THE RELATIONSHIP BETWEEN ULTRASONIC ATTENUATION AND SPEED IN TISSUES AND THE CONSTITUENTS: WATER, COLLAGEN, PROTEIN, AND FAT

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ABSTRACT

It has been known for some time that the ultrasonic propagation properties of biological materials are strongly affected at the macromolecular level. Four tissue constituents that are of particular importance acoustically are water, proteins, and in particular, collagen, a structural protein, and fat. A comparison of ultrasonic attenuation and speed to the concentrations of water, collagen, proteins, and fat, given in wet weight percent, has been accomplished. From the comparison, it appears that the ultrasonic propagation properties of tissue are, indeed, functions of the constituent concentrations.

INTRODUCTION

An infinitesimal ultrasonic wave propagating through an isotropic, unbounded medium, can be specified in terms of the inertial, restoring, and loss parameters of the medium. These are the density, the adiabatic compressibility, and the attenuation, respectively. The density and compressibility are embodied in the speed and impedance parameters of the medium, while the attenuation includes any process by which ultrasonic energy is absorbed as heat, redirected at material inhomogeneities, or otherwise extracted from the wave process. Thus, the ultrasonic speed and loss terms may embody unique "tissue signatures".

In this and subsequent sections, a number of results are cited which lend support to the hypothesis that the ultrasonic propagation properties of tissues are, indeed, functions of their constituent percentages, and that an algorithm based on this hypothesis can be developed.

The ultrasonic propagation properties of tissues, namely attenuation and speed, are considered to be determined largely at the macromolecular level. This idea is supported by studies conducted as far back as the early 1950s. For instance, Carstensen et al. (1953) discovered that the absorption and speed of sound in blood are determined largely by the protein content, and that the ultrasonic absorption coefficient is directly

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proportional to the protein concentration, whether the protein is in solution or contained within cells. Several years later, Carstensen and Schwan (1959) showed that a small fraction of the absorption arose due to the cellular organization of the blood. In another study (Pauly and Schwan,1971) it was shown that approximately two thirds of the absorption in liver tissue occurred at the macromolecular level, with the remaining one third being attributed to macroscopic structure.

Table 1 outlines specific ultrasonic propagation properties and tissue constituents. In this review, the specific ultrasonic propagation properties which will be discussed include attenuation, absorption, and the speed of ultrasound. As shown in Table 1, attenuation includes absorption, reflection, refraction, diffraction, and scattering.

TABLE 1

Ultrasonic Propagation Properties	Tissue Constituents
ATTENUATION	WATER
Absorption	PROTEIN
Reflection	Globular
Refraction	Structural
Diffraction	(e.g. collagen)
Scattering	FAT
SPEED	ASH
	CARBOHYDRATE

Several authors have provided comprehensive compilations of available data for the acoustical properties of tissues. Most notable of these are compilations by Goldman and Hueter (1956), Chivers and Parry (1978), and Goss et al. (1978a,1980). Table 2a is based on these compilations. It shows the range of values for ultrasonic attenuation at 1, 3, and 5 MHz, and for ultrasonic speed, for biological materials selected because their collagen and/or fat concentrations were known. Table 3a shows the ranges of water, collagen, fat, and total protein percentages for these same biological materials. Values appearing in parentheses were calculated from the reported dry weight percentage, assuming an appropriate water content. Blanks in the tables indicate that the data were either unavailable or could not be found.

TABLE 2a**
Ranges of the Ultrasonic Attenuation Coefficient and Ultrasonic Speed for Selected Tissues

Tissue	Attenuation Coefficient (Np/cm) 1 MHz	3 MHz	5 MHz	Speed (m/s)
Bone				
-skull	1.5-2.2	8-20		2920-3360
-axial	1.4	1.5-6		3160-4360
-transverse				3180-3490(PL)
Brain				
-human	0.074-0.23	0.29-0.69	0.58-1.38	
-non-human	0.032-0.11	0.12-0.43	0.28-0.54	1506-1580
	0.026-0.032*	0.088(I)*	0.160(I)*	
Cartilage	0.58	1.44	2.19	1665
CSF	0.0012			1499-1515
Eye				
-Aq/Vit humor	0.02(E)	0.04(E)	0.06(E)	1490-1544
Fat	0.044-0.090	0.076-0.46	0.14-1.0	1410-1479
				1438-1602(OF)
				975-1225(SF)
Heart	0.09-0.24	0.16-0.64	0.36-0.87	1570-1585
	0.027-0.039*	0.088(I)*	0.149(I)*	
Kidney	0.09-0.12	0.28-0.35	0.5-0.6(E)	1558-1568
	0.0-0.087*	0.086(I)*	0.145(I)*	
Liver	0.074-0.15	0.19-0.50	0.35-0.79	1553-1607
	0.019-0.027*	0.095(I)*	0.174(I)*	
Lung	3.5-5.0	3.6-8.8	6.0-11.6	300-1118
Milk - whole	0.04-0.042	0.12-0.14	0.20-0.26	1480-1485
St. Muscle	0.12(I)			1568-1595
-against gr.	0.064-0.15	0.22-0.30	0.40-0.70	1545-1631
-with gr.	0.16-0.20	0.44-0.56	0.70-1.4	1585-1603

TABLE 2a** continued
Ranges of the Ultrasonic Attenuation Coefficient and Ultrasonic Speed for Selected Tissues

Tissue	Attenuation Coefficient (Np/cm) 1 MHz	3 MHz	5 MHz	Speed (m/s)
Plasma	0.01-0.02	0.03-0.06	0.067-0.10	1571
Skin	0.14-0.66	0.3-1.2(I)	0.43-1.7	1498-2030
Spleen	0.06	0.23	0.46	1515-1591
Tendon	0.074-0.146*	0.53(I)*	0.92(I)*	
-against gr.	0.54-0.73	1.25-1.88	1.95-2.86	1750
-with gr.	0.41-0.58	1.37	2.35	
Testis	0.012-0.038*	0.040-0.051(I)*	0.040-0.090(I)*	
Tongue				
-against gr.	0.29	0.87	1.5	
-with gr.	0.14	0.42	0.70	
Water (20-40 deg. C)	0.0001-0.0003	0.0013-0.0023	0.0037-0.0063	1483-1529

E - extrapolated
I - interpolated
OF- orbital fat
SF- subcutaneous fat
PL- plesio-velocity
* - absorption coefficient
**- See Table 2b for references

TABLE 2b
References for Table 2a

Bone: Dussik et al. (1958), Theismann and Pfander (1949), Hueter (1952), Ballantine et al. (1954), Martin and McElhaney (1971), Kishimoto (1958), Adler and Cook (1975), Lang (1970), Floriani et al. (1967), Lees et al. (1979)

Brain: Colombati and Petralia (1950), Kikuchi et al. (1957), Kremkau at al (1977), Oka and Yosioka (1976), Hueter and Bolt (1951), Esche (1952), Guttner et al. (1952), Yosioka et al. (1968), Robinson and Lele (1972), Ludwig (1950), Frucht (1953), Goss et al. (1979).

Cartilage: Dussik and Fritch (1955, 1956), Dussik et al. (1958).

CSF: Van Vennoij (1971), Ballantine et al. (1954).

Eye: Begui (1954), Filipczynski et al. (1967), Freeman (1963).

Fat: Dussik and Fritch (1955, 1956), Dussik et al. (1958), Colombati and Petralia (1950), Frucht (1953), Pohlman (1939), Schwan et al. (1953), Schwan and Carstensen (1956), Chivers and Hill (1975), Buschmann et al. (1970), Lizzi and Laviola (1975), O`Brien et al. (1980a).

Heart: Esche (1952), Frucht (1953), Hueter (1948), Yuhas et al. (1976), Yuhas et al. (1977), Goldman and Richards (1954), Goss et al. (1979).

Kidney: Esche (1952), Ludwig (1950), Frucht (1953), Hueter (1948), Goldman and Richards (1954), Kessler (1973), Marcus and Carstensen (1975), Goss et al. (1979).

TABLE 2b continued
References for Table 2a

Liver: Dussik and Fritch (1955, 1956), Colombati and Petralia (1950), Esche (1952), Ludwig (1950), Frucht (1953), Chivers and Hill (1975), Hueter (1948), Goldman and Richards (1954), Marcus and Carstensen (1975), Hueter et al. (1954), Hueter (1958), Pauly and Schwan (1971), Mountford and Wells (1972), Goss et al. (1979).

Lung: Dussik et al. (1958), Dunn and Fry (1961), Dunn (1974), Bauld and Schwan (1974), Reid (1965).

Milk: Hueter (1958), Maynard and Goss (1977).

St. Muscle: Dussik et al. (1958), Colombati and Petralia (1950), Ludwig (1950), Frucht (1953), Pohlman (1939), Buschmann et al. (1970), Kossoff et al. (1973), Goldman and Richards (1954), Marcus and Carstensen (1975).

Plasma: Carstensen et al. (1953), Urick (1947), Colombati and Petralia (1950).

Skin: Dussik and Fritch (1955, 1956), Dussik et al. (1958), O`Brien et al. (1980a).

Spleen: Ludwig(1950), Frucht (1953), Chivers and Hill (1975), Goldman and Richards (1954).

Tendon: Dussik and Fritch (1955, 1956), Dussik et al. (1958), Goss et al. (1979).

Testis: Brady et al. (1976), Goss et al. (1978b), Goss et al. (1979).

Tongue: Hueter (1948).

Water: Pinkerton (1949), Nyborg (1975).

TABLE 3a**
Water, Collagen, Fat, and Total Protein Concentrations
(% wet weight) for Tissues of Table 2a

Tissue	Water	Collagen	Fat	Total Protein
Bone	22-34	(13-20)	0.00	(13-20)
Brain	72-85	(0.03-0.34)	8.6	(6-11)
Cartilage	70-73	10-20		20-25
CSF	99		0.00	0.015-0.040
Eye				
-Aq/Vit humor	99-99.9	0.01-0.067	0.004-0.007	0.01-1.0
Fat	10-35		50-86	3.2-17.0
Heart	63-79.2	(0.40-2.6)	3.6-21	15-19
Kidney	75.9-82.7	0.39-1.47	3.3-6.7	15.4-16.8
Liver	66.9-80.3	(0.18-1.1)	3.7-10	16.5-21.2
Lung	76.7-79.0	(1.8-2.4)	2.3-3.8	16.8-19.3
Milk - whole	87-88		3.5-5	3-4
St. Muscle	63-75.7	(0.4-3.1)	4.0-13.3	17.3-21.8
Plasma	90-95		0.9-2.0	5.4-8.0
Skin	72	18.6-27.5		(17-28)
Spleen	74.4-77.4	(0.5-1.2)	3.0-3.9	17.1-18.8
Tendon	62.9	30.0-31.6		(22-35)
Testis	84.0-85.0		0.045	(9-11)
Tongue	61-74.3		5.3-23	13.7-18.5
Water	100	0.00	0.00	0.00

(Parentheses indicate calculated values)
** See Table 3b for references

TABLE 3b
References for Table 3a

Bone: Chvapil (1967), Ruch and Patton (1966), Wolf (1976).
Brain: Altman and Dittmer (1961), Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1963).
Cartilage: Robb-Smith (1954), Chvapil (1967), Mathews (1975).
CSF: Altman and Dittmer (1961), White et al. (1968).
Eye: Altman and Dittmer (1961), Chvapil (1967), Mathews (1975), Van Heyningen (1962), Dawson (1972).
Fat: Ruch and Patton (1966), Wolf (1976), Watt and Merrill (1963), Galton (1971).
Heart: Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1967).
Kidney: Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1963).
Liver: Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1963), Freese and Lyons (1979).
Lung: Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1963).
Milk: Watt and Merrill (1963), White et al. (1968).
St. Muscle: Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1963).
Plasma: Nyborg (1975), Altman and Dittmer (1961), Wolf (1976), White et al. (1968), Carstensen et al. (1953), Ganong (1967).
Skin: Chvapil (1967), Ruch and Patton (1966).
Spleen: Chvapil (1967), Ruch and Patton (1966), Watt and Merrill (1963).
Tendon: Chvapil (1967), Harkness (1968).
Testis: Neufeld (1937), Wolf and Leathem (1955).
Tongue: Watt and Merrill (1963).

LITERATURE SURVEY

WATER

Water is the most abundant tissue constituent, making up as much as 70 to 80 percent of many tissues (see Table 3a). Water concentration is nonuniformly distributed throughout the body. For example, adipose tissue is about 10% water, whereas blood is about 83% water. On the average, the total body water is about 60% of the body weight for young males, about 50% for young females, and about 76% for babies (Wolf, 1976). In general, total body water tends to decrease with age to about 52% for males and 46% for females. The amount of water in lean body tissue is constant at around 71 - 72%. Since fat is relatively free of water, the total body water to body weight ratio is strongly a function of the amount of fat present (Ganong, 1967). Thus, due to the abundance and variability of water in tissues, the role of water in affecting ultrasonic propagation properties is explored.

The ultrasonic absorption of water, which is equal to the attenuation of water since no scattering sites are present, is much less than that of soft tissues, although its ultrasonic speed is comparable to that of soft tissues. Because of this, tissues containing exceptionally large amounts of water, e.g., testis, exhibit a relatively low ultrasonic attenuation. Another way in which the propagation properties of water differ from those of tissues is in the frequency dependence of attenuation and absorption. The ultrasonic absorption coefficient in water is proportional to the square of the frequency, and is given approximately by

$$\alpha' / (f^{**}2) = 15.7 * (10^{**}-17) \quad \text{sec*sec/cm} \qquad [1]$$

at 37 deg. C (Pinkerton, 1949), where α is the absorption coefficient in Np/cm, while most tissues exhibit attenuation coefficients that vary approximately linearly with frequency (Goldman and Hueter, 1956; Johnston et al. 1979).

Several investigators have suggested that water influences the ultrasonic propagation properties in brain tissue. For instance, Kremkau et al. (1977) observed that the ultrasonic attenuation in infant brain was approximately one third that of adult brain. This corresponds to a much higher water concentration in infant brain, being approximately 90%, as compared to 76 - 79% for adult brain (Altman and Dittmer,

1961). The ultrasonic attenuation of an adult hydrocephalic brain, also characterized by a high fluid content, was slightly less than that of the infant brain (Kremkau et al. 1977). Oka and Yosioka (1976) reported that the attenuation of an edematose brain was less than that of normal adult brain. Wladimiroff et al. (1975) measured the speed of sound in fetal brain from the sixteenth day of gestation to term and found that the speed increased with age from 1513 to 1540 m/s. These changes are attributed to an increase in the concentration of solids, or conversely, to a decrease in the concentration of water.

The ultrasonic attenuation coefficient in tissues was characterized according to their water concentration by Goss (1978), wherein it was shown that

$$A / f = 9.00 * (10**-12) * (W**-.74) \qquad [2]$$

where A is the ultrasonic attenuation coefficient (cm**-1), and W is the water concentration. The best fit parameter, r**2, for this relation was 0.62 (Unity represents a perfect fit.), which indicates a marginally good fit.

COLLAGEN

Collagen is believed to play an important role in the acoustical properties of tissues for several reasons. One reason is that collagen, a high tensile strength insoluble fiber found in most connective tissues, including the connective tissue of cartilage, tendon, bone, skin, and muscles, is the most abundant protein in the human body. It constitutes twenty-five to thirty-three percent of the total protein, and, therefore, about 6 percent of the body weight (White et al. 1968).

A second reason is that there is evidence suggesting that collagen exhibits widely different acoustic properties from those of the other common tissue constituents (Fields and Dunn, 1973; Goss and O'Brien, 1979). It is known, for instance, that collagenous fibers exhibit a static elastic modulus (Young's modulus) approximately 1000 times greater than that of other tissues (Fields and Dunn, 1973). Since ultrasonic speed is proportional to the square root of the elastic modulus, this suggests that the ultrasonic speed would be significantly greater for collagen than for other constituents. Direct

measurements of ultrasonic speed in tendon threads suggest that this could be the case (Goss and O`Brien, 1979; Edwards and O`Brien, 1979, 1980). The higher speed in collagen implies that collagen also has a higher characteristic acoustic impedance. This, in turn, implies that there will be an impedance mismatch between collagen and surrounding tissue, and that collagen is therefore responsible for much of the reflections and scattering that occur within tissues. This idea is supported by Fields and Dunn (1973), for instance, who have suggested that collagen is largely responsible for the echographic visualizability of soft tissues.

That collagen is responsible for reflections and scattering is also indicated by the following. In the early 1950`s, when pulse-echo diagnostic ultrasound was in its infancy, the observation was made that the reflections from breast were due mainly to the connective tissue sheets in lobulated fat, as opposed to the fat alone (Wild and Reid, 1954). They (Wild and Reid, 1953) also examined the ultrasonic reflection from an *in vitro* cube of striated muscle. Here it was observed that no echos were detected when the sound beam was directed parallel to the muscle fibers, while many echos were received when the orientation was changed by 90 degrees, in which case the fibers were perpendicular to the direction of propagation. It was also observed that this anisotropy in echo return was disrupted by mechanically rupturing the cube of muscle in order to break up the connective tissue.

A few years later, the ultrasonic propagation properties of articular tissue were examined (Dussik and Fritch, 1955, 1956; Dussik *et al*. 1958). Based on these examinations it was concluded that, for the most part, tissues with a high collagen concentration exhibited greater values of ultrasonic attenuation and speed, than did soft tissue containing lesser concentrations of collagen. Dussik and Fritch (1955, 1956) also suggested that aging of dense fibrose tissue is accompanied by an increase in the ultrasonic attenuation. Fry *et al*. (1971) showed that echoes returned from the interior of cat liver, where the connective tissue between hepatic lobules is poorly developed, were of low amplitude, while in pig liver, where this structure is dense and is regularly distributed throughout the liver, echoes of much greater amplitude were returned. A similar observation has also been noted in female breast tissue. It was reported that post-menopausal breast tissue, and pre-menopausal breast tissue with

fibrosing adenosis, a condition which is characterized by an increase in connective tissue replacing the normal glandular tissue, also exhibited an increase in reflectivity over that of a normal breast (Fry et al. 1972). All of these studies suggest a relationship between collagen concentration and attenuation.

Examination of the ultrasonic propagation properties of normal breast tissues by two-dimensional imaging gave rise to the following qualitative results. Fat had the lowest speed and attenuation compared to all other parts of the breast. Normal parenchymal tissue showed medium speed and attenuation. Infiltrating medullary carcinoma had an attenuation between that of fat and normal tissue and a high speed, and the connective tissues associated with muscle boundaries of the scirrhous carcinoma had the highest speed and attenuation (Greenleaf et al. 1975, Greenleaf et al. 1976). Clearly, a relationship between increasing structural protein concentration and increasing ultrasonic speed and attenuation can be inferred from these results.

Examination of the data in Tables 2 and 3 also suggests such a relationship with respect to collagen (Figure 1). For instance, bone, cartilage, skin, and tendon have collagen concentrations in the range of 10 to 35 percent wet weight, which is more than a factor of 3 greater than any of the other tissues listed. These same high collagen concentration tissues also possess an attenuation coefficient several times higher than the other tissues, with the exception of lung. Thus it would seem that a quantitative relationship between ultrasonic attenuation and collagen concentration could be developed.

Further evidence to support the hypothesis that attenuation and speed could be related to collagen concentration came about in 1976, when it was proposed (Johnston and Dunn, 1976) that transmission of ultrasound through the subarachnoid space into the brain could be modeled as a simple three layer transmission system. The two outside layers are the brain on one side, and the physiological saline coupling solution of the experimental arrangement on the other, and are considered to have the same acoustic impedance. It was found that for this model to fit the data, the intermediate layer would have to be about 250 micrometers thick, and possess an acoustic speed of about 1800 m/s, some 300 m/s higher than that of the surrounding layers. From the data in Tables 2 and 3 it can be seen that this high speed would correspond to a material of very high collagen concentration. Examinations have shown that the

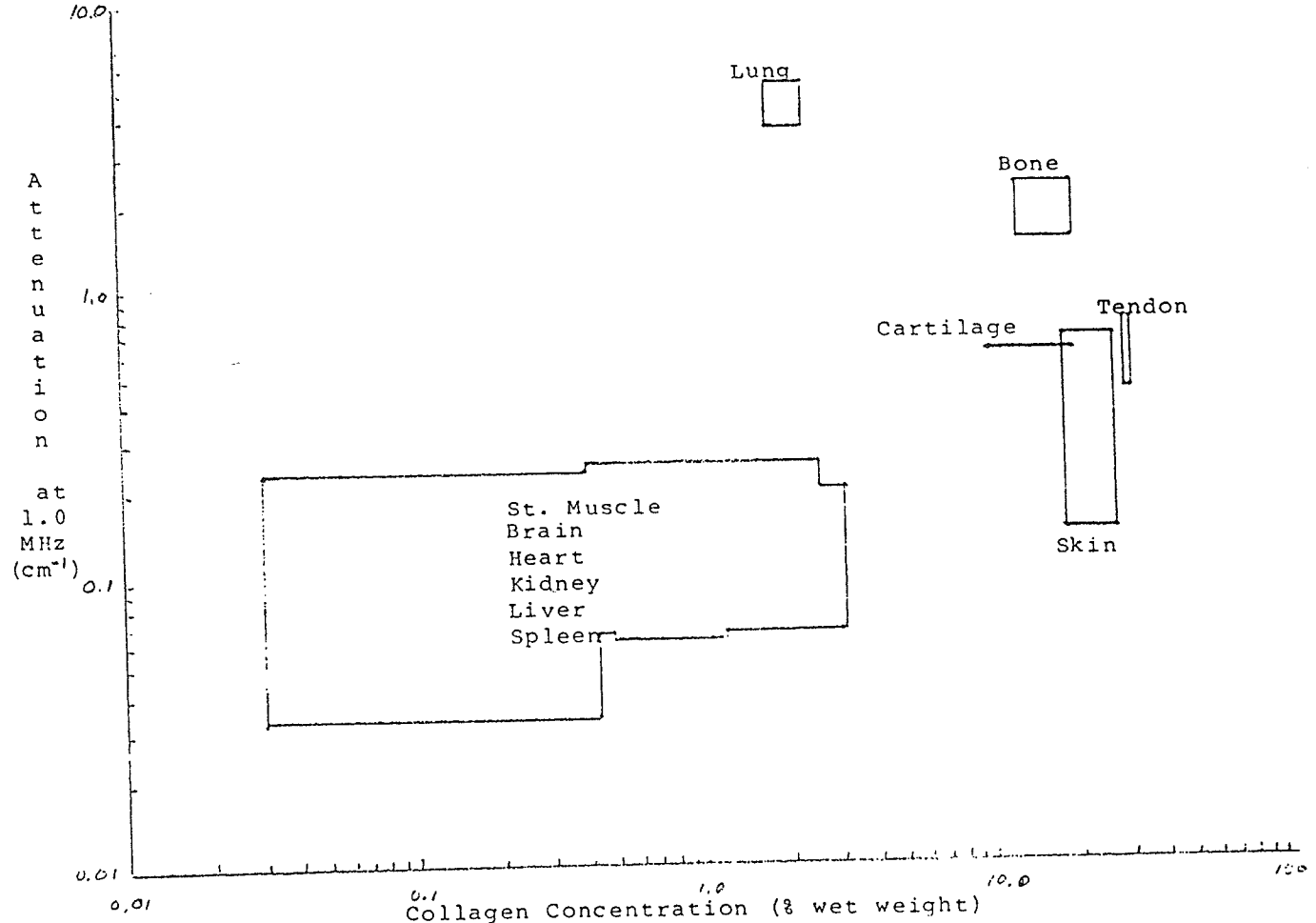

Figure 1: Attenuation vs. collagen concentration for tissues in Tables 2 and 3.

meninges, the membrane surrounding the brain, consisting of the dura mater, the arachnoid, and the pia mater, does, in fact, contain a high concentration of collagen.

Several studies of the relationship between attenuation and collagen concentration in infarcted tissues have been made. Pathological studies of infarcts indicate fibroblasts and capillaries appear within 24 hours, and that within a few days, the fibrin is replaced by collagen, which becomes increasingly dense over the next few months (Friedberg, 1966). A quantitative study of the attenuation in normal and infarcted canine myocardium, which was made around 2 months after the infarct and over the frequency range of 2 to 10 MHz, indicates that the attenuation increased in the infarcted tissue (Yuhas et al. 1976; Mimbs et al. 1977). Later reports (O`Donnell et al. 1979) strongly support the idea that there is a direct correlation between ultrasonic attenuation and collagen concentration. They investigated the existence of this correlation in regions of cardiac ischemic injury, wherein they observed a decrease in attenuation immediately post-occlusion, followed by an increase in attenuation. Thus, there is a correlation between the increase in attenuation and the increase in collagen in infarcted tissue (see also, Namery and Lele, 1972).

Recently, a study was conducted (O`Brien et al. 1980a) in which an attempt was made to characterize cutaneous wound tissue using a scanning laser acoustic microscope. Results of this study indicate that there is an increase in speed and attenuation coincident with an increase in the age of scar tissue. It is suggested that the increase in these acoustic parameters is caused by both the increase in collagen concentration and the change in the nature of collagen.

Using a least squares linear regression, a power function relationship between the ultrasonic attenuation in the 1-10 MHz range, and the wet weight percentage of collagen in a tissue was developed (O`Brien, 1977). To a first approximation this yielded

$$A = 0.11*(C**0.51) \qquad (r**2 = 0.93) \qquad [3]$$

where A is the attenuation in Np/cm and C is the wet weight percentage of collagen. Similarly, an examination of the relationship between ultrasonic speed and collagen concentration yielded

$$v = 1588 + 32(\ln C) \qquad (r^{**}2 = 0.84) \qquad [4]$$

where v is the speed in m/s. Comparison with speed measurements made at 100 MHz in tendon collagen has shown that this expression yields a value within 2 percent of the actual measured speed (Goss and O`Brien, 1979).

The mechanisms by which the scattering of ultrasound occurs in tissues has also received some attention. This is partially due to the fact that much of the currently available medical ultrasonic equipment, like imaging systems and Doppler blood flow meters, obtain information from ultrasonic energy that is scattered, as well as that which is reflected, from within tissues or organs. For the same reasons as those mentioned above in regard to reflectivity, it is thought that collagen may be responsible for much of the scattering that occurs. The relationship between collagen concentration and the difference between ultrasonic attenuation and absorption coefficients was examined (Pohlhammer and O`Brien, 1979). This difference, defined as the scatter coefficient, S, may be thought of as a measure of 4-pi steradian scattering since it encompasses any method by which ultrasonic energy may be redirected from a direct path from source to reciever. A linear least squares regression was applied to attenuation and absorption data for brain, liver, heart, kidney, and tendon, at several different frequencies, yielding

$$S = m*(C^{**}b) \qquad [5]$$

where S is the scatter coefficient, having units of 1/cm,

$$m = 0.08*(f^{**}1.05) \qquad (\text{with } r^{**}2 = 1.00),$$
$$b = 0.44*(f^{**}-0.37) \qquad (\text{with } r^{**}2 = 0.89),$$

and f is the frequency in MHz.

It has been determined that a typical ratio of absorption coefficient to attenuation coefficient is about 0.3 (Goss et al, 1979). For this reason it is felt that uncertainties in absorption and attenuation coefficients, and, hence, in S, will not be so large as to render this scatter coefficient relation useless. An interesting observation about this relationship is that it suggests that as the frequency is increased, the scatter coefficient tends to approach a value which is independent of the amount of collagen present.

PROTEIN

Although collagen is the most prevalent protein, other proteins cannot be ignored, as several investigators have shown that qualitative relationships exist between ultrasonic propagation properties and total protein concentration. For instance, in an attempt to characterize tissues according to their ultrasonic attenuation, a number of tissues, including brain, liver, kidney, blood, and articular tissues, were examined and grouped according to their function, such as: 1) metabolic material transport, 2) fat and water storage, 3) protoplasmic activity, physiological function, 4) structural, supporting,stress conveying, high in structural proteins, 5) framework protection, 6) gaseous exchange (Dunn, 1976; Johnston et al., 1979). Upon examination of this classification, it was found that there is a relatively narrow range of attenuation values within each group, and that the speed of sound increases and the attenuation approximately doubles from group to group in order of increasing attenuation. Furthermore, as one proceeds in this manner, tissues of ever increasing structural protein content are encountered. This suggests that ultrasonic attenuation can be used to characterize tissues according to functional criteria, and/or their protein concentration.

One other study that has also suggested that there exists a relationship between protein concentration and ultrasonic propagation properties in tissue is a study by Freese and Lyons (1979), wherein it was shown that ultrasonic backscatter is a function of protein concentration in normal human liver. The linear correlation of the backscatter magnitude with protein content in normal liver exhibited a best fit parameter of r = 0.776.

Lenticular tissue is a high protein material with a varied spatial distribution of water. The innermost zone of the lens typically has less than half the water concentration of the outermost zone (Dawson, 1972). The ultrasonic attenuation coefficient in lenticular tissue, if extrapolated to a frequency of 1 MHz by assuming a linear dependence upon frequency, would be between 0.09 and 0.23 cm**-1. Begui`s (1954) measurements at 3 MHz yielded an attenuation coefficient in the range of 0.59 to 0.69 cm**-1, and Lizzi et al, (1976) reported a value of 0.92/(MHz*cm) in enucleated human eye over the frequency range of 10 to 17 MHz. The latter report also qualitatively

indicated that the lenticular attenuation coefficient was greater in the rabbit.

These studies have indicated that the propagation properties of tissues can be correlated with total protein concentration as well.

FAT

Fat, or more correctly, lipid, is an almost water free tissue. Because of this, the total amount of water in the body is largely dependent upon the total amount of body fat. On the average, babies have less fat than young males, and young males have less fat than young females, and this is reflected in the average total body water, viz., 76%, 60%, and 50%, respectively (Bradley, 1972).

At least 10 percent of the body weight of the normal mammal is due to lipid (fat). The most abundant type of lipid is neutral fat (triglycerides), which is found throughout the body, and especially in certain depots of specialized connective tissue, namely the adipose tissue (White et al. 1968). An examination of Table 2a reveals that fat possesses an attenuation similar to that of other tissues, with the exception of those previously pointed out as being high collagen - high attenuation tissues. Because of this, many investigators have not considered fat concentration to be an important parameter for the ultrasonic characterization of tissues, as it would not add any distinguishable attenuation characteristics. However, fat does have an ultrasonic speed some 50 to 100 m/s less than most other tissues, and there is evidence to suggest that the speed in subcutaneous fat, in particular, is as much as 300 to 600 m/s lower (O`Brien et al. 1980a). For this reason, fat concentration has recently begun to be considered as a possible characterizing parameter. In particular, the lower ultrasonic speed may mean that tissues of high fat concentration may possess characteristic acoustic impedances that differ enough from their surroundings to produce noticeable reflections at their boundaries.

One organ for which the acoustical properties of fat may be of particular importance is the female breast. It has been shown (Greenleaf et al. 1975, Greenleaf et al. 1976) that in excised, unfixed specimens, fat yields the lowest attenuation coefficient and lowest speed of any of the breast tissues. In another study, it was shown (Kossoff et al., 1973) that the speed of ultrasound in post-menopausal breast averaged 3 to 4 percent lower

than in pre-menopausal breast, with the difference being attributed to a proliferation of fat that occurs as the glandular tissue deteriorates during and following menopause. Thus, these authors suggested that it was possible to distinguish between different states of the breast, including pre- and post-menopausal conditions, as well as to identify various benign and malignant conditions, by measuring the ultrasonic speed through it.

In a few organs, most notably fatty liver, the fat appears as tiny droplets which are distributed throughout the organ. Due to the lower ultrasonic speed of fat, it is hypothesized that these droplets may cause a significant amount of scattering, thereby causing a significantly greater amount of the attenuation in liver than can be accounted for if one considers only the attenuation of fat itself and the amount of fat involved. In an investigation by Freese and Lyons (1979) the attenuation and backscatter coefficients were measured for normal and fatty human liver samples. It was found that the frequency normalized attenuation in fatty liver was significantly greater than for normal liver. Also in fatty liver, a high correlation between backscatter and lipid content was demonstrated, with the backscatter being substantially greater for moderately and extremely fatty livers, suggesting that a simple test based on the magnitude of backscatter is feasible, in principle, for diagnosing liver conditions which influence the lipid concentration. However, the authors have advised that further investigation be required before any firm conclusions can be drawn from this result.

Measurement of the attenuation coefficient of fat tissue located in the sole of the foot has yielded a consistently higher value than from other body areas, such as the abdomen (Dussik and Fritch, 1956). It is interesting to observe that the sole is one of the few places where lipid tissue serves a structural and protective function, whereas the primary function of most fat tissue is energy storage (Windle, 1976).

A backscatter spectral analysis technique has been used to measure the ultrasonic attenuation of orbital fat tissue (Lizzi and Laviola, 1975). This technique has yielded an attenuation of 0.3/(MHz*cm) in the frequency range of 6 to 12 MHz. More recently it has been indicated that the attenuation is 0.17/(MHz*cm) over the frequency range of 5 to 15 MHz. It was also shown that the attenuation increased to 0.20/(MHz*cm) in abnormal orbital fat (Graves' disease) which was later shown to be infiltrated with

connective tissue (Coleman et al., 1976).

Thus, it appears that fat concentration can be correlated with some conditions and pathologies, and with the attenuation and speed of some tissues. This suggests that fat concentration must now be considered as an important parameter in the acoustical characterization of tissues.

CONCLUSION

There is a relatively strong influence of collagen, protein, fat, and water upon the ultrasonic propagation properties of tissues. Equations relating ultrasonic speed and attenuation to lipid, water, and collagen concentration, such as those derived by Goss (1978), demonstrate this influence numerically. It is interesting to note in these relationships that, although the concentration of collagen in tissues is generally much smaller than that of fat, there tends to be a greater correlation between collagen, attenuation, and speed, than between lipid, attenuation, and speed. From this review it is evident that a quantitative relationship exists between the concentrations of certain tissue constituents and the ultrasonic attenuation and speed exhibited by the tissues as a whole.

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