A Thesis For The Degree Of Master Of Science

Acoustic characterization Tofu and Acorn Curd (Dotori Muk) for Potential Tissue Mimicking Materials

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ABSTRACT

The purpose of this study is to characterize Tissue Mimicking Materials (TMMs) by various acoustic parameters including sound speed, the magnitude and the frequency dependence of the attenuation coefficient, and the magnitude and the frequency dependence of the backscattering coefficient. The acoustic properties need to be extensively measured for acoustic characterization. To reduce the measurement time and the manual operation errors, an automatic system was developed. In this study, Tofu and Acorn Curd (Dotori Muk) were suggested as TMMs, which are low in cost and easily available. The acoustic properties including sound speed, the attenuation coefficient and the backscatter coefficient of Tofu and Muk were measured in this study. Sound speed was measured by time of flight in a pulse echo setup. The attenuation coefficients and the backscattering coefficients were measured by a broadband method using 1, 5, 10MHz transducers in the frequency domain. Stability of acoustic properties among the different packets of Tofu and Muk was also tested in this research. In conclusion, Tofu and Muk have similar acoustic properties of some of tissues and may be used as TMMs in various research fields.

국문초록

이 논문의 목적은 음속, 감쇠계수의 크기와 주파수 종속성, 그리고 후방산란 계수의 크기와 주파수 종속성을 포함하는 다양한 음향 변수를 이용해서 생체조직 모사 물질을 특성화 하는 것이다. 음향학적 특성들은 반복되는 측정을 요하므로 측정 시간을 절약하고 수 작동 오차를 감소시키기 위해서 자동 측정법과 자동 분석 시스템을 개발하였다. 이 논문에서는 생체조직 모사 물질로 두부와 도토리 묵을 제안하였다. 음속은 펄스 에코 장치에서 도달 시간으로 측정하였고, 감쇠계수와 후방산란 계수는 주파수 영역에서 1, 5, 10 MHz 트랜듀서를 사용한 대역폭 방법 (broadband method)을 사용하여 측정하였다. 또한 이 논문에서는 여러 다른 포장의 두부와 묵의 음향학적 특성이 일치하는지를 연구하였다. 결론적으로 두부와 묵은 음향학적 특성이 생체 조직과 유사하므로, 생체조직 모사물질로서 여러 연구분야에 사용될 수 있다.

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Chapter 1

1.INTRODUCTION

1.1General

Tissue-mimicking materials (TMMs), which simulate acoustic properties of biological tissues, play important roles in the research of ultrasonic bioeffects, scattering analysis, and transducer technologies. In this study, Tofu and Acorn Curd (Dotori Muk) were suggested as tissue mimicking materials, which are low in cost and easily available. The acoustic properties including sound speed, attenuation coefficient, and the backscatter coefficient of Tofu and Muk were measured in this study. Sound speed was measured by time of flight in a pulse echo setup. Attenuation coefficients and backscatter coefficients were measured by a broadband method using 1, 5, 10MHz transducers in the frequency domain. The acoustic properties need to be extensively measured. To reduce the manual operations errors and consume less time, an automatic measurement and analysis system was developed.

It has been anticipated that the quantitative analysis of the backscattered signals from tissues can provide useful information about the tissues, and may lead to the development of fruitful functional ultrasonic imaging (Meziri et al., 2005; Donnell & Miller 1981) if it can be utilized.

1.2 Previous Works

Tofu was suggested as a TMM substitute in 1999, by Szabo (Szabo et al., 1999). Wu (2001) measured the acoustic properties of three types (soft, firm, extra-firm types) of commercially available Tofu. However, Wu only measured the density, sound speed and attenuation coefficient. To our knowledge, the backscatter coefficient is still not reported yet.

Variation in attenuation and sound speed can depend on the properties of the materials. If we measure the variations in ultrasound properties, we can extract some information about properties of the materials. Currently about 150 groups in the worldwide are using this ultrasonic technology to characterize all kinds of the materials for different purposes. (Andrei et al., 2001) The study of tissue characterization using this technology is under progress. Beside the sound speed and attenuation, the scattering signal has been used to characterize the materials.

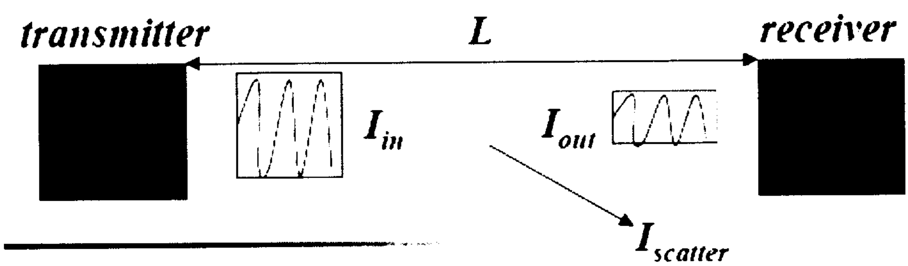


Figure 1: The information of material brought by ultrasound (Andrei et al, 2001)

Some groups are also using the quantitative backscattering signals to characterize the tissues. (Waag & Astheimer 1990; Shung & Thieme, 1993) In this study, acoustic characterizations with five parameters, namely, sound speed, the magnitude and the frequency dependence of attenuation coefficient and the backscatter coefficient are proposed.

1.3 Specific Aims of Research

This technology is already used for the pure liquid system and the experimental setup is already developed to measure the particle size of pure liquid (Andrei et al, 2001). In comparison to pure liquid, tissue is inhomogeneous and has complex structures, which often makes it difficult to be characterized. Hence, those kinds of inhomogeneous materials, which have the similar acoustic properties with tissues, are extremely useful for this research. Meanwhile, this kind of research involved extensive measurements of the acoustic properties.

Specifically, this research can be divided into three areas. The first one is to measure the acoustic properties of Tofu and Muk as potential TMMs. The second one is to build an automatic system to measure the acoustic properties. The third one is to do some basic research for characterization of TMMs.

1.4 Overview

Chapter 2 describes the method to measure the density, sound speed, attenuation coefficient and the backscattering coefficient in detail.

Chapter 3 provides a complete description of the experiment setup and introduces an automatic measurement system of the acoustic properties.

Chapter 4 presents the measurements of the acoustic properties of Tofu and Muk. Comparison of the results with the previous research and the acoustic properties of some tissues are provided along with the reasoning as to why Tofu and Muk can be used as TMMs. The emphasis is on the benefits of Tofu and Muk in using them as TMMs. Their applicability is also mentioned.

Chapter 5 presents the theory of tissue characterization using acoustic properties.

Chapter 6 tests the stability of acoustic properties of Tofu and Muk and provides the standard distribution, variation range of sound speed and attenuation coefficient of the Tofu samples.

Chapter 7 summarizes the findings in this research and then provides some suggestions for future work.

Chapter 2

2.THE METHODS TO MEASURE THE ACOUSTIC PROPERTIES

The measurement methods of sound speed, the density, the attenuation coefficient, and the backscatter coefficient of the sample are explained in this chapter.

2.1 Measurement of sound speed and thickness of the sample

This method requires measurements of time of flights for calculating the time delays: the time delay between the two surface-reflected signals, Δt_1, and the time delay between the two pulse-echo signals of reflector with and without the sample, Δt_2, (He, 2001).

$$\Delta t_1=2L/C \tag{2.1}$$

$$\Delta t_2=2(L/C_w-L/C) \tag{2.2}$$

,where C and C_w are sound speeds of the sample and water, respectively. From equation (1) and (2), the sample thickness (L) (Fig. 1) and sound speed (C) of the sample can be solved as:

$$L=(\Delta t_2+\Delta t_1)\, C_w/2 \quad (2.3)$$

$$C=(1+\Delta t_2/\Delta t_1)\, C_w \quad (2.4)$$

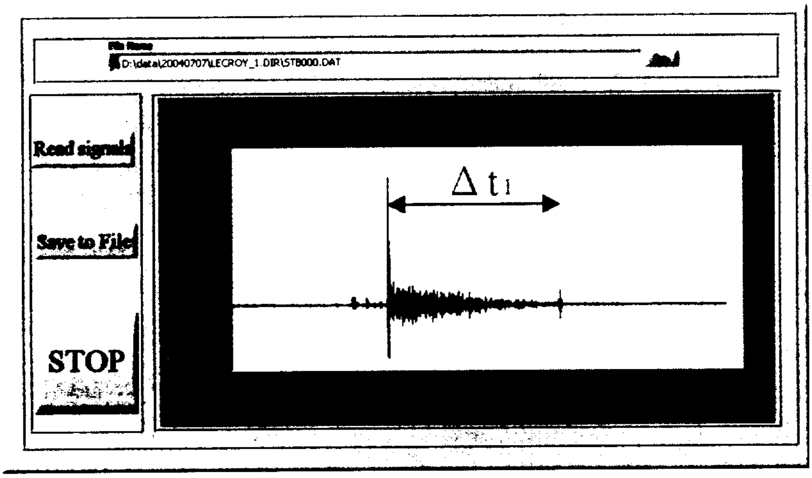


Figure 2: A received echo signal in Labview program. The left maximum signal is the reflected signal from the 1st interface; the rightmost signal is the reflected signal from the 2nd interface. The signals between the two surfaces are the volume scattering signals within the sample.

2.2 Measurement of the sample density

The 15×15×25 mm hexahedral samples of Tofu and Muk were put into a water-filled thin tube and the volume was measured by an increase of the water level. Its weight was measured by an analytical balance to calculate density, $\rho = m/V$, where, m is the mass and V is the volume of the sample. The mean density of 10 pieces of Tofu and Muk were 1.14 ± 0.05 g/cm^3 and 1.23 ± 0.05 g/cm^3, respectively.

2.3 Measurement of attenuation coefficient

Attenuation is assumed to be the same within the sample of Tofu or Muk, and the extremely large signals from air bubbles and other inhomogeneous contents inside the samples were excluded for analysis. Attenuation coefficient of the sample at a frequency f is given as (Wu, 2001)

$$\alpha(f)=8.68\times\log_e(T^2A_w/A_t)/2L \qquad (2.5)$$

, where L is the thickness of the sample, A_w and A_t are the spectrum amplitudes without and with the sample, respectively. T is the transmission coefficient and is given as,

$$T=(4Z_wZ_s)/(Z_w+Z_s)^2 \qquad (2.6)$$

,where Z_w and Z_s are the characteristic acoustic impedances of water and the sample, respectively.

2.4 Measurement of backscattering coefficient

A broadband substitution method was used for measuring the backscattering properties (Donnell & Miller, 1981). An ultrasonic beam with an effective diameter D (beam diameter of 3-dB points) penetrates a cylindrical region that produces the scattering signals. The scattering volume was defined by the ultrasonic beam cross-section and the duration of an electronic gate at the measurement site as shown in Fig 3.

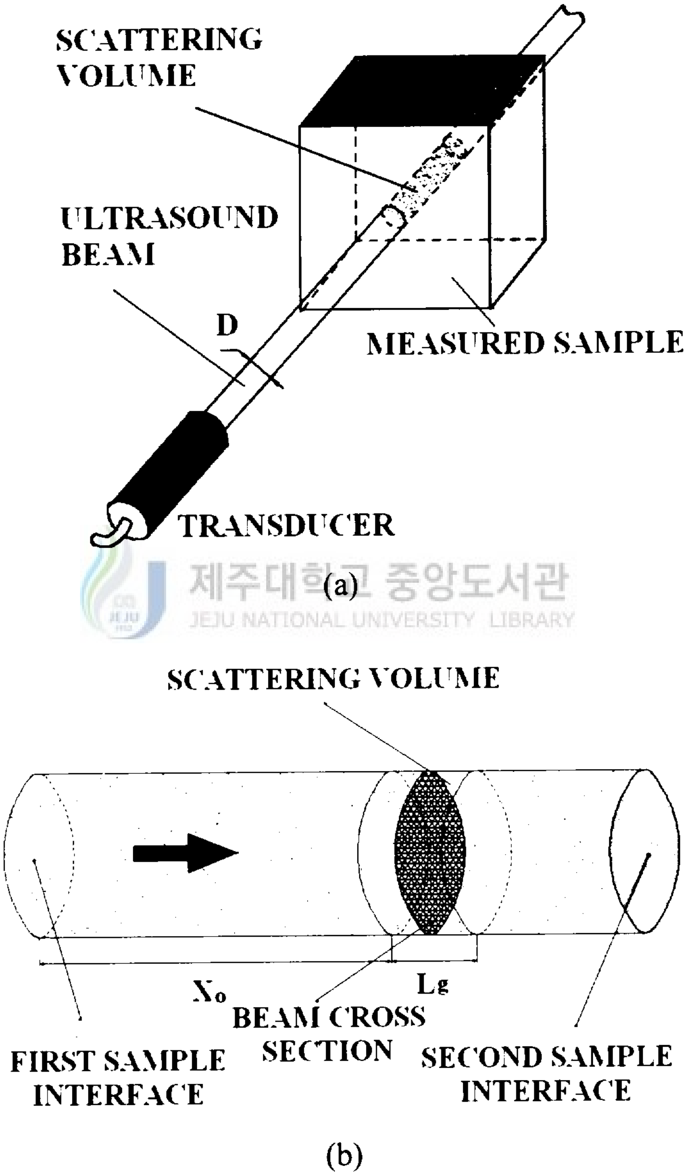


Figure 3: (a) Ultrasonic beam incident in a cylindrical volume of the sample (b) The scattering volume.

This technique consists of measuring the power spectrum, $P_s(f)$ of the backscattered signal from the scattering volume in the sample. This spectrum is then normalized to the power spectrum, $P_r(f)$ from a flat stainless-steel reflector instead of the sample at the same position. The power spectrum is calculated by the Fast Fourier Transform, and its calculation is programmed in Labview.

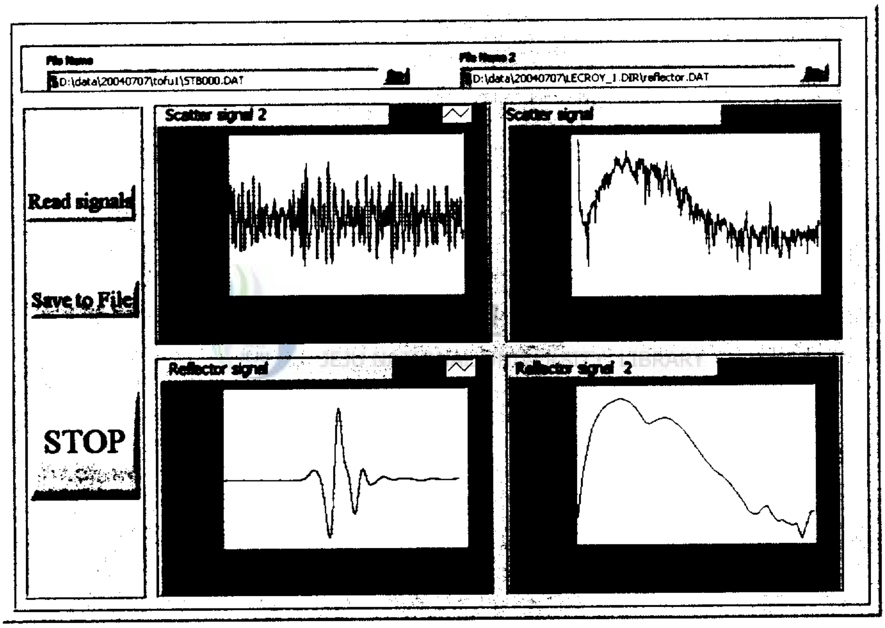


Figure 4: Labview program window. The up-left and up-right windows show the scattered signal from the scattering volume and its power spectrum, respectively. The down-left and downright windows show a signal reflected from a flat stainless-steel reflector and its power spectrum, respectively.

The backscattering coefficient is calculated by,

$$B(f)=[R^2|S(f)|^2/2A(f)C]\times\exp[4a(f)x_0]\times\left(\frac{\exp[\alpha(f)C\tau]-\exp[-\alpha(f)C\tau]}{2\alpha(f)C\tau}\right)^{-1} \quad (2.7)$$

$$|S(f)|^2=P_s(f)/P_r(f) \quad (2.8)$$

,where A(f) is frequency dependent –3 dB beam cross section at the measurement site, and measured with an NTR system (ONDA ATMS. Inc, L.A, CA, USA). A(f) was measured to be 8.20 mm^2 for 5MHz and 2.31 mm^2 for 10MHz. C is sound speed in the sample. τ is time gate. R is the distance between the transducer and the center of measurement volume. x_0 is the distance from measurement volume to the first interface of the sample. $\alpha(f)$ is attenuation coefficient. Prior to backscatter measurements, attenuation coefficient of the specimen over the same frequency range was determined. |S(f)| is the backscatter transfer function.

The energy loss due to attenuation of the distance from the measurement volume to the sample interface was compensated by the term $\exp[4\alpha(f)x_0]$ in the equation of (2.7). The energy loss due to the measurement volume itself was compensated by the term $\left(\frac{\exp[\alpha(f)C\tau]-\exp[-\alpha(f)C\tau]}{2\alpha(f)C\tau}\right)^{-1}$.

Typically, scattering volume is selected by electronic gating from the scattered signals in the sample volume. For obtaining optimal results, τ time gate should be kept long enough (Akita & Ueda, 1988). In this experiment, the pulse and gate were fixed to 5μs. An XYZ positioner accurately controlled the transducer position. The scattering volume should be located in the far field. R was fixed to 10 cm in these experiments.

For each specimen, the backscattering data were obtained at 60 different positions on a plane approximately parallel to the surface of the sample. Three planes were also chosen at different x_0 (time delay t_0 = 4μs, 8μs, 12μs) and the mean value of the 180 data was taken.

Chapter 3

3.EXPERIMENTAL SETUP AND AUTOMATIC MEASUREMENT SYSTEM

The setup of the experiment as well as an automatic measurement system of the acoustic properties is presented in this Chapter.

3.1 Experiment Setup

The echoed signals were obtained in a water tank, which was filled with degassed water at room temperature (17 ± 1.0^0C). All of the experiments were performed in the pulse-echo set up as seen in Fig 3.1. Tofu or Muk samples were mounted on a plastic square holder in the water tank for about 30 minutes to allow the temperature to be equilibrated. The sample was slightly pressed to remove air bubbles on the surfaces of the sample before each experiment. Care was taken to avoid any damage both on the surface and inside of the sample. A 1 MHz, a 5 MHz and a 10 MHz transducer (Panametrics V326, A315S-SU, A314 S, CA, USA) were used in this experiment.

3.2 Automatic measurement system

The measurement of acoustic properties is time consuming and requires multi-steps. Errors could also be introduced by the manual operation of a measurement system. In order to solve these problems, an automated measurement system was developed in this research. This system could make it possible to measure and analyze acoustic properties extensively for various applications in both diagnostic and therapeutic purposes.

3.2.1 Building of the automatic measurement system

This system is based on the National Instruments board, Namil Motion System and Labview software. A pulser/receiver (Panametrics 5900PR, CA, USA) was used to generate the pulse and to receive the echoed signals. The received signals were sent to an oscilloscope (Lecroy LT354 USA) to observe the signals in time domain. Meanwhile, the signals through a 14-Bit 100 MS/s digitizer (National Instruments PXI-5122) were sent to Labview program (APAMS-CUNI) for automatic data analysis, in order to extract useful information from the data. Labview program was also used to help controlling of the experiment processes.

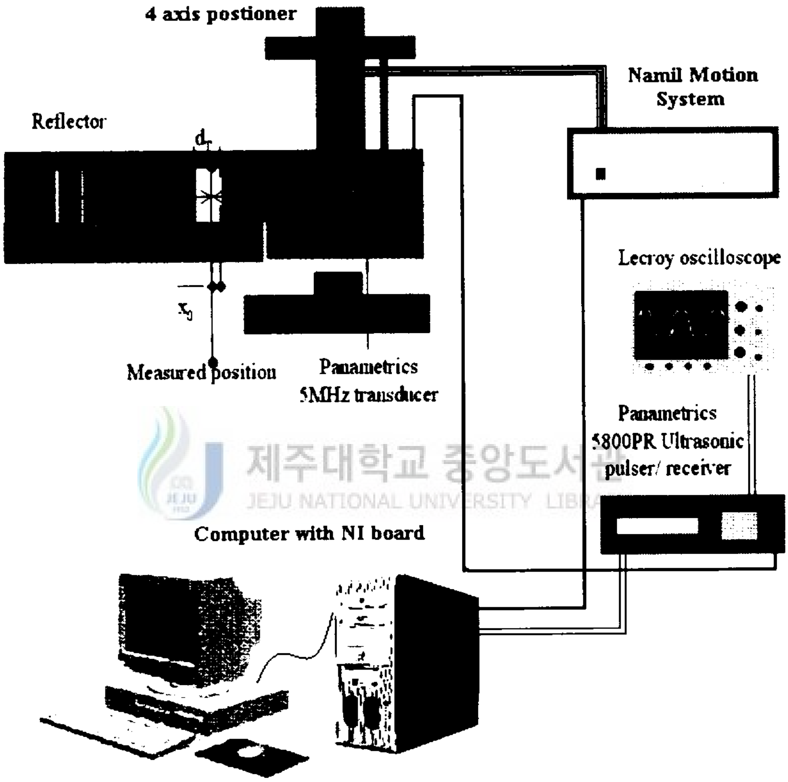


Figure 5: The experimental set up

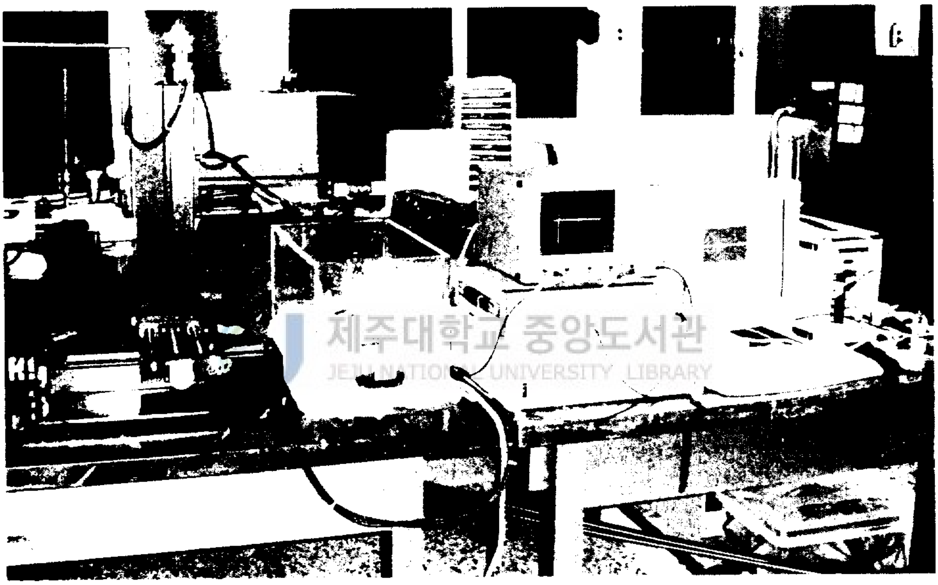


Figure 6: The automatic measurement system

3.2.2 Benefits of the automatic measurement system

Firstly, it is easy to obtain the acoustic properties from the tissues or any other materials.

Secondly, it will decrease the manual operation errors. For instance, when reading peak value of the wave from the oscilloscope, we should adjust the cursor to the peak position manually, and read the value of data visually. It may produce some errors. The Labview program in the system will find out the position of a peak value accurately and read the peak value automatically.

Thirdly, it will save the time of experiment and analysis. The measurement of the backscattering coefficient needs to measure at many different positions in the samples to get the statistical value. The number of measurement positions is over 180 and the repetitions are required for the successful experiment. It takes huge amount of time to readjust and read the value from the different measurement positions. However, the automatic measurement system makes the whole process short and efficient.

Fourthly, it will help the development of the measurement method. There is still some room to improve the measurement method of the acoustic properties, especially, the backscattering coefficient. It is easy to compare two different methods, by programming algorithms of the different method to this system.

3.2.3 Further developments in automatic system

This automatic measurement system is still under development. The real time measurement functions of the sound speed and attenuation have already been completed. In the future, an automatic measurement function of the backscattering coefficient will be added to this system. All the measurement functions will be done in real time.

The stability of the acoustic properties of the different materials will be tested. If the stability of materials is proved and the mean value and the standard deviation of the acoustic properties of the various materials are known, the database of the acoustic properties of the different materials could be built. Through the database, the system could have the abilities to specify a material. Furthermore it can be combined with artificial intelligence techniques.

Chapter 4

4.TOFU AND MUK AS A TISSUE MIMICKING MATERIALS

The reasons and benefits of Tofu and Muk as TMMs, and the acoustic properties of Tofu and Muk will be discussed in this Chapter.

4.1 Introduction

The materials that simulate acoustic properties of some kind of soft tissues are called Tissue-mimicking materials (TMMs). High quality TMMs can be produced and Madsen ever made an effort to develop a long-term stable TMM (Madsen et al, 2003). But the construction process is often very complex and time consuming.

Hence, Tofu was suggested as a TMM substitute by Szabo. (Szabo et al., 1999) because of its availability and low cost. Moreover Tofu can be easily modified for specific purposes.

In this chapter, the acoustics properties of Tofu and Muk were measured and compared. From the Table 1, 2, 3, the acoustic properties of Tofu and Muk are in the range of some soft tissues.

4.2 Benefits and Limitations of Tofu and Muk as TMMs

The tissue-mimicking materials (TMMs) play important roles in the research of ultrasonic bioeffects, scattering analysis, and transducer technologies.

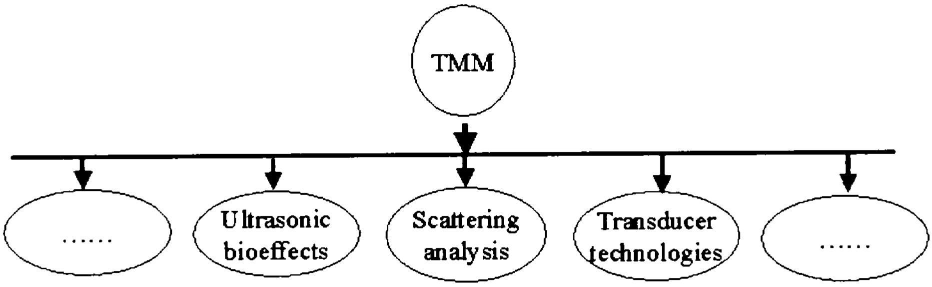


Figure 7: The applications of TMMs

Why can Tofu and Muk be used as TMMs?

The acoustic properties of Tofu and Muk are similar to some kinds of soft tissues. The details are explained in following section. Tofu and Muk are inhomogeneous gelatin-based materials. Besides, there are several benefits to use Tofu and Muk as TMMs:

Firstly, comparing with the traditional TMMs, Tofu and Muk are cheap and easily available in the normal market. However, traditional TMMs are expensive and only can be obtained from the special shop.

Secondly, according to the different purposes, Tofu and Muk can be easily modified. Depending on the nature of the experiment, different layers of Tofu and Muk can be mixed together and other materials can also be put inside. For instance, in the study of thermal effect, the thermometer can be put inside Tofu and Muk (Kim et al, 2004) They can also be built as a model for the research on characterization of tissues and ocean bottom sediment.

Finally, Tofu and Muk are disposable TMMs. In the research of thermal lesions by high intensity ultrasound, the acoustic properties of TMMs may be changed due to the high temperature. It is not economical to use expensive and high quality TMMs.

On the other hand, Tofu and Muk may not be consistent in acoustic properties of Tissue among the different brands or among the different packets of the same brand. Their acoustic properties cannot be modified on purpose. Hence, the stability test for the same brand of Tofu and Muk were conducted. The details are presented in Chapter 5.

4.3 The acoustic properties of Tofu and Muk.

To our knowledge, only a few scientists measured some acoustic properties of Tofu. Wu (2001) measured its sound speed and attenuation coefficient. The measurement of the backscattering coefficient from Tofu was not reported yet, so the backscattering coefficient as well as sound speed and attenuation coefficient of Tofu was measured. Another kind of curd, namely Dotori Muk (acorn curd), was suggested as a potential TMM in this study, so the acoustic properties of Muk were also measured.

Table 1 The results of the density and sound speed of Tofu and Muk and comparison with the previous experiments.

Parameters \ Sample	Tofu	Muk	Wu's result		
			Tofu1	Tofu2	Tofu3
Density (g/cm^3)	1.14±0.05	1.23±0.05	1.17±0.04	1.15±0.05	1.10±0.05
Sound speed (m/s)	1501.3±0.5	1513.4±0.4	1480~1490		

Tofu 1 2 3 are three different types of Tofu (brand name: Nasoya, Vistasoy USA), which is dependent on the hardness of the Tofu. (Wu, 2001)

Tofu density was measured as 1.14±0.05g/cm^3, which is similar to Wu's results, 1.10~1.17g/cm^3 as shown in Table 1. The density of Muk was measured as 1.23±0.05 g/cm^3 and is higher than that of Tofu. The sound speed of Tofu is 1501.3±0.5 m/s and is a little bit higher than Wu's results. The sound speed of Muk is 1513.4±0.4 which is higher than that of Tofu.

Table 2 Comparison of attenuation coefficient with some soft tissues

	AC at 3MHz (Np/cm)	AC at 5MHz (Np/cm)	AC at 7MHz (Np/cm)	Mean Slope (Np/cm/MHz)
Liver	0.24 ±0.09	0.43± 0.09	0.60±0.13	0.08
Spleen	0.28 ±0.06	0.44± 0.08	0.64±0.10	0.09
Heart	0.26 ±0.07	0.41± 0.08	0.58±0.13	0.08
Tofu	0.34± 0.05	0.51± 0.06	0.66±0.05	0.083
Muk	0.18± 0.03	0.23± 0.05	0.27±0.05	0.025
Tofu 1[&]	/	/	/	0.085
Tofu 2[&]	/	/	/	0.115
Tofu 3[&]	/	/	/	0.108

*Data is from (Fei and Shung, 1985)[&] data is form (Wu, 2001). Tofu 1 2 3 are three different type of Tofu (brand name: Nasoya, Vistasoy USA), which is depended on the hardness. AC is attenuation coefficient.

From the attenuation coefficient data shown in Table 2, Tofu is close to kidney beef at 3 & 5 MHz, and beef liver and spleen at 7 MHz. Mean slope of attenuation coefficient of Tofu (0.083 Np/cm/MHz) is close to that of Tofu 1 (0.085 Np/cm/MHz) in Wu's results, and this is similar to that of the beef liver, beef spleen and the rat heart in Fei and Shung's experiments (0.08 ~0.09 Np/cm/MHz). The attenuation of Muk (0.025 Np/cm/MHz) is less than that of most of soft tissues and Tofu.

Table 3: Comparison of backscattering coefficient with soft tissues

	BSC at 3MHz (cm^{-1}/sr^{-1})	BSC at 5MHz (cm^{-1}/sr^{-1})	BSC at 7MHz (cm^{-1}/sr^{-1})	Frequency dependence
Liver (beef)*	$(0.601 \pm 0.051) \times 10^{-3}$	$(0.176 \pm 0.017) \times 10^{-2}$	$(0.532 \pm 0.051) \times 10^{-2}$	3.09
Spleen (beef)*	$(0.165 \pm 0.016) \times 10^{-3}$	$(0.632 \pm 0.059) \times 10^{-3}$	$(0.250 \pm 0.024) \times 10^{-2}$	3.96
Heart (Rat)*	$(0.101 \pm 0.009) \times 10^{-3}$	$(0.484 \pm 0.047) \times 10^{-3}$	$(0.154 \pm 0.017) \times 10^{-2}$	3.40
Tofu	\	$(0.118 \pm 0.089) \times 10^{-1}$	$(0.334 \pm 0.058) \times 10^{-1}$	3.13
Muk	\	$(0.117 \pm 0.089) \times 10^{-2}$	$(0.430 \pm 0.059) \times 10^{-2}$	3.81

*Data is from (Fei and Shung, 1985)

BSC is backscattering coefficient

Table 3 shows that frequency dependence of Tofu and Muk (3.13 and 3.81) is in the range (3.09 ~3.96) of the one of some tissues measured by Fei and Shung, but the absolute values of the backscattering coefficients of Tofu are much larger than those of tissues in this study. It was already established that the measurements of the backscattering coefficient are generally influenced by frequency, temperature, density, and particle size of the specimen (Akita & Ueda, 1988). Other reasons for the measurements are probably from an unpolished reflector, a positioning system, adjustment of the sample with the beam, and so on. Error analysis and calibration of the measurements of the absolute backscattering coefficients should be pursued for further studies. However, the backscattering coefficient of Muk was measured to be much smaller than those of Tofu and close to the ones of some soft tissues. The particle size and inhomogeneity of Muk are thought to be small compared to those of Tofu. The development of an automatic measurement system would be helpful for further studies, since the backscattering measurement is time consuming and inaccurate in the positioning system. More consistent measurements for stability and accuracy tests would be required, so that Tofu and Muk could be used as TMMs in various applications.

4.4 Conclusions

The acoustic properties including sound speed, attenuation coefficient, and the backscattering coefficient were measured on Tofu and Muk using a pulse-echo setup. It was found that Tofu is similar to some soft tissues in terms of attenuation coefficient, while Muk is similar to some soft tissues in terms of the backscattering coefficient. Based on these results, Tofu and Muk may be used as tissue mimicking materials for various applications of tissue characterization, diagnostic experiments, therapeutic purposes of monitoring of the thermal effects (Kim et al, 2004), and ultrasonic bioeffects.

Chapter 5

5.CHARACTERIZATION OF TISSUE MIMICKING MATERIALS

The basic theory of ultrasonic characterization and the contribution of our research to this field will be present in the chapter.

5.1 Introduction

Sound speed, attenuation coefficient, and the quantitative backscattering coefficient were considered as the important physical parameters to characterize a material ultrasonically. These parameters might be used to differentiate some kinds of tissues including the normal tissues from the diseased ones.

5.2 The theory of characterization

It has been known for quite some time that the acoustic properties of a homogeneous liquid depend on its chemical composition and there have been several successful attempts to use ultrasound for characterizing the chemical properties of such liquids. (Andrei et al, 2001)

Table 4: Sound speed and intrinsic attention of various 1M electrolytes. (Andrei et al, 2001)

1 mol/L in Water	Sound speed (m/s)	Attenuation @ 100MHz (dB/cm/MHz)	Temperature (C^0)	Density (g/cm^3)
Water	1498	0.18	25	0.997
KCl	1547	0.18	23.7	1.04
LiCl	1552	0.18	25.4	1.02
NaCl	1559	0.18	25.6	1.04
$CaCl_2$	1572	0.18	25.8	1.06
$CuSO_4$	1555	0.94	25.8	1.13
$MgSO_4$	1623	0.63	26.6	1.1
$MnSO_4$	1593	0.69	25.7	1.12
$AlCl_3$	1640	0.22	23.9	1.08

Table 4 shows the measurements of sound speed and attenuation coefficient of various kinds of pure liquids. It is found out that attenuation coefficient of pure liquid is linear increase with frequency at low frequency range. The mean slope of attenuation coefficient varies with different liquid. See Fig 8. The same phenomena also happen to soft tissues.

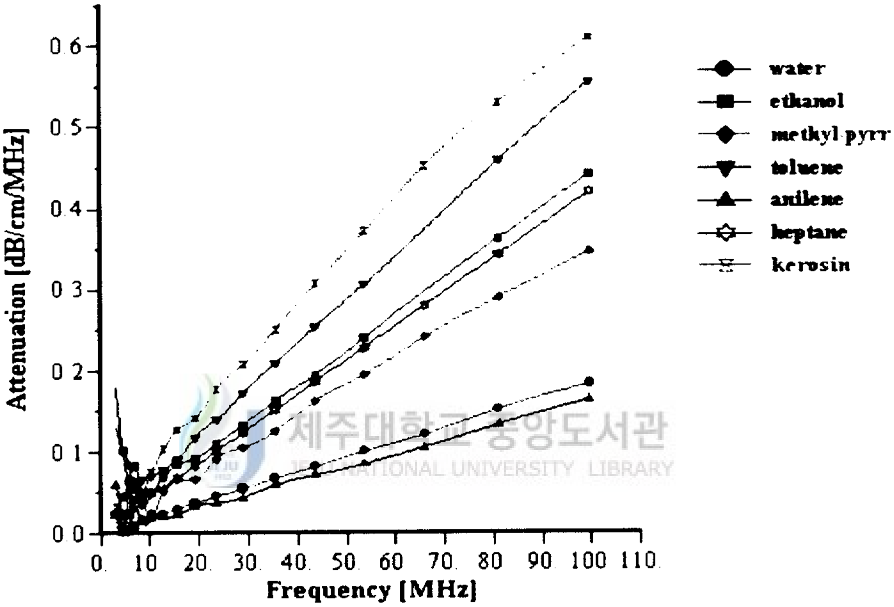


Figure 8: Attenuation spectra pure low attenuation liquids. (Andrei et al, 2001)

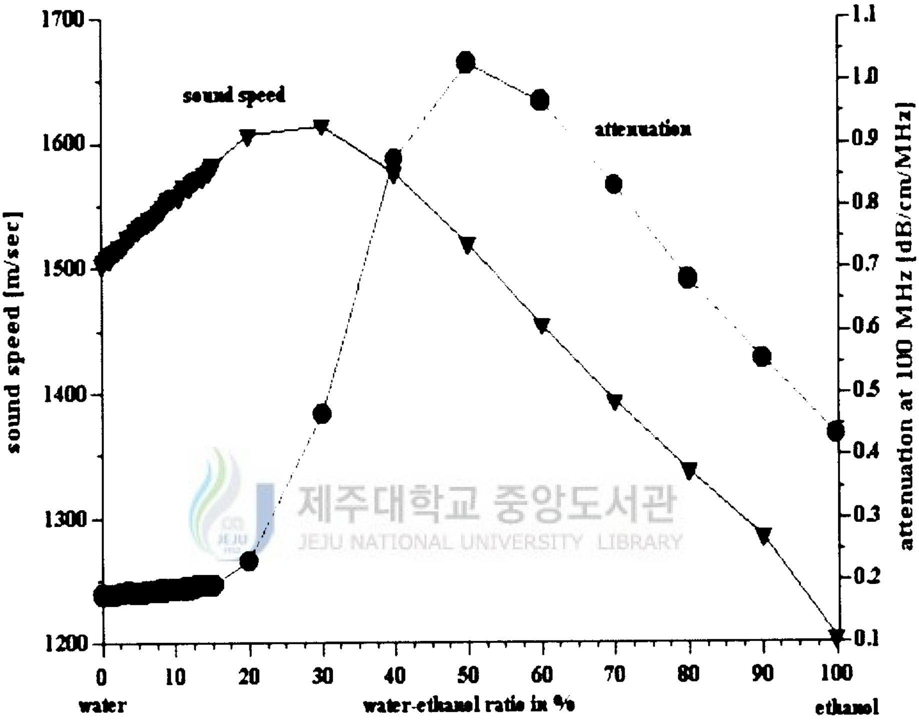


Figure 9: Sound Speed and Attenuation of water-ethanol mixture (Andrei et al, 2001)

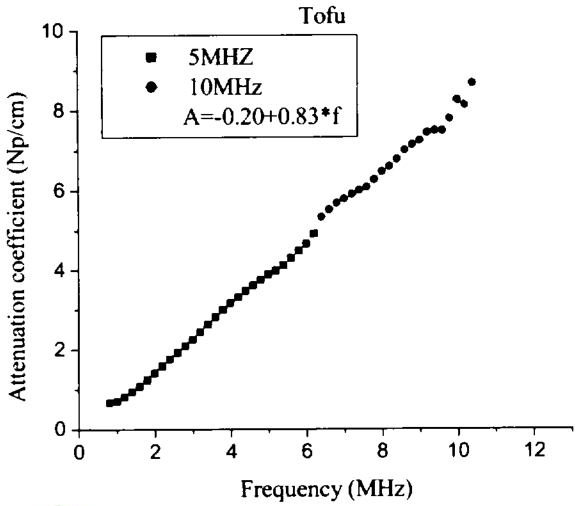
As illustrated in Fig. 9, both attenuation coefficient and sound speed vary with the water-to-ethanol ratio. However, sound speed and attenuation coefficient linearly increase up to 20% of ethanol in water. The results in Fig. 9 show that there is effect of chemical composition on the acoustic properties of homogenous liquids. Hence, there is a possibility to use acoustic properties to characterize liquids.

5.3 Characterization of Tofu and Muk

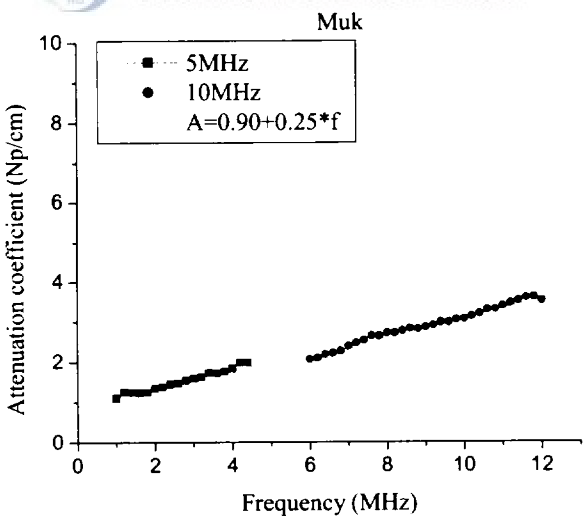
Tofu and Muk, gelatin-based inhomogeneous solid materials may be used as TMMs, whose acoustic properties were measured. Frequency dependence of acoustic properties was analyzed in this study.

The frequency dependence of attenuation coefficient is shown in Fig 10 The squares are the data from a 5MHz transducer and the circles are the data from a 10MHz transducer. It is already established that attenuation of tissues increases linearly with frequency.

The data shown in Fig 10 are the linear part around the center frequency of each transducer. The attenuation coefficients of Tofu and Muk are similar in the low frequency, but they are different in the high frequency since the slope is different. The mean slopes of Tofu and Muk are 0.083Np/cm/MHz and 0.025Np/cm/MHz, respectively. The mean slope of attenuation coefficient from a 10MHz transducer was a little different from the one from a 5MHz transducer. These differences are thought to be mainly because of the errors from the different beam characteristics at the measurement site, since the distance from the sample and transducers were fixed to be the same.

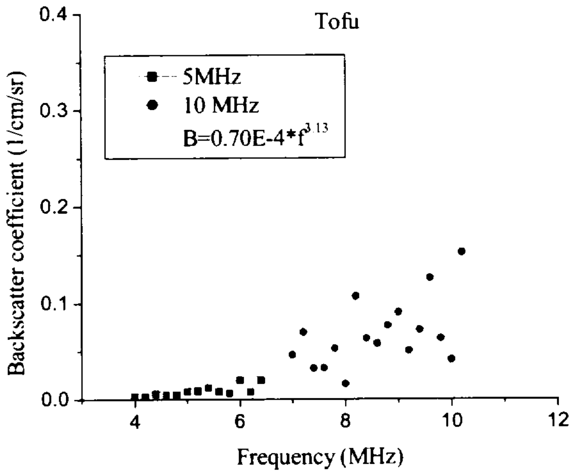


(a)

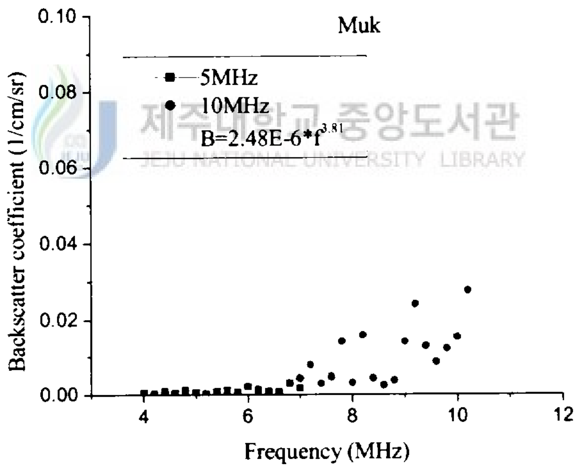


(b)

Figure 10: The attenuation coefficints of (a) Tofu and (b) Muk.



(a)



(b)

Figure 11: The backscattering coefficients of (a) Tofu and (b) Muk.

Previous experiments show that the backscattering coefficient increases as a function of about $3^{rd} \sim 4^{th}$ power of frequency. The power term is called frequency dependence (Wang & Shung, 1997). Our results of frequency dependence for Tofu and Muk are 3.13 and 3.81 respectively, as shown in Fig. 11. The black squares represent the data from the 5MHz transducer and the dots represent the data from the 10MHz transducer. Measurement variations from the curve fitting values increased with frequency as shown in Fig 11 and the main reason may be related to the variance of the particle size normalized to a wavelength due to the inhomogeneity of Tofu and Muk. In the Table 5, the frequency dependence of some soft tissue was shown. It is predicted that tissues could be characterized by the acoustics properties.

Table 5: The frequency dependence of the backscattering coefficient of some tissues.

Material	Frequency Range (MHz)	Frequency Dependence (f^X)
Bovine Myocardium	3-10 [a]	X=3.3
	2-7 [b]	X=2.7
	10-30 [f]	X=3.5
Bovine Liver	2-7 [b]	X=2.0
	3-7 [c]	X=1.7
	10-30 [f]	X=2.4
Bovine Kidney (Cortex)	2-7 [b]	X=2.3
	1-7 [d]	X=1.7
	1-7 [e]	X=2.2
	10-30 [f]	X=2.5

[a]Data is from (Shung & Reid, 1977). [b]Data is from (Fei & Shung, 1985). [c]Data is from (Campbell & Waag, 1984). [d]Data is from (Turnbull & Foster, 1986). [e]Data is from (Insana & Hall, 1991). [f]Data is from (Maruvada & Shung, 2000).

Chapter 6

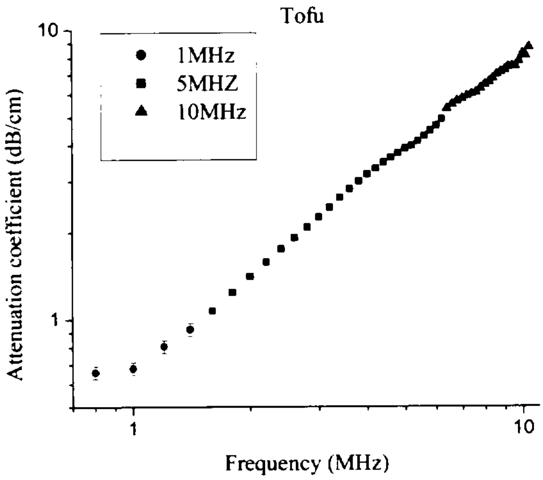
6. STABILITY TEST OF THE ACOUSTIC PROPERTIES OF TOFU AND MUK

6.1 Introduction

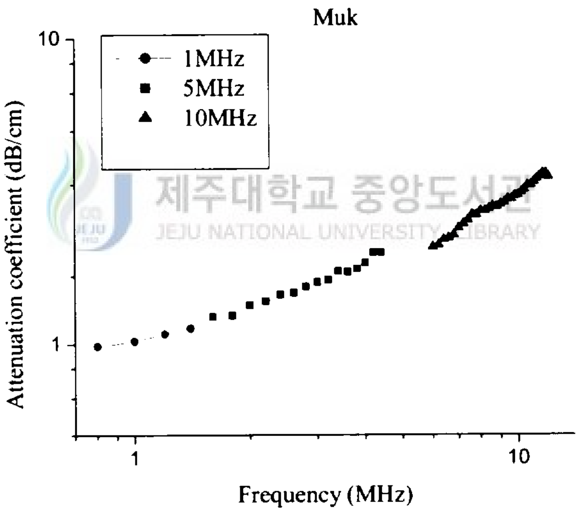
In order to use the disposable characteristics of Tofu and Muk as TMMs, the variations of the acoustic properties among the different packets should be measured to be consistent. This stability test was done in this chapter. In this study, the acoustic properties of Tofu and Muk were measured by the automated measurement system.

6.2 The stability analysis and results

Ten packets of Tofu (Pulmuone, 100% bean, Korea) and Dotori Muk (MANMI, 64.28% acorn powder and 35% corn powder, Jeju, Korea) were obtained from a market. Their acoustic properties in terms of the speed of sound, the attenuation coefficient, and the backscattering coefficient were measured within a half hour after opening the package using the automated system, since the properties could be changed with time.



(a)



(b)

Figure 12: The experimental results of attenuation coefficient of (a) Tofu and (b) Muk. Lines and error bars for 1 MHz are the mean and the standard deviation from 10 different packets.

The measurements of the attenuation coefficient are summarized in Table 4. It is also shown in Fig 12 with the previous results of 5 MHz and 10 MHz. The circles are the data from the 1 MHz transducer. The squares and the triangles are the data from the previous results of 5 MHz and 10 MHz transducers, respectively. Even though the mean slopes of the attenuation coefficient of Tofu and Muk were measured to be different from the previous results, they are in the range of acceptable error bound as shown in Fig 12. As it is already established that attenuation of a tissue increases linearly with frequency, the attenuation coefficient was also measured to be a linear function. The variations among the different packets are small as shown in the error bars and the standard deviation, so Tofu and Muk could be used as stable TMMs if they are from the same brand and used within a half hour after opening the package.

Table 6: The measurements of sound speed from 10 different packets of Tofu and Muk at 17 ± 1.0^{0}c.

Sound speed (m/s)	Mean	SD	Min	Max	Range
Tofu	1429.6	1.277	1428.4	1431.8	3.4
Muk	1418.7	2.042	1417.0	1421.7	4.7

SD is the standard deviation.

Table 7: The results of attenuation coefficient of Tofu and Muk. ACMS is attenuation coefficient mean slope. SD is standard deviation. (N=10)

ACMS (Np/cm/MHz)	Mean	SD	Min	Max	Range
Tofu	0.0732	0.00098	0.07142	0.07489	0.00347
Muk	0.0266	0.00137	0.02419	0.02880	0.00461

Table 8: The results of the backscattering coefficient frequency dependence. BCFD is backscattering coefficient frequency dependence.

BCFD (0.8 MHz ~1.4 MHz)	Packet 1	Packet 2	Packet 3
Tofu	2.98	2.83	2.88
Muk	3.61	3.32	3.59

The power terms of frequency dependence of the backscattering coefficient of 3 different Tofu and Muk packets are 2.83~2.93 and 3.32~3.61, respectively. They show some variations among the different packets compared to sound speed and attenuation coefficient, but they are still in the reasonable range. The stability of the absolute value of the backscattering coefficient will be tested further, with an improved automated measurement system in the future.

6.3 Conclusions

The experimental results show that the sound speed and the attenuation coefficient of ten packets of Tofu and Muk were measured to be stable within a certain range. The mean and the standard deviation of the sound speed of ten packets of Tofu and Muk are 1429.6 $\pm$ 1.277 m/s and 1418.7 $\pm$ 2.042 m/s respectively. The attenuation coefficients of Tofu and Muk are 0.0732 $\pm$ 0.00098 Np/cm/MHz and 0.0266 $\pm$ 0.00137 Np/cm/MHz, respectively. The power terms of frequency dependence of the backscattering coefficient of 3 different Tofu and Muk packets were measured to be 2.83~2.93 and 3.32~3.61, respectively. The attenuation coefficient is more stable than the sound speed and the power terms of frequency dependence of the backscattering coefficient, which may be more useful for the tissue characterization. Both of Tofu and Muk were measured to be stable in their acoustic properties among the different packets and could be potentials for stable TMMs. More applications of using these inexpensive and disposable TMMs should be followed for further study.

Chapter 7

7.CONCLUSIONS AND FUTURE WORKS

This chapter concludes with summaries and suggestions for future work.

7.1 Conclusions

In this research, Tofu and Muk are suggested as TMMs and their acoustic properties were measured. The results show that Tofu is similar to some soft tissues in terms of attenuation coefficient, while Muk is similar to some soft tissues in terms of the backscattering coefficient. Base on these results, Tofu and Muk may be used as tissue mimicking materials for various applications.

Furthermore, the stability of acoustics properties of Tofu and Muk was tested. The mean and the standard deviation of the sound speed of ten packets of Tofu and Muk are 1429.6 ± 1.277 m/s and 1418.7 ± 2.042 m/s respectively. The attenuation coefficients of Tofu and Muk are 0.0732 ± 0.00098 Np/cm/MHz and 0.0266 ± 0.00137 Np/cm/MHz, respectively. The power terms of frequency dependence of the backscattering coefficient of 3 different Tofu and Muk packets were measured to be 2.83~2.93 and 3.32~3.61, respectively. The experimental results show that the sound speed and the attenuation coefficient of ten packets of Tofu and Muk were measured to be stable within a certain range. The attenuation coefficient is more stable than the sound speed and the power terms of frequency dependence of the backscattering coefficient, which may be more useful for the tissue characterization.

To measure the acoustics properties, an automatic measurement system was built, which makes it possible to do extensive measurement and analysis of the acoustic properties of the different kinds of TMMs. These research works are the basic studies for acoustic characterization. Tofu and Muk could be used as TMMs for the research of tissue characterization.

7.2 Future works

Over the years, several methods are developed in measuring the backscatter coefficient. Standard narrow-band substitution method, a broadband method, and a modified substitution method were developed successively. So far there has been no one method that could satisfy the most accurate measurement of the backscatter coefficient. In 1999, a TMM sample was produced in University of Wisconsin and sent to 10 different laboratories in order to compare the measurements of its acoustic properties. The agreements of the backscatter coefficients measured from the sample at the labs were not impressive (Madsen et al, 1999). There is still a lot of room for improvement in the development of quantitative backscatter coefficient.

In the future, a function of automatic measurement of the backscattering coefficient will be added to this system. All the measurements will be done in real time. The stability of the acoustic properties of the different materials will be tested. If the stability of materials is proved and the mean value and the standard deviation of the acoustic properties of the various materials are known, the database of the acoustic properties of the different materials could be built. Through the database, the system could have the abilities to specify a material. Furthermore it can be combined with artificial intelligence techniques.

The backscattering dependence on frequency is an important topic to be explored. Furthermore, the stability of the acoustic properties of biological tissues or TMMs and the sensitivity of the acoustic properties difference among different kinds of biological tissues or TMMs could be tested in the future. If the stability and sensitivity of acoustic properties are proved, the automatic system could be developed into a complete system, which can characterize some materials including soft tissues acoustically with those parameters.

REFERENCES

Akita M. and Ueda M., "The effect of windowing on spectral estimation of echoes scattered by a random medium," J. Acoust. Soc. Am. 83 No 4, 1988.

Fei D.Y. and Shung K.K., "Ultrasonic backscatter from mammalian tissues," J. Acoust. Soc. Am.78 (3). 1985.

He P., "Simultaneous measurement of sound velocity and wall thickness of a tube," Ultrasonics, 39: 407-411, 2001.

Kim Y.T., Jho M.J., Yun Y.H., Pu Y.C., "Thermal sensitivity of the bean curd by ultrasonic irradiation", J. Acoust. Soc. Kor., 23(7), pp. 503-513, 2004.

Insana M.F., Madsen E.L.,"Tests of the accuracy of a data reduction method for determination of acoustic backscatter coefficients," J. Acoust. Soc. Am. 79(5): 1230-6, 1986.

Madsen E.L., Dong F., "Interlaboratory Comparison of Ultrasonic Backscatter, Attenuation, and Speed Measurements," J. Ultrasound Med., 18: 615-631,1999.

Madsen E.L., Frank G.R., Krouskop T.A., Varghese T., Kallel F. and Ophir J., "Tissue-Mimicking Oil-in-gelatin dispersions for use in heterogeneous electrograph phantoms," Ultrasound imaging, 25,17-38 2003.

Madsen E.L., Insana M. F., "Method of data reduction for accurate determination of acoustic backscatter coefficients," J. Acoust. Soc. Am 76: 913-923, 1984.

Maruvada S., "High frequency ultrasound measurements of the attenuation and backscatter from biological tissues," A Thesis for PHD in Acoustics of Pennsylvania University.

Maruvada S., Shung K.K. and Wang S.H., "High-frequency backscatter and attenuation measurements of selected bovine tissues between 10 and 30 MHz," Ultrasound in Med. & Biol., Vol.26, No.6, pp. 1043-1049, 2000.

Meziri M., Pereira W.C.A., Abdelwahab A., Degott C., Laugier P. "In vitro chronic hepatic disease characterization with a multiparametric ultrasonic approach," Ultrasonics, 43(5): 305-13, 2005.

O'Donnell M. and Miller J.G., "Quantitative broadband ultrasonic backscatter: an approach to nondestructive evaluation in acoustically inhomogeneous materials," J. Appl. Phys., 52:pp.1056-1063, 1981.

O' Donnell M. and Miller J.G., "Relationship between Collagen and Ultrasonic Backscatter in Myocardial tissue" J. Acoustic Soc Am; 69:580-588, 1981.

Paeng D.G. and Shung K.K., "Cyclic and radial variation of the Doppler power from porcine whole blood," IEEE Trans. Ultrason. Ferroelectr. Freq. Control. 50, No.6, 2003.

Shung K.K. and Paeng D.G., "An unexplored tool for blood flow visualization and hemodynamic measurements," J. Appl. Phys., Vol.42, pp. 2901-2908, 2003.

Sigelmann R.A., Reid J.M., "Analysis and measurement of ultrasound back -scattering from an ensemble of scatterers excited by sine-wave bursts," J. Acoust. Soc. Am., 53: 1351-1355, 1973.

Szabo T.L., Clougherty F., Grossman C., "Effects on nonlinearity on the estimation of in situ values of acoustic output parameters," J. Ultrasound Med, 18(1): 33-41, 1999.

Van M.S., Heiden D., Machteld G.M., Kroon D., Bom N. and Borst C., "Ultrasound backscatter at 30 MHz from human blood: Influence of rouleau size affected by blood modification and shear rate," Ultrasound in Med. & Biol., Vol.21, No. 6, pp. 817-826, 1995.

Wang S.H., "Measurement of ultrasonic backscatter from blood and contrast agents," A Thesis for PHD in Bioengineering of Pennsylvania State University, 1997.

Wang S.H., Shung K.K., "An approach for measuring ultrasonic backscattering from biological tissues with focused transducers," IEEE Trans. Biomed. Eng. 44: 549-554, 1997.

Wu J., "Tofu as a tissue-mimicking material," Ultrasound in Med. & Biol, Vol.27, No.9, pp. 1297-1300, 2001.

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