460
1440
1420
Acoustic Velocity (ms^{-1})
0
10
20
30
40
Temperature (C)
◆ Agar
■ Urethane
▲ Zeredine
● C Milk (0.5)
✳ C Milk (0.7)

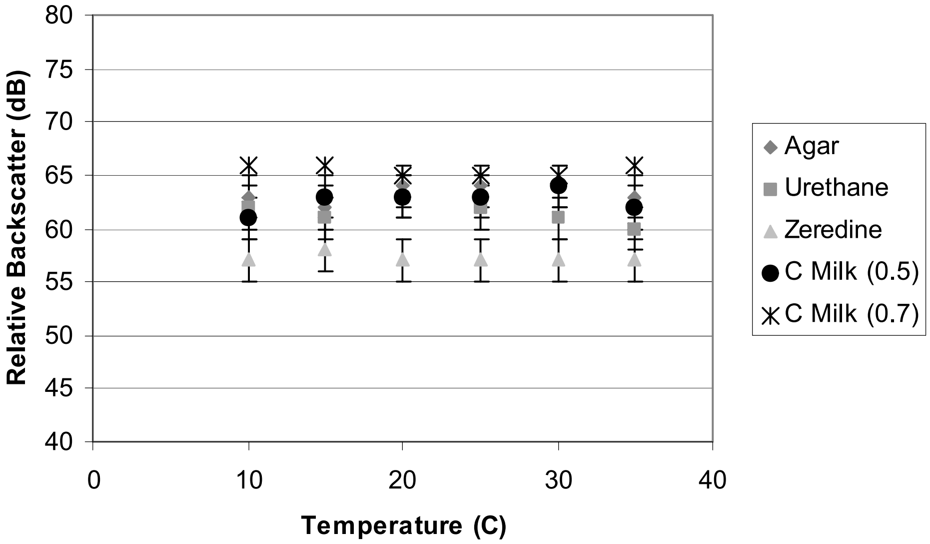
-

Figure 6


1.2
1
0.8
0.6
0.4
0.2
0
Attenuation Coefficient (dB cm-1 MHz-1)
0
10
20
30
40
Temperature (C)
Agar
Urethane
Zeredine
C Milk (0.5)
C Milk (0.7)

-

Figure 7


Relative Backscatter (dB)
80
75
70
65
60
55
50
45
40
0
10
20
30
40
Temperature (C)
◆ Agar
■ Urethane
▲ Zeredine
● C Milk (0.5)
✱ C Milk (0.7)