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A Basic Study on the Variation of Temperature Characteristics for Attenuation Coefficient and Sound Velocity in Biological Tissues

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= **Abstract** =

This study is concerned with the temperature dependence characteristics of ultrasound parameters in biological tissues, which are basic on the noninvasive deep body temperature estimation. Used parameters are ultrasonic attenuation coefficient and sound velocity. In order to accomplishment our purpose, several signal processing methods were used. Attenuation coefficient was estimated by spectral difference method and sound velocity was estimated by P-P method. And we also examined these methods through a series of IN VITRO experiments that used tissue-mimicking phantom samples and biological tissue samples.

In order to imitate the biological soft tissue two kinds of phantom samples are used, one is agar phantom sample which is composed of agar, graphite, N-propyl alcohol and distilled water, and the other is fat phantom sample which is composed of pure animal fat. And the ultrasound transmission mode and reflection mode experiments are performed on the pig's spleen, kidney and fat.

As a result, it is found that the temperature characteristics are uniform in case of phantom samples but not in biological tissues because of complicate wave propagation within them.

Consequently, the possibility of temperature measurement using ultrasound on biological tissue is confirmed and its results may contribute to the establishment of reference values of internal temperature measurement of biological tissues.

Key Words : Ultrasonic parameters, tissue characterization, temperature characteristics, tissue-mimicking phantom

1. INTRODUCTION

It is about 1950s that the ultrasound has been applied to the fields of medical diagnosis. The fields of the research focused early are to make the image of the internal structure of human body, that bring a rapid development to realize ultrasound scanner. Recently, in virtue of effort to overcome the limitation of the resolution of ultrasound scanner, the studies of quantitative analysis of the ultrasound signal are performed in many filed.

The tissue characterization[13-24], so-called, is one of these study. The subjects of these study are the ultrasound parameters in tissue such as the att-

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enuation, velocity, dispersion, scattering, reflection, refraction, diffraction, frequency dependence and temperature dependence of ultrasound, which are abstracted by processing signal derived from the transmission or reflection waves. The parameters derived from them are applied to the development of new types of ultrasound scanner which is allowed to define abnormal tissue in diagnosis and to improve a quality of image.

On the other hand, the research on a noninvasive instrumentation of temperature in deep region is no more than a basic study yet[3-12]. Though most methods have progressed this study in focus on the change of parameters of ultrasound varing with temperature, it has a difficulty to specify criteria, since the complexity of a various propagating mechanism, the demerit of ultrasound, which derived from the limitation of the resolution and ununiformity of tissue cause its reappearance to be not clear.

Therefore, the purpose of this study is to inspect attenuation coefficient and ultrasound velocity which is based on measuring temperature within tissue, and, on a basis of it, we try to put emphasis on the noninvasive instrumentation of the temperature. In the fields of the application that can be expected by coming to realize this instrumentation it can be applied in the case of monitoring temperature continously like CCU (Coronary Care Unit) or requiring the noninvasive instrumentation such as the control of temperature in hyperthermia.

2. THE ANALYSIS OF THE PROPAGATION CHARACTERISTICS OF ULTRASOUND

Acoustic attenuation[1]

The technique of the instrumentation of temperature in biological tissue by using ultrasound is divided into the active method which take an information on temperature from a reflected signal, and the passive method which detect and process a weak signal of ultrasound generating as heat source.

In the passive method, the signal of the generated ultrasound is so weak that it is very hard to detect it, and it requires an high precision amplifier, and so on, which dont' come to activate yet.

Accordingly, the active methods is used for most of researches. In this paper, therefore, we adopt the active method and use the pulse transmission and reflection methods to improve reliability for the effect of the experiments.

In order to estimate the ultrasonic attenuation coefficient of biological tissue, the model which the ultrasound propagated through the biological tissue and detected from the transducer is depicted in Fig. 1. Let us suppose that the ultrasound radiate to the tissue perpendicularly. In this study, the used model is time-invariant system because the used ultrasound has a shape of impulse. Accordingly, the specturm of received signal Y(t) from the receiver in Fig. 1 express as follow.

$$Y(f) = H_T(f)\ X(f) \quad \cdots\cdots (1)$$

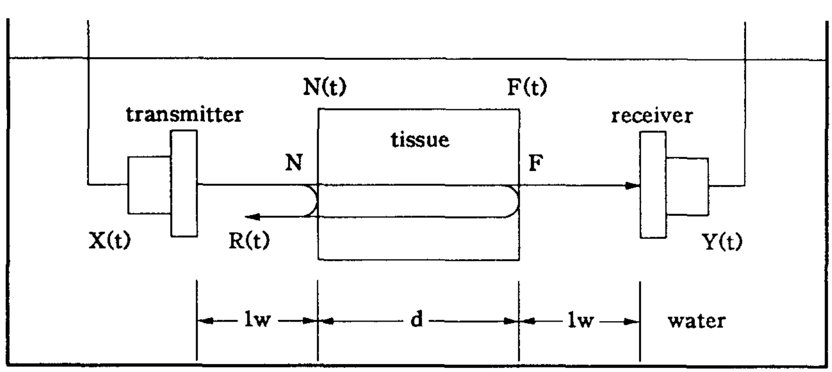


Fig. 1 Attenuation model of ultrasonic signal

$Y(f)$: The fourier transform of transmission wave which passes through the tissue
$X(f)$: The fourier transform of incident wave
$H_T(f)$: The transfer function

According to Pauli and Schwan's paper[2], in general the transfer function in transmission $H_T(f)$ of signal passing through the tissue only is

$$H_T(f)=H_1(f)H_2(f)\exp(-(\alpha+j\beta)d) \quad (2)$$

$H_1(f)$: The transfer function of transmitter
$H_2(f)$: The transfer function of receiver
α, β : The attenuation and phase coefficients of tissue
d : The thickness of tissue

The transfer function of transmission signal passing through the water and tissue, that is, the transfer function in transmission of this model $H_T(f)$ is

$$H_T(f)= H_1(f)\tau_1 \exp(-(\alpha_W+j\beta_W)l_W)\ H_2(f)\tau_2 \exp(-(\alpha+j\beta)d) \quad (3)$$

τ_1, τ_2 : The transmission ratio in boundary between water and tissue
α_W,β_W : The attenuation and phase coefficients of water
l_W : The distance between transducer and tissue

Under the same condition, eliminating the tissue only is

$$Y_W(f)=H_{TW}(f)\ X(f) \quad (4)$$

$Y_W(f)$: The fourier transform of transmission wave which passes through the water only
$X(f)$: The fourier transform of incident wave
$H_{TW}(f)$: The transfer function in transmission

$$H_{TW}(f)=H_1(f)H_2(f)\exp(-(\alpha_W+j\beta_W)(l_W+d)) \quad (5)$$

The ratio $Y_W(f)$ and $Y(f)$ is

$$Y_W(f)/Y(f)=(1/\tau_1\tau_2)\exp(((\alpha-\alpha_W)+j(\beta-\beta_W))d) \quad (6)$$

As the acoustic impedance of water is nearly same as that of the biological tissue, τ_1 times τ_2 is about one. And taking the absolute value to find the magnitude of Eq.(6)

$$|Y_W(f)/Y(f)|=\exp((\alpha-\alpha_W)d) \quad (7)$$

So the attenuation coefficient $\alpha(f)$ of tissue is

$$\alpha(f)=\alpha_W-\alpha=-10\text{Log}\,|H_{TW}(f)/H_T(f)|^2/d \quad (8)$$

Spectral difference method[17]

In Fig. 1, if the power spectral density of incident wave is $S_i(f)$, power transfer function of tissue is

$$|H_T(f)|^2= S_T(f)/S_i(f) \quad (9)$$

Taking the logarithm on the both sides, we can rewrite

$$10\ \text{Log}\,|H_T(f)|^2 = 10\ \text{Log}\,S_T(f) - 10\ \text{Log}\,Si(f) \quad (10)$$

And Eq.(8) is same as

$$10\ \text{Log}\,|H_T(f)|^2 = -\alpha(f)d \quad (11)$$

In Eq.(10), (11) attenuation coefficient $\alpha(f)$ is

$$\alpha(f)=\frac{10\ \text{Log}\,Si(f)-10\ \text{Log}\,S_T(f)}{d}(\text{dB/cm}) \quad (12)$$

Accordingly, we can obtain the attenuation coefficient using the difference of logarithm power spectrum of the incident wave and transmission wave.

Sound velocity estimation

In order to detect the quantitative changes of sound velocity by the temperature variation of tissue, the model which estimates the ultrasonic velocity is modified.

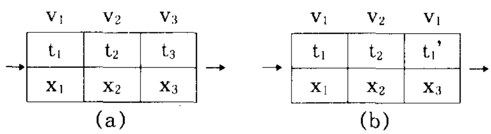


Fig. 2 Models for ultrasound velocity estimation
(a) case of three kinds of tissue
(b) case of two same kinds of tissue among three layer tissues

Fig. 2(a) shows the case of three different kinds of tissue, and Fig. 2(b) shows the case of two same kinds of tissue among three layer tissues. In Fig. 2 (a) v_1 represents the ultrasound velocity of tissue 1, v_2 represents that of tissue 2, and v_3 represents that of tissue 3. X_1, x_2 and x_3 represent the thickness of tissues, and t_1, t_2 and t_3 represent the propagation time respectively. Fig. 2(b) shows the fact that the tissue 1 is equal to the tissue 3.

To begin with, the time when ultrasound transmit into three layer tissues in Fig. 2(a) equals to following equation

$$T_d = t_1 + t_2 + t_3 \quad \cdots\cdots (13)$$

Similarly, the propagation time in Fig. 2(b) is as follow

$$T_d' = t_1 + t_2 + t_1' \quad \cdots\cdots (14)$$

Using Eq.(13) and Eq.(14), the difference of propagation time, ΔT_d can write

$$\Delta T_d = T_d - T_d' = t_3 - t_1' \quad \cdots\cdots (15)$$

So we can show that Eq.(15) become as follow

$$\Delta T_d = \frac{X_3}{V_3} - \frac{X_3}{V_1} = X_3\left(\frac{V_1 - V_3}{V_1 V_3}\right) \quad \cdots\cdots (16)$$

We obtain

$$V_3 = V_1\left(\frac{X_3}{\Delta T_d V_1 + X_3}\right) \quad \cdots\cdots (17)$$

Therefore, we can eatimate the sound velocity by Eq.(17) if the 1st tissue is water and the 3rd tissue is objective tissue.

Temperature dependence characteristics of sound velocity

When we estimate the sound velocity by proposed model, we can express temperature dependence, to discuss variation of the sound velocity characteristics by the temperature, as follow

$$\Delta V(T - T_0) = V(T) - V(T_0)$$
$$= 2[d/t(T) - d/t(T_0)] \ (m/sec/℃) \quad \cdots\cdots (18)$$

where d is thickness, t is propagating time, T is measured temperature and T_0 is based temperature (20℃). As it obtains variation of sound velocity by temperature variation. We find out the temperature dependence charateristic of sound velocity of tissue.

3. EXPERIMENTS

Configuration of experiments

To discuss the temperature dependence of ultrasound from the objective tissue, first of all, we must acquire interesting ultrasonic data. Configuration of total system in this experiments was shown in Fig. 3.

Extraction of ultrasound signals

Ultrasound signals were acquired using the system in Fig. 3. After we initialize a system by the computer, driving pulse generator and giving negative pulse to transducer, ultrasonic signal was radiated to medium from transducer. The received signal was transfered to DM-902, that was, AD/DA convertor and memory. The HP8447F amplifier was used for amplifying a weak signal. Its amplification gain is 22 dB as the preamplifier and 25 dB as the main amplifier.

This analog signal was converted instantaneously to digital and stored into the internal memory. It was transfered to the main computer through GP-IB card(IEEE-488) and saved as a data file.

Also the receivd signals are measured at 2℃ increments from 20℃ to 46℃ in the water tank system which has 0.5℃ control resolution. The data size were 8-bit 2048 points. The distilled water was used as a propagation medium. To decrease the effects of diffraction of reflection and dispersion, the sound absorption material was used. We keep the temperature of water in tank uniformly to restrain water from convection during the expements. The beam correction for distance variation wasn't needed when we supposed the beam characterization as a gaussian distribution.

4. DATA PROCESSING AND RESULTS

Signal processing

We analyzed the data to examine attenuation coefficient and temperature characteristics. The used signal processing methods were the spectral difference method for estimation of attenuation coefficent and the peak-peak method for estimation of sound velocity. The data size was 8 bit 2048 point per 1 frame and sampling frequency of A/D converter was 100 MHz.

Fig. 4 showed flow chart of estimation process of attenuation coefficient from acquired signal, and Fig. 5 showed process of sound velocity estimation.

Experiments by using phantom tissues

To verify the variation of ättenuation coefficient and sound velocity dependence of the temperature, several phantoms were used. The transmission wave was used as received signal. And the temperature of phantom was changed by using thermocontroller.

Composition of agar phantoms show in Table 1. Agar phantom 1 was composed agar 15g, distilled water 400cc, graphite 50g and n-propyl alcohol 45 cc. And agar phantom 2 was composed agar 15g, distilled water 400cc, graphite 30g and n-propyl alcohol 45cc. Fat phantom made of pig's fat tissue.

We used specimen box in this experiments. The dimension of specimen box showed in Fig.6. Also we estimated attenuation coefficient by spectral difference method after measuring transmission signal from the empty speciment box. We calculated the time and estimated the sound velocity to transmit specimen.

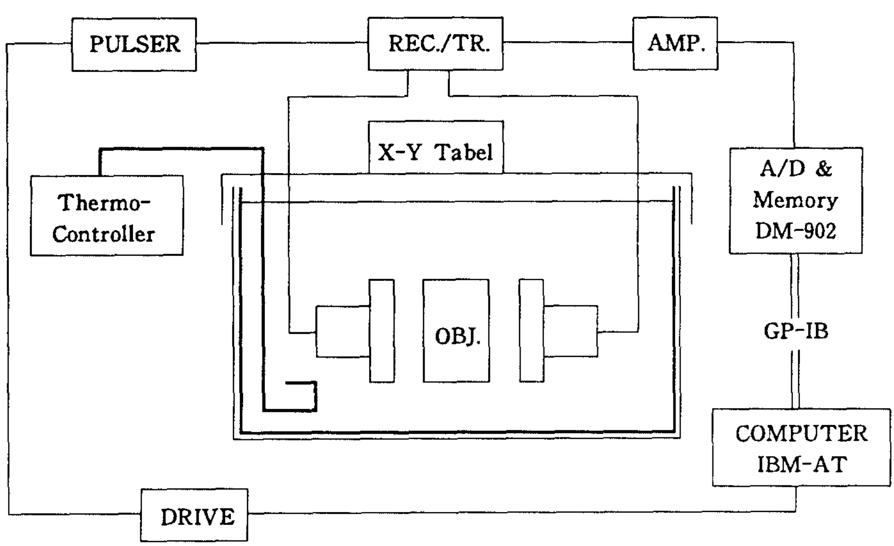


Fig. 3 Configuration of ultrasonic signal acquisition system

Ultrasonic transmitter and reciever were installed in a same line with 4.5cm distance. To consider velocity response of specimen temperature according to changement of water temperature, the experiments were done with sufficient time interval between the measurements. Also, We used distilled water in order to minimize influence of air bubbles that were produced during the increment of temperature. And we used ultrasound transducer with 5 MHz.

Fig. 7 show received signals from agar phantom 1 sample (a) 20℃ (b) 44℃, and Fig. 8 show (a) attenuation characteristics, (b) sound velocity characteristics of phantom 1 sample.

Consideration of temperature characteristics of phantom tissues

Table 2 showed characteristics of depending temperature of phantom signals that we acquired from the experiments. As we know from this table, the values of temperature characteristics of attenuation and sound velocity decreased according to the increment of temperature.

Generally, the degree of hardness was relaxed because the molecules bond was loosen in proportion to increase of temperature. So the decrease of attenuation quantity and sound velocity were coincident with the result of our experiments. Also, we could show that the changing quantity of sound velocity was 1000 times greater than that of attenuation quantity. Consequently as we showed this experimental results, sound velocity was more useful parameter than attenuation quantity in the case of noninvasive temperature measurements by using ultrasound, and we confirmed that the changing of parameter about temperature was almost linear.

Experiments by using biological tissues and consideration

Experimental results by using phantom tissues proved validity of designed model. Consequently,

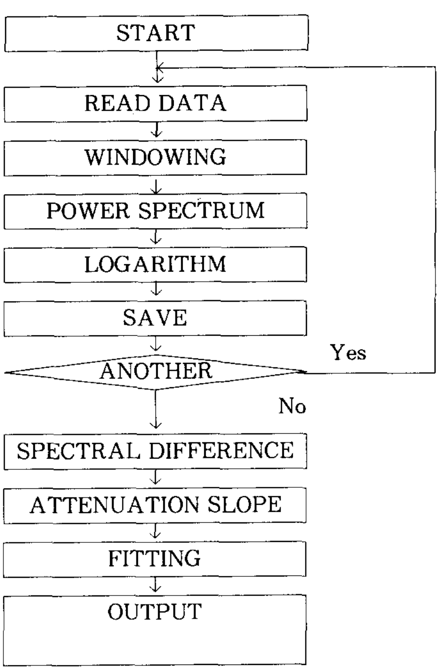


Fig. 4 Flow chart of signal processing for estimation of attenuation coefficient

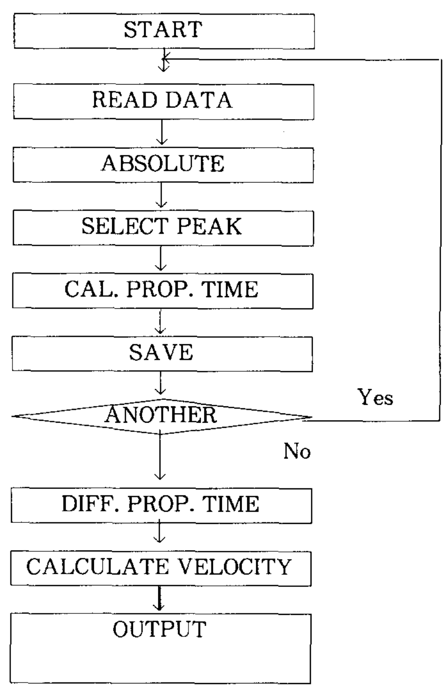


Fig. 5 Flow chart of signal processing for estimation of sound velocity

using these algorithms, we will study it's usefulness by applying serveral biological tissues. Used biological tissues were pig's spleen, kidney and fat tissues. The used modes in this study were transmission and reflection mode. We went up temperature by 2℃ from 20℃ to 46℃ when signals were acquired. The experimental methods were the same as that of phantom tissues. Fig. 9 shows the temperature dependence characteristics of spleen tissue. And Table 3 shows temperature dependence characteristics of biological tissues.

As that case of phantom tissues, the good results were found at the characterization of the ultrasonic attenuation and the sound velocity variation when the actual biological tissues were used, too. But nonuniform temperature characteristics was measured between transmission and reflection signal from the tissues. The reason of a this phenomenon is considered as the nonlinear response of temperature variation caused by complex ultrasound propagation mechanism in this system.

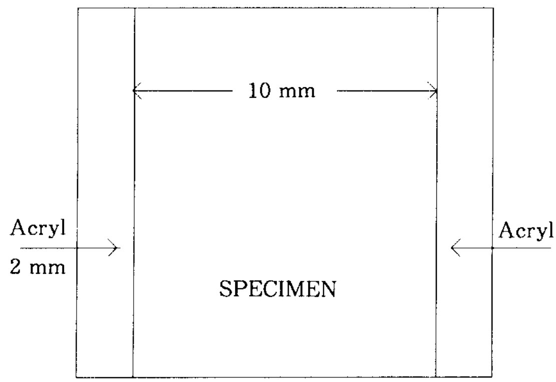
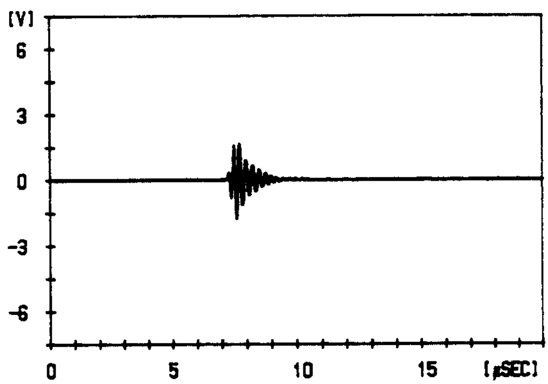
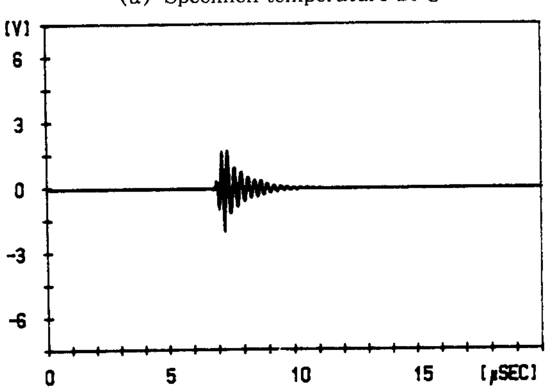


Fig. 6 Dimension of specimen box

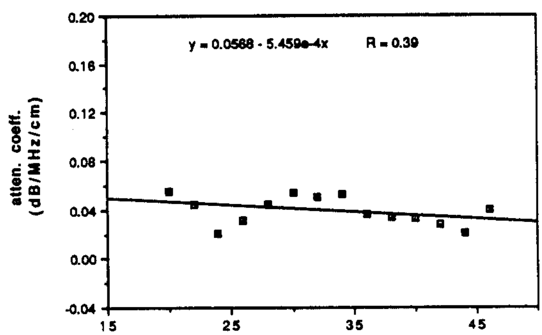


(a) Specimen temperature 20℃

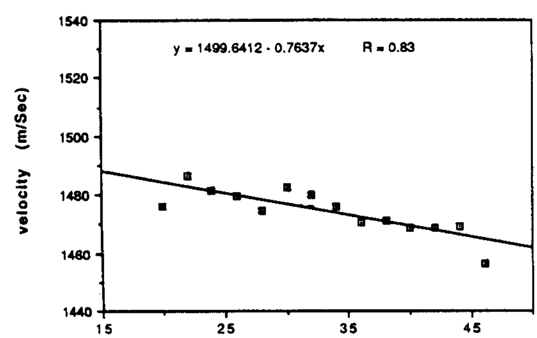


(b) Specimen temperature 44℃

Fig. 7 Received signal from agar phantom 1 sample



(a) Attenuation characteristics



(b) Sound velocity characteristics

Fig. 8 Temperature dependence characteristics of agar phantom 1 sample

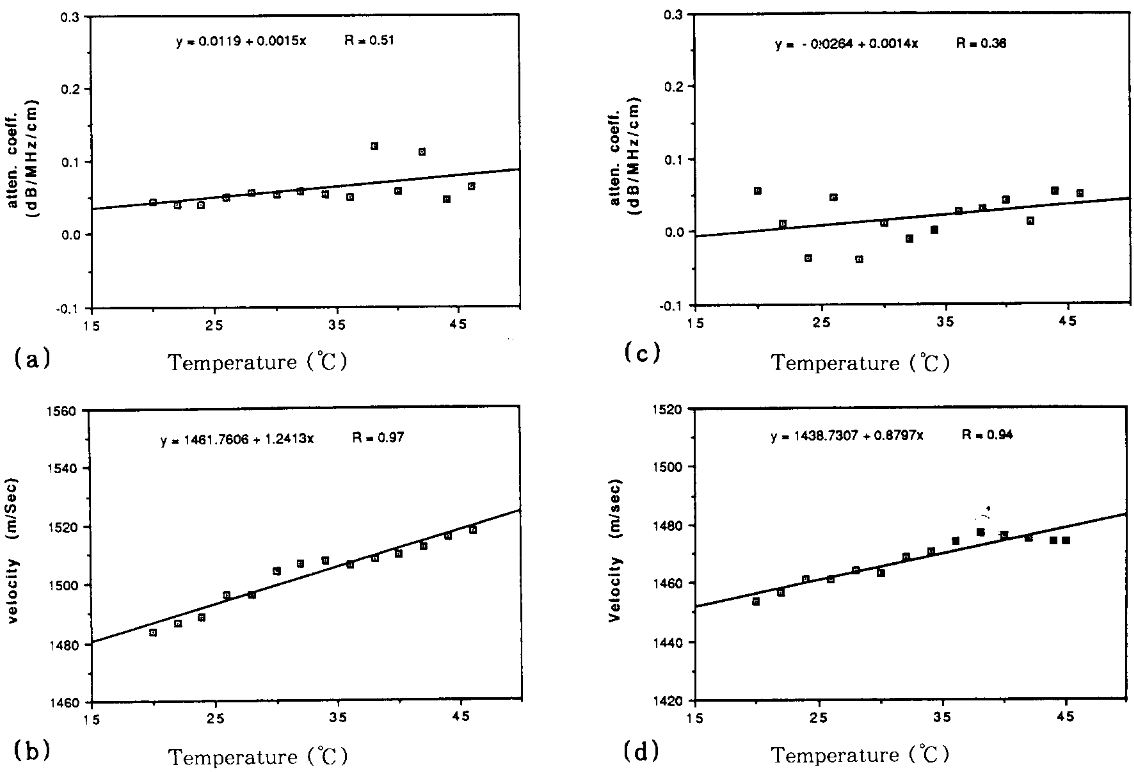


Fig. 9 Temperature characteristics of spleen tissue
(a) transmission mode characteristics of attenuation coefficient
(b) transmission mode characteristics of sound velocity
(c) reflection mode characteristics of attenuation coefficient
(d) reflection mode characteristics of sound velocity

Table 1 Composition of agar phantoms

	agar	d-water	graphite	N-propyl alcohol
No. 1	15 g	400 cc	50 g	45 cc
No. 2	15 g	400 cc	30 g	45 cc

Table 2 Temperature dependence characteristics of phantom samples

PARAMETERS / RHANTOMS	ATTENUATION COEFFICIENTS (dB/MHz/cm/℃)	SOUND VELOCITIES (m/sec/℃)
AGAR PHANTOM 1	−0.0005459±0.0056	−0.7637±1.7181
AGAR PHANTOM 2	−0.0006755±0.0047	−0.1084±4.2890
FAT PHANTOM	−0.0048000±0.0067	−1.5492±2.3862

Table 3 Temperature dependence characteristics of biological tissues

TISSUES	ATTENUATION COEFF. (dB/MHz/cm/℃)		SOUND VELOCITIES (m/sec/℃)	
	REFLECTION	TRANSMISSION	REFLECTION	TRANSMISSION
SPLEEN	0.0014±0.0151	0.0015±0.0110	0.8797±1.4810	1.2413±0.6012
KIDNEY	0.0017±0.0150	0.0020±0.0030	1.0483±1.4161	0.7103±0.5342
FAT	−0.0147±0.0233	−0.0032±0.0085	−1.9163±3.7710	−1.9281±3.6511

5. CONCLUSION

We studied on the variation of temperature characteristics of ultrasonic attenuation coefficient and sound velocity. In the experiments by using phantom samples, the temperature characteristics of both ultrasonic parameters show decreasing tendency. Also through a series of experiments by using biological tissues, we could show that the changing quantity of ultrasound velocity was about 100 times greater than that of attenuation quantity. Therefore sound velocity was more useful parameter than attenuation coefficient in the case of noninvasive temperature measurements by using ultrasound.

Consequently, the possibility of temperature measurement using ultrasound on biological tissue is confirmed and its results may contribute to the establishment of reference values of internal temperature measurement of biological tissues.

But internal sturcture of human body is very complicate. Therefore, it requires furder studies-development of appropriate algorithms, precision of measurements, realtime processing, establishment reference values by processing of a lot of data, IN VIVO experiments, etc-in order to applying the clinical fields.

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