EXPERIMENTAL INVESTIGATION OF ATTENUATION AND VELOCITY OF ULTRASOUND IN SOME SOFT TISSUES

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ABSTRACT

In this paper principles of a narrowband technique for pulse echo attenuation and velocity measurements are presented. The effects of various experimental parameters on the results are also investigated. The velocity, attenuation, and the slope of the acoustic attenuation with frequency in plexiglass, bovine liver, human female normal breast, and cancer breast specimens are given. Human female breast specimens are also examined histologically to extract the correlation between the normal or pathologic conditions of the tissue and the acoustic parameters. The results demonstrate that: (a) The pathological tissues have high acoustic velocity and attenuation compared to those for the normal breast tissues, (b) Linear frequency dependent attenuation relationship could be obtained for normal breast while nonlinear relationship for the others, (c) Acoustic velocity increases with frequency in the range from 0.8 M Hz to 4 MHz from 1480 m/s to 1960 m/s for cancer breast specimen while it does not vary strongly for the others, and (d) The attenuation coefficient of liver is monotonically decreasing functions of temperature while it increases for the others.

Key words: Ultrasound; Acoustic Velocity, Acoustic Attenuation, Normal breast cancer breast, Bovine Liver, pathological conditions.

INTRODUCTION

During the last ten years, there has been an increased interest in ultrasonic tissue characterization. When an ultrasonic wave propagates through tissue, it can be scattered, absorbed, reflected, and undergoes a change in velocity. The measurement of these interactions, and their frequency and temperature dependence can provide much information on the fundamental properties of soft tissues.

The ultrasonic absorption coefficient of a material characterizes the rate at which energy is converted to local heating, where as the attenuation coefficient encompasses all loss mechanisms, including the scattering or redistribution of longitudinal waves [1].

Attenuation is viewed as a promising tissue characterization parameter in diagnostic ultrasound. The magnitude and frequency dependence of attenuation is a complicated function of the composition (collagen, fat, water) and biochemical environment of an organ [2], thus forming a potential basis for tissue characterization.

The velocity of propagation of ultrasound is also an important factor for tissue characterization, dependent upon the density and elasticity of the transmitting medium. Preliminary results for pathological variation of human liver suggest that sound velocity may indeed be more useful than the attenuation coefficient for assisting diagnosis of diffuse liver diseases. Excellent separation of results is found for normal liver, fatty liver, and cirrhosis (Hayashi et al 1985)[3].

In the present work, the velocity, the attenuation coefficient, and the slope of the acoustic attenuation with frequency in plexiglas, bovine liver, normal breast, and cancer breast specimens are measured over a frequency range from 0.8-4 MHz. The general aim is to find parameters which discriminate between healthy and diseased tissue and which can

easily be estimated from the reflected ultrasonic signal.

THEORETICAL BASIS

In this part we will deal with the fundamental relations of attenuation measurements and the velocity of sound in tissues.

1. Attenuation Measurements

The term attenuation refers to loss in energy from the ultrasonic beam. Linear analysis has been used by several investigators in the description of the attenuation in liver tissue [4] i.e. they assumed that the acoustic attenuation coefficient of liver tissue denoted by $\alpha(f)$, increases linearly with frequency f.

$$\alpha(f) = \beta\, f \text{ dB/cm} \quad \text{for } f>0 \qquad (1)$$

where β is the attenuation coefficient slope with frequency (f).

Evidence indicates that in the special case of normal liver, this may be a valid procedure since the attenuation in the material appears to be nearly linear. However it can not be assumed that attenuation in general varies linearly with frequency. This applies to pathological tissues and tissue other than liver[4].

Recent researchers take the nonlinear frequency dependent equation for attenuation as their basis for several studies on attenuation coefficient estimation [5], where

$$\alpha\,(f) = \alpha_o.f^n \qquad (2)$$

α (f) being the attenuation in dB/cm, f the frequency in MHz, α_o describes the magnitude and n the frequency dependence of attenuation within the bandwidth.

Preliminary studies on a small population demonstrated that the two parameter power law fit of data may provide a more useful discrimination of tissue types than could be obtained by using a single parameter such as the attenuation magnitude at the center frequency[5].

In non-biological media (e.g. plexiglas), observed temperature dependence of ultrasonic attenuation varies considerably, depending on the frequency and mechanisms that are responsible for attenuation. Very complicated dependence might be expected from biological media on the basis that many mechanisms will be involved, and their relative contributions may also be temperature and frequency dependent. Then equation (2) can be written in the general form to be:

$$\alpha\,(T,f) = \alpha_o\,(T).\, f^n \qquad (3)$$

where T is the temperature in °C

Lin and Ophir described the method employed for attenuation measurements [6]. Briefly, a pulse of ultrasound, emitted by an appropriate transducer, is reflected from a plane surface situated normal to the direction of sound propagation. The reflected pulse, which is isolated by a time-gating circuit, is received by the same transducer, and amplified. The attenuation due to a double traverse of a tissue specimen, cut to have plane parallel surface, is the difference between the received echo signal with and without the sample interposed between transducer and plane reflector, provided a logarithmic spectral display of amplitude is employed. The attenuation of a tissue at a temperature (T), for a frequency (f) is computed as:

$$\alpha\,(T,f) = (20 \log V_r/V_s)/2d \qquad (4)$$

where V_r is the peak-to-peak amplitude without sample, representing the echo from the reflector, V_s is the peak-to-peak amplitude with the sample, and d is the sample thickness in cm. The effect of the specimen near surface reflection is negligibly small.

2. Measurement of Sound Velocity in tissues.

Absolute measurement methods permit direct measurement of sound velocity in a medium without reference to the sound velocity in some previously characterized medium. The most general and common methods are variants of a general pulse transit time, or time of flight (TOF) initially developed as a variable-path technique for liquids [7]. The velocity is obtained from the difference in the sound trip transit times as the path length between the transmitting transducer and a plane reflector is varied by a measured amount. The absolute measurement techniques are generally unsuitable for studying solid tissues, where it is

difficult either to measure the path length accurately or to vary it. Relative methods are made possible because reliable published data of absolute sound velocity values are now available for a number of substances which may be used as reference media in the measurement scheme. The most common of these reference media is pure water, but saline of known sodium chloride concentration is also used. In the present work reference media is pure water.

A simple means of obtaining sound velocity measurement relative to some reference medium, is a variation of the pulse (TOF) technique discussed above. All that is required is an oscilloscope with a fast delayed time base capable of measuring the time shift Δt at the position of received sound pulse with and without the tissue specimen in place. A time base sweep of 1 msec.cm^{-1} would be sufficiently fast for most purposes [7]. Then with a knowledge of the sound velocity in the tank, C_W, the average velocity, Δt, over the total tissue path traversed by the sound beam, Δx, may be calculated from [7].

$$1/C_t = 1/C_w - \Delta t / \Delta x \qquad (3.5)$$

EXPERIMENTAL PROCEDURES

1. *Experimental Setup*

The experimental setup is the same as that shown in Figure (1). A rectangular temperature controlled water tank, made of plexiglass, was designed with dimensions 55,35, and 30 cm. The tank is somewhat large to give the facility of easy movement and easy mounting of target and transducer, also to fulfill the condition of moving the transducers for large distance on the Z-axis for getting the beam pattern. A special mounting for target was designed to supply it with the facility of free movement in the three directions x-axis, y-axis and Z-axis. The rod holding the transducer was fixed to the system through three screws placed on the vertex of a triangle, each screw has a spring, different movement of the screws helped in tilting the transducer surface in different directions. The tank was filled with highly filtered distilled water to get good results.

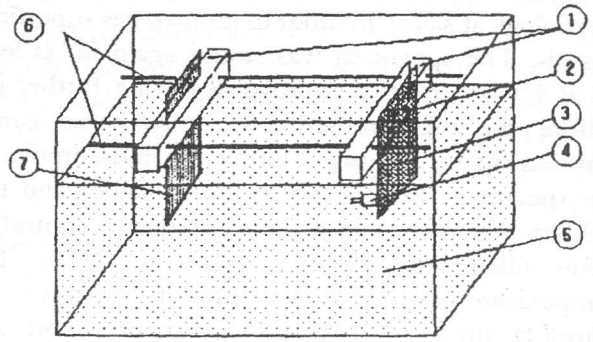

Figure 1 Rectangular water tank

1. SLIDING BARS
2. ADJUSTING SCREWS
3. TRANSDUCER HOLDER
4. ULTRASONIC TRANSDUCER
5. DISTILLED WATER
6. SLIDING RODS
7. STAINLESS STEEL REFLECTOR / SAMPLE HOLDER

Figure 1. Rectangular water tank.

The transducer is utilized as both a pulse transmitter and a receiver, and a stainless steel reflector (target) is located in the focal region of the transducer and aligned for normal wave incidence. The sample was interposed between the transducer and reflector. Six narrow band transducers (0.8, 1, 1.5, 2, 2.2, and 4 MH_Z) were used. The ultrasonic pulse-echo-instrument series 4100MGB kretztechnik is used as the source of the excitation of transducers and as a display of transmitted and reflected acoustic pulses.

2. *Samples Preparation*

Fresh bovine liver specimens were obtained from an autopsy which was performed within 48 hours after death. Normal and cancer human breast specimens were obtained from 10 cancer breast cases at Medical Research Institute Hospital immediately after surgery. Each specimen was prepared in a manner similar to the method described by Closstermans et al [8]. After excision, the specimen was stored at 4°C for up to 48 hours. Therefore, a slice of 1.00 ± 0.3 cm thickness was carefully cut using a special jig to ensure uniform known thickness and parallel cut surfaces. The cut surface area was about 30 cm^2. The sample was degassed for

90 min. at a pressure of 0.5 bar while immersed in physiological saline in order to remove gas superficial vessels. The specimen was stored again for at least 2h at 4°C in order to improve degassing further [9]. Before the measurement, the tissue was gently warmed up for 20 min. During the measurements, the specimen was constrained in a holder and this holders was placed in a thermostatically controlled basin filled with distilled water at 27°C. The temperature of 27°C was chosen because the warming up time was still acceptably short and appearance of gas bubbles was still assumed to be prevented [10].

RESULTS AND DISCUSSION

1. *Attenuation Measurements*

1.1 *Frequency dependence*

In the present study the attenuation magnitude and its frequency dependence for plexiglas, bovine liver, normal human female breast tissue, and cancer breast tissue are given in Figure (2). The correlation coefficient r, a measure of the match between measured attenuation values and the power law fit, is found to be 0.885 for plexiglas, 0.9995 for liver, 0.9902 for normal breast, and 0.9730 for cancer breast. The power law fit is found to be :-

$= 2.3580\ f^{0.4060}$ for plexiglas
$= 0.6760\ f^{1.3206}$ for bovine liver
$= 1.3740\ f^{1.0486}$ for normal breast tissue
$= 3.2189\ f^{0.7786}$ for cancer breast tissue

A linear relationship is obtained between attenuation coefficient for normal breast while nonlinear relationship for the others.

A useful format for interpretation of the results is a graph of attenuation/frequency vs. frequency [5]. Dividing attenuation by frequency normalizes the data, reducing the scale over which the values extend and facilitating visual estimation. Figure (3) gives measured attenuation/frequency (α/f) values for plexiglas, bovine liver and normal and cancer breast tissue of human female vs. frequency. For normal breast tissue, the slope of the normalized attenuation curve is nearly horizontal, indicating that n is equal to 1 and the relationship between frequency and attenuation is almost linear. In contrast, n is significantly different from 1.0 for plexiglas, bovine liver, and cancer breast.

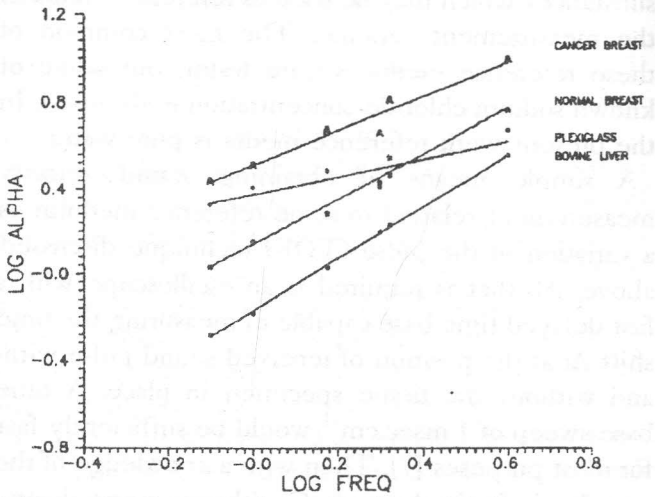

Figure 2. Change of attenuation with frequency.

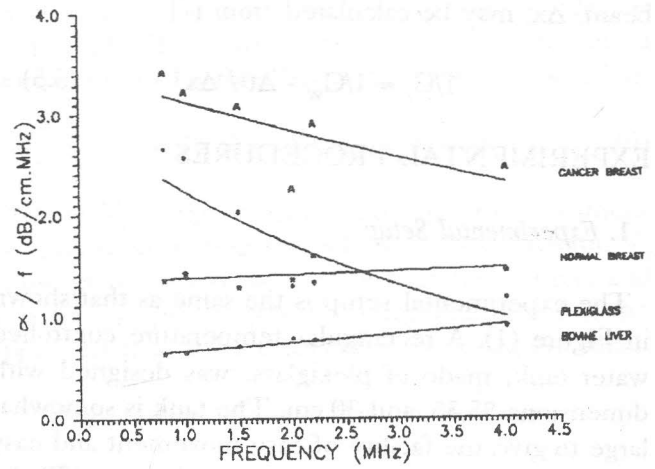

Figure 3. Change of attenuation/Frequency with frequency.

Bovine liver had the highest value, n=1.3206 which could contribute to higher frequency dependence. Plexiglas and cancer breast tissue were found to have n values of 0.4060 and 0.7786, respectively.

Theoretically, such a change in frequency dependence could be linked to a shift in the distribution of relaxational time constant [5]; however, evaluation of the underlying mechanism will require further studies.

1.2 *Temperature dependence*

In the present study the effect of temperature on the attenuation coefficient in plexiglas (non-biological media), bovine liver, normal and cancer breast (biological tissue) is studied. The results are shown in Figure (4).

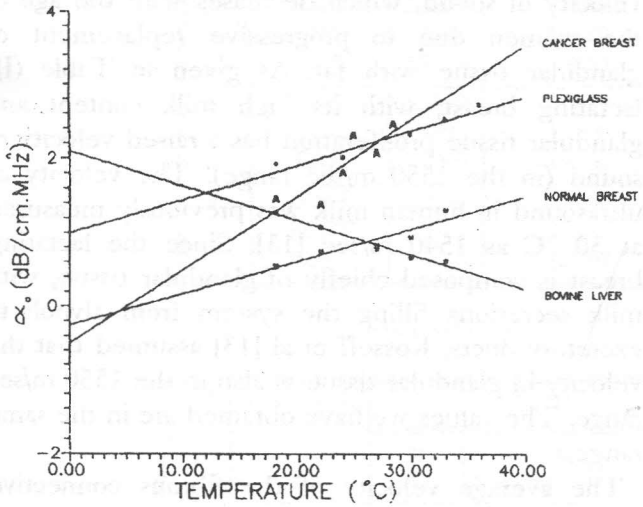

Figure 4. Change of attenuation with temperature.

As seen from Figures, at temperature between 18 and 40°C, and frequency of 2 MH_Z, the attenuation coefficient of liver is a monotonically decreasing function of temperature with slope ($d\alpha/dT$), while it increases for the others.

2. *Velocity Measurements*

2.1 *Frequency dependence:*

Figure (5) shows the changes induced in the acoustic velocity with frequency for plexiglas (non biological media), for bovine liver, and human normal and cancer breast (biological soft tissues).

Acoustic velocity does not vary strongly with frequency in the range from 0.8 MHz to 4 MHz for plexiglas, bovine liver and normal breast specimens, however the acoustic velocity increases from 1480 m/s to 1960 m/s for cancer breast specimen. Applications of relaxation theory and general relationship between ultrasonic attenuation and dispersion have been used to show that dispersion in hemoglobin solution and in human brain is closed to the expected dispersion (Kremkau et al. 1981) [11]. From average measurements on sheep and cat livers, Frizzell and Gindorf (1981) [9] concluded that there is negligible difference between the sound velocity at 100 MHz and that at low MHz frequencies. The high values of attenuation and velocity of ultrasound in cancer breast tissue (see Figures 2 & 5) may be due to a relatively large degree of dispersion [7].

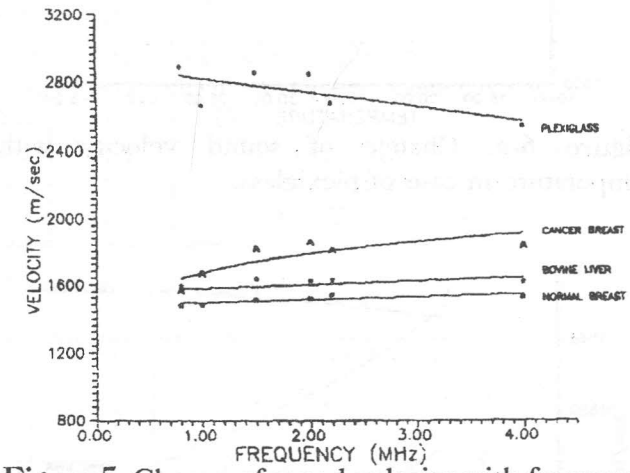

Figure 5. Change of sound velocity with frequency.

2.2 *Temperature dependence:*

It is important to know the temperature at which the measurement is made, but controlling and varying the temperature can provide a convenient means of testing the system over a range of speeds of sound. Figure 6 (a and b) show the temperature dependence of sound velocity in plexiglas (non-biological media), bovine liver, normal breast, and cancer breast soft tissues. Increased velocity of sound from one tissue to another correlates with increased protein content, collagen, and with increased water content [7].

The very low velocity of sound in fat results in its being an acoustically important component of some tissues. The female human breast, which has a high proportion of fat, tends to possess a low average velocity of sound, which decreases with the age of the women due to progressive replacement of glandular tissues with fat [12,13].

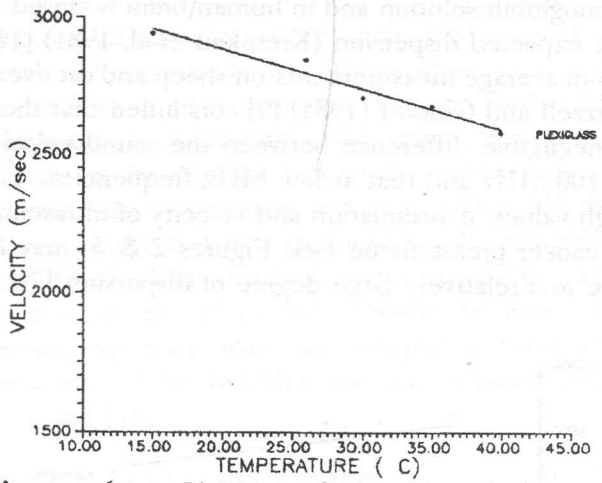

Figure 6-a. Change of sound velocity with temperature in case of plexiglass.

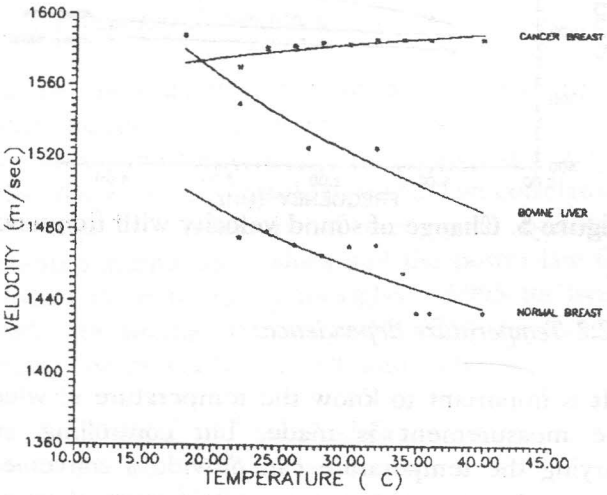

Figure 6-b. Change of sound velocity with temperature in case of biological tissues.

3. *Attenuation and Velocity of Ultrasound in the Case of Human Female Breast:*

The present study is designed to determine the in vitro range of acoustic parameters for normal and abnormal tissues in human female breast.

3.1 *Results in the case of normal breast tissues*

The breast of the adult, premenopausal female is a modified secretory gland composed of glandular, connective and adipose tissues [14,15]. The average value of the acoustic parameters through the breast is obviously dependent on its values in the traversed internal tissues. Acoustic measurements were carried out at 27 °C for different normal breast tissues. Table (I) shows the values of velocity attenuation at 2 MHz, and slope of the attenuation coefficient with frequency. The female human breast, which has a high proportion of fat, tends to possess a low average velocity of sound, which decreases with the age of the women due to progressive replacement of glandular tissue with fat. As given in Table (I), lactating breast, with its high milk content and glandular tissue proliferation has a raised velocity of sound (in the 1550 m/sec range). The velocity of ultrasound in human milk was previously measured at 30 °C as 1540 m/sec [13]. Since the lactating breast is composed chiefly of glandular tissue, with milk secretions filling the system from alveoli to excretory ducts, Kossoff et al [13] assumed that the velocity in glandular tissue is also in the 1550 m/sec range. The values we have obtained are in the same range.

The average velocity of the fibrous connective tissues (for the specific breast diagnosed by pathological studies of excised tissue) is 1518 m/sec. Large deviations from this value are less common than in the normal, particularly in regard to older patient where it might be in low range. This is consistent with distributed nature of the disease, and in particular the presence of many liquid filled cysts which would tend to constrain the value of the velocity. Also it is clear from Table (I) that the value of n is nearly close to 1 which means a linear relationship exists between attenuation and frequency for normal tissues.

2. *Results in the Case of Breast Tissues Containing Pathological Changes :*

The breast is subject to a number of pathological changes, some of which may be localized while others may be distributed throughout the breast tissues. The mean value of acoustic parameters under study for subjects under the classification of breast carcinoma are given in Table (II). Table (III) gives the test of significancy between normal breast and cancer breast.

Table (I) Acoustic Parameters For Normal Breast Subjects.

AGE	Menopause	Attenuation			Velocity	Histological Examination
		α	α_n d/B/cm.MHz	n	m/sec	
36	FRE	2.2557	1.2189	1.0511	1480	ADIPOSE (FATTY TISSUE)
27	FRE	1.7400	0.8679	1.0035	1486	
35	FRE	1.8101	0.9247	0.9690	1475	
40	FRE	2.8421	1.3740	1.0486	1488	
39	FRE	2.8204	1.3669	1.0450	1461	
59	POST	2.8048	1.3620	1.0422	1465	
60	POST	2.9228	1.4059	1.0559	1472	
28	FRE	3.3500	1.5627	1.1001	1517	GLANDULAR TISSUE (LACTATING BREAST)
38	FRE	2.4893	1.2800	0.9596	1550	
41	FRE	3.2000	1.6586	0.9481	1523	
48	POST	2.9230	1.4000	1.0620	1517	FIBROUS CONNECTIVE TISSUE
43	POST	3.2744	1.5201	1.1071	1514	
55	POST	2.7638	1.3292	1.0561	1523	

Table (II) Acoustic Parameters For Cancer Breast Subjects.

AGE	Menopause	Attenuation			Velocity	Histological Examination
		α	α_n d/B/cm.MHz	n	m/sec	
36	FRE	4.3320	1.4882	0.8000	1586	INVASIVE DUCTAL CARCINOMA
40	FRE	5.5216	3.2187	0.7786	1655	
60	POST	4.3152	2.5183	0.7770	1615	
27	FRE	3.3500	1.8780	0.8350	1616	INTRADUCTAL CARCINOMA
48	POST	3.5308	2.0000	0.8200	1608	INVASIVE LOBULAR CARCINOMA
38	FRE	2.3550	1.3972	0.7531	1540	INFILTRATING DUCTAL CARCINOMA
35	FRE	2.7500	1.5142	0.7632	1523	

Table III. Significance Test.

	α dB/cm		α_o dB/cm.MHz		n		Velocity m/sec	
					Normal Breast	Cancer Breast		
	Normal Breast	Cancer Breast	Normal Breast	Cancer Breast	Normal Breast	Cancer Breast	Normal Breast	Cancer Breast
Mean	2.73	3.74	1.33	2.14	1.03	0.79	1498	1592
σ	0.49	1.08	0.22	0.64	0.05	0.03	27.63	46.24
N	13	7	13	7	13	7	13	7
t-Test	Significant		Significant		Significant		Significant	
Level of Significance	<0.05		<0.01		<0.01		<0.01	

By comparing the acoustic parameters when the beam propagates through presumed normal tissues and when it propagates through pathological mass, it may be possible to differentiate between various benign and malignant conditions, provided that the acoustic parameters values in such tumors are significantly different. The values of n for pathological tissues are less than 1 and the attenuation is generally greater than that obtained for normal subjects. Also the pathological tissues have high acoustic velocity compared to that for normal breast tissues.

CONCLUSION

From the obtained results we can conclude the following:

- The attenuation in soft tissues is strongly dependent on the temperature, and the transducer's frequency.
- The acoustic velocity does not vary strongly with frequency for plexiglas, bovine liver and normal breast specimens, however it varies significantly for cancer breast specimens. Also, the acoustic velocity is found to be temperature dependent.
- Pathological breast tissues are found to have higher attenuation and velocity compared to that for normal breast tissues.

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