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Measurements of Acoustic Properties of Tofu and Acorn Curd as Potential Tissue-mimicking Materials

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Abstract

The purpose of this study is to measure the acoustic properties of Tofu and Acorn Curd (Dotori Muk), which are possibly used as tissue mimicking materials (TMMs). Due to its availability and low cost, Tofu was suggested as a TMM by several researchers who measured only sound speed and attenuation. The acoustic properties of Tofu and Muk including the backscattering coefficient were measured in this paper. Sound speed was measured by the time shift in a pulse echo setup. Attenuation coefficients and backscattering coefficients were measured by a broadband method using both 5 MHz and 10 MHz transducers in the frequency domain. The measured acoustic properties of both Tofu and Muk are observed to be similar to those of biological tissues such as beef liver or beef heart.

Keywords: *Tissue Mimicking Materials, Sound speed, Attenuation, Backscattering coefficient, Tofu, Acorn Curd*

I. Introduction

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. Madsen et al.[1] ever made an effort to develop long-term stable TMMs, since high quality TMMs are important for those researches. However, their construction processes are often complex and time consuming, so the high quality TMMs are expensive. For these reasons, Tofu drew attention as a TMM substitute[2] because it is a gelatin-based material, readily available, and low in cost. Moreover, Tofu has an advantage of easy modification for specific purposes. Nevertheless, few works have been performed on acoustic properties of Tofu. For instance, Wu[3] reported the sound speed and attenuation coefficient of Tofu. However, the backscattering coefficient was not characterized yet to our knowledge.

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[4, 6] if it can be utilized. The backscattering coefficient at a certain frequency is defined as the differential scattering cross section per unit volume at a scattering angle of 180°[7]. However, it is not easy to measure accurately the backscattering coefficient by experiments. Over the years, several methods have been developed for measuring the backscattering coefficient. A standard narrow-band substitution method, a broadband method[3,6], and a modified substitution method were developed successively[8]. In 1999, two kinds of TMM samples were produced in University of Wisconsin and sent to 10 different laboratories in order to compare the measurements of their acoustic properties. The agreements of the backscattering coefficients measured from the sample at the different labs were not impressive[9]. So far there has been no such a unified method that can guarantee the most accurate measurement of the backscattering coefficient. The present study employed a broadband method to measure the backscattering coefficient, because the method easily obtains the scattering coefficient over a broad frequency range with a single transmission. However, it is less accurate compared to the narrowband method.

In this study we have measured backscattering coefficient as

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well as sound speed and attenuation of Tofu. In addition, we propose another kind of curd, Dotori Muk (acorn curd), as a potential TMM, and its acoustic properties were also measured. The methods for measuring sound speed, attenuation coefficient, and backscattering coefficient were described in details in the following section. The data obtained in this study were compared with the previous measurements on Tofu and some biological tissues. Provided Tofu or Muk be similar to biological tissues in their acoustic properties, they can be used as a disposable TMM which can also be easily modified for the studies on tissue characterization and thermal lesions by high intensity ultrasound, and so forth[1,4,5].

II. Experiments and Methods

2.1. Material Properties

Packs of Tofu (Pulmuone, 100% bean, Korea) and Dotori Muk (MANMI, 64.28% acorn powder and 35% acorn powder, Jeju, Korea) were obtained from a market. Three 4 x 4 cm^2 specimens with the thickness of 4-5 cm were prepared from three different packs for experiments.

2.2. Experimental setup

The echoed signals were obtained in a water tank, which was filled with degassed water at room temperature (20±1.0℃). All of the experiments were performed in the pulse-echo set up as seen in Fig. 1. Tofu or Muk sample was mounted on a plastic square holder in the water tank for about 30 minutes to allow the temperature to be equilibrated, and 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 surfaces and inside of the sample. A 5 MHz and a 10 MHz transducer (Panametrics V326, A315S-SU, CA, USA) were used in this experiment.

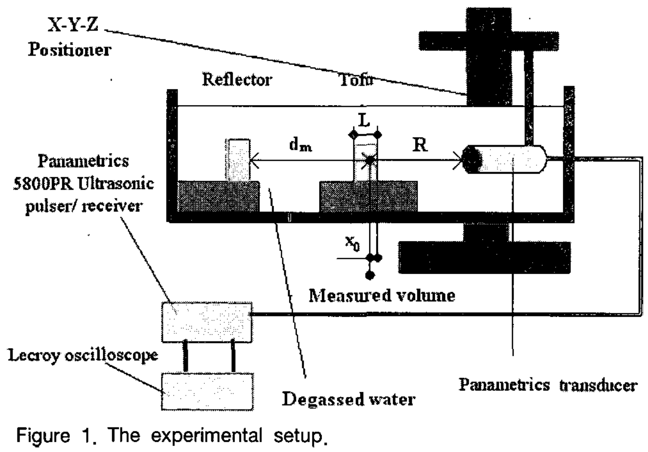


Figure 1. The experimental setup.

2.3. Data acquisition

A pulser/receiver (Panametrics 5800PR, CA, USA) was used to generate the pulse and to receive the echoed signals. The received signals were sent to an oscilloscope (Lecroy LC547AL USA) to observe the signals in time domain and to take an average of the power spectrum over 50 pulses in frequency domain in order to improve the signal-to-noise ratio. The saved data in the oscilloscope were transferred to a personal computer for analysis by the software of Labview 7.1. Linear and non-linear curve fitting was done by Matlab 6.5.

2.4. Measurement of sound speed and thickness of the sample

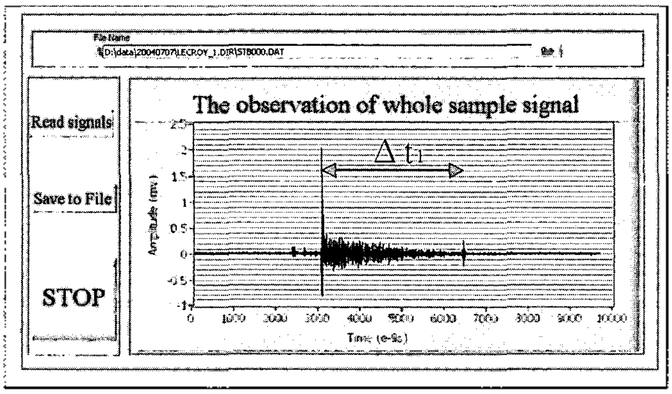


Figure 2. A received echo signal in Labview program. The left maximum signal is the reflected signal from the 1st interface; the rightmost signal is the reflected signal from the 2nd interface. The signals between the two surfaces are the volume scattering signals within the sample.

This method requires measurements of time of flights for calculating the time delays: time delay between the two surface-reflected signals, Δt_1, and time delay between the two pulse-echo signals of reflector with and without the sample, Δt_2, [10]

$$\Delta t_1=2L/C \tag{1}$$

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

, 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:

$$L=(\Delta t_2+\Delta t_1)\ C_w/2 \tag{3}$$

$$C=(1+\Delta t_2/\Delta t_1)\ C_w \quad (4)$$

2.5. 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.

2.6. 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[3]

$$\alpha(f)=8.68\times\log_e(T^2A_w\ /A_t)/2L \quad (5)$$

, 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,

$$T=(4Z_wZ_s)/(Z_w+Z_s)^2 \quad (6)$$

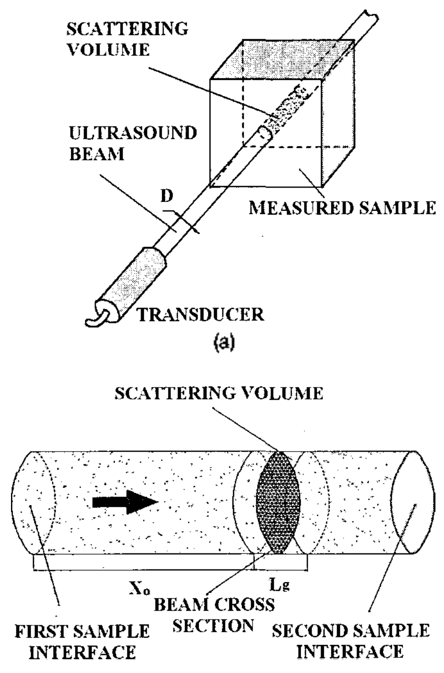


Figure 3. (a) Ultrasonic beam incident in a cylindrical volume of the sample (b) The scattering volume.

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

2.7. Measurement of backscattering coefficient

A broadband substitution method was used for measuring the backscattering properties[6]. 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.

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

The backscattering coefficient is calculated by,

$$B(f)=[R^2|S(f)|^2/2A(f)C]\times\exp[4\alpha(f)x_0]$$
$$\times\left(\frac{\exp[\alpha(f)C\tau]-\exp[-\alpha(f)C\tau]}{2\alpha(f)C\tau}\right)^{-1} \quad (7)$$

$$|S(f)|^2=Ps(f)/Pr(f) \quad (8)$$

, 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

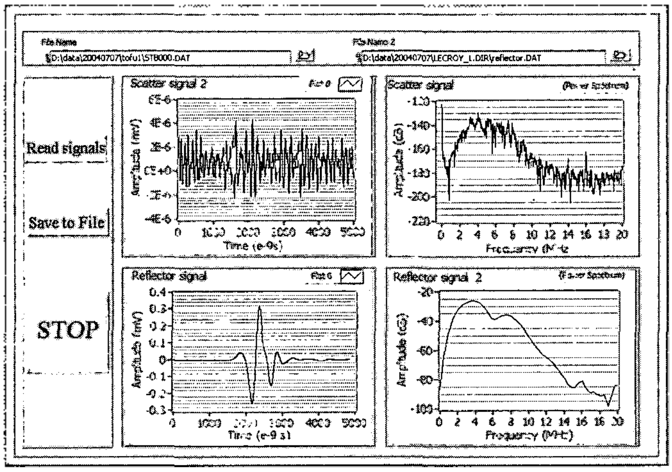


Figure 4. The top-left and top-right windows show the scattered signal from the scattering volume and its power spectrum, respectively. The bottom-left and bottom-right windows show a signal reflected from a flat stainless-steel reflector and its power spectrum, respectively.

Table 1. The results of 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 are dependent on the hardness of Tofu[3].

transducer and the center of measurement volume. x_0 is the distance from the 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 were compensated by the term $\exp[4\alpha(f)x_0]$ in the equation of (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[14]. 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 our 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.

III. Results and discussion

Tofu density was measured to 1.14±0.05g/cm^3, which are similar to Wu's results, 1.10~1.17g/cm^3 as shown in Table 1. The density of Muk was measured to 1.23±0.05g/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 m/s which is higher than that of Tofu.

The measurement results of attenuation coefficient are shown in Fig. 5. The squared data are from the 5MHz transducer and the circled data are from the 10MHz transducer. It is already

Table 2. Comparison of attenuation coefficient of Tofu and Muk with some soft tissues and the previous experimental results.

	AC at 3MHz (Np/cm)	AC at 5MHz (Np/cm)	AC at 7MHz (Np/cm)	Mean Slope (Np/cm/MHz)
Liver (beef)*	0.24±0.09	0.43±0.09	0.60±0.13	0.08
Spleen (beef)*	0.28±0.06	0.44±0.08	0.64±0.10	0.09
Heart (rat)*	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 are from *Fei and Shung [11] and &Junru Wu. Tofu 1 2 3 are three different types of Tofu (brand name: Nasoya, Vistasoy USA). AC is attenuation coefficient[3].

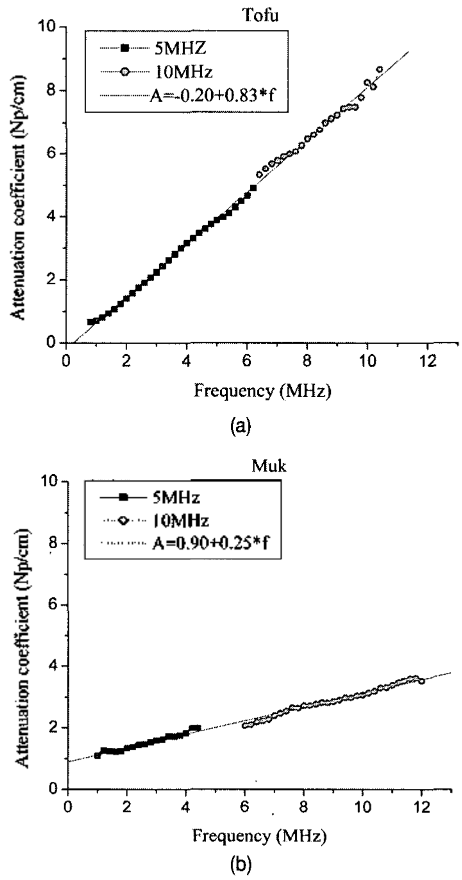


Figure 5. The experimental results of acoustic properties of Tofu and Muk: Attenuation coefficient of (a) Tofu and (b) Muk.

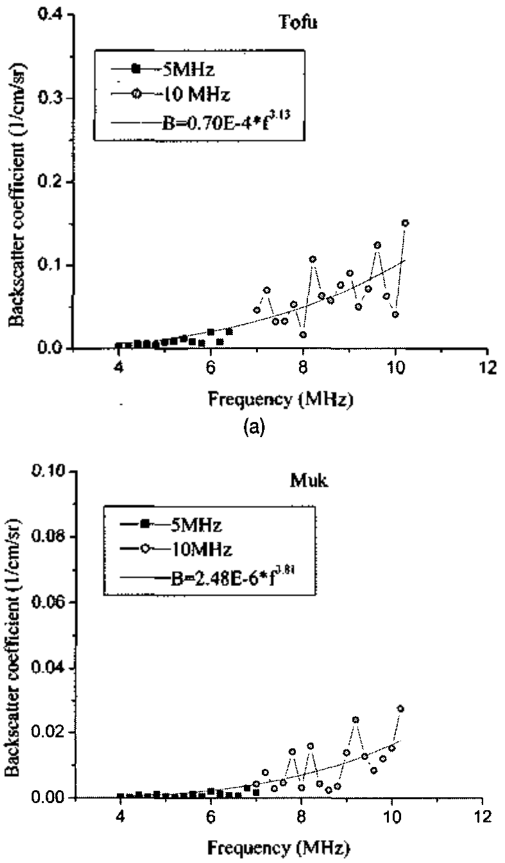
Table 3. Comparison of the backscattering coefficient with that of soft tissues.

	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)*	$(0.601\pm0.051)\times10^{-3}$	$(0.176\pm0.017)\times10^{-2}$	$(0.532\pm0.051)\times10^{-2}$	3.09
Spleen (beef)*	$(0.165\pm0.016)\times10^{-3}$	$(0.632\pm0.059)\times10^{-3}$	$(0.250\pm0.024)\times10^{-2}$	3.96
Heart (Rat)*	$(0.101\pm0.009)\times10^{-3}$	$(0.484\pm0.047)\times10^{-3}$	$(0.154\pm0.017)\times10^{-2}$	3.40
Tofu	\	$(0.118\pm0.089)\times10^{-1}$	$(0.334\pm0.058)\times10^{-1}$	3.13
Muk	\	$(0.117\pm0.089)\times10^{-2}$	$(0.430\pm0.059)\times10^{-2}$	3.81

Data are from *Fei and Shung [11]. BSC is the backscattering coefficient.

established that attenuation of tissues increases linearly with frequency. The data shown in Fig. 5 are the linear part of the whole data. 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 the 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.

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 it 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 tissues and Tofu.



(a)

(b)

Figure 6. The experimental results of acoustic properties of Tofu and Muk. The backscattering coefficient of (a) Tofu and (b) Muk.

Previous experiments show that the backscattering coefficient increases as a function of about 3rd~4th power of frequency. The power term is called frequency dependence [8]. Our results of frequency dependence for Tofu and Muk are 3.13 and 3.81 respectively. The black squares represent the data from the 5MHz transducer and the dots represent the data from 10MHz transducer. Measurement variations from the curve fitting values increased with frequency as shown in Fig. 5, 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.

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 ones of some tissues measured by the 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[14]. Other possible reasons for our measurements are probably from the unpolished reflector, errors of the positioning system and adjustment of the sample with the beam, and so on. Error analysis and calibration of our 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.

IV. Conclusions

The acoustic properties including sound speed, attenuation coefficient, and 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. Base 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 [2,5,14], and ultrasonic bioeffects.

Acknowledgement

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[Profile]

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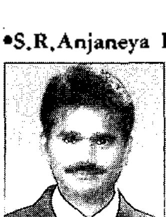

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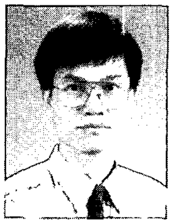

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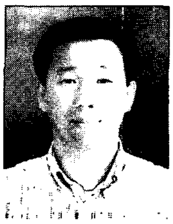

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