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ULTRASONIC ABSORPTION AND ATTENUATION IN MAMMALIAN TISSUES

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Abstract—The ultrasonic absorption was determined, by the transient thermoelectric method, for brain, heart, kidney, liver, tendon, and testis from cat, mouse, pig and beef. Comparison of these absorption (α) values with published values of attenuation (A) shows: (1) that the α and A coefficients have nearly the same frequency dependencies in the range 0.5–7 MHz, (2) that the magnitudes of α and A differ appreciably and that difference depends upon the method of measurement and tissue type, and (3) that there appears to be little species difference, at least as revealed by measurement of liver and tendon.

INTRODUCTION

The importance of having available details of the ultrasonic propagation properties of biological materials are twofold. First it can be expected that such available information for a wide range of biomaterials (including pathological states) will contribute to the development of more quantitative ultrasonic medical diagnostic methods employing more than only the time of arrival and the amplitude of backscattered signals, as in the current most sophisticated procedures (Wells, 1977). Such developments are hampered by the absence of detailed information regarding the basic ultrasonic properties of tissues. Second, the physical mechanisms by which ultrasound interacts within tissues is poorly understood owing to the complexity of the processes involved and the varying values for the acoustic properties of different tissues reported in the literature, making data interpretation quite difficult. Attenuation and velocity are most often measured, with ultrasonic absorption in biological tissues receiving little attention (Goss *et al.*, 1978a and 1978b). Thus the distinction between attenuation and absorption is not often appreciated.

The present study was undertaken to identify the magnitude and frequency dependencies of ultrasonic absorption in various biological tissues. The relation between this loss parameter and the attenuation values previously reported, and generally used in the analyses of theoretical loss mechanisms in tissues, are also examined.

METHODS

Absorption measurements in fresh biological tissues were made in the frequency range from 0.5 to 7 MHz at 37°C using the transient thermoelectric technique (Dunn, 1962). The thermocouple wire diameter and the ultrasonic beam width (13 μm diameter and 4 mm or greater half-power beam width, respectively) were selected to reduce errors associated with viscous heating and with heat conduction away from the junction to about 10% (Goss *et al.*, 1977 and 1978c). The ultrasonic intensity at the site of the thermocouple junction was corrected for loss in the intervening tissue.

Mammalian tissues were obtained immediately after death and stored at room temperature in physiological saline until measured, usually within 1–2 hr after excision. Beef tendon, liver, and kidney were obtained from previously bled animals approximately 2 yr of age from the slaughterhouse as were pig liver specimens, while mouse (LAF_1/J, Jackson Labs) testis and liver, and cat brain, liver, kidney, and heart were surgically removed from healthy animals maintained in the laboratory. Horse testis was surgically removed from an autopsy specimen, less than 24 hr after death. Care was taken to avoid stretching, crushing, or otherwise mechanically deforming tissue

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specimens prior to or during measurement and thus avoid introduction of bubbles into the sample (Bamber *et al.*, 1977; Fizzell *et al.*, 1979).

RESULTS AND DISCUSSION

1. *Ultrasonic absorption*

Ultrasonic absorption measurements using the transient thermoelectric technique were made in six biological tissues of varying tissue macrostructure, as a function of frequency in the range from 0.5 to 7 MHz at the temperature of 37°C (Table 1). Also included in Table 1 are the best least squares linear regression power fit describing the frequency dependence of absorption (where F is the frequency in MHz), and the correlation coefficient R which describes the goodness of that fit (to better than 90% confidence level with $R = 1$ indicating a perfect fit). The results of these measurements, summarized in Fig. 1, reveal a nearly linear frequency dependence of absorption for all of the six tissues studied, with the power to which the frequency is raised always falling in the range from 1.0 to 1.18. The frequency dependence of absorption is seen to exhibit little variation with tissue type, even though differences in water, total protein, and collagen content vary by as much as 20, 15, and 30%, respectively, among these six tissues. However, these data reveal, among these six tissues, rather pronounced differences in the magnitude of the ultrasonic absorption

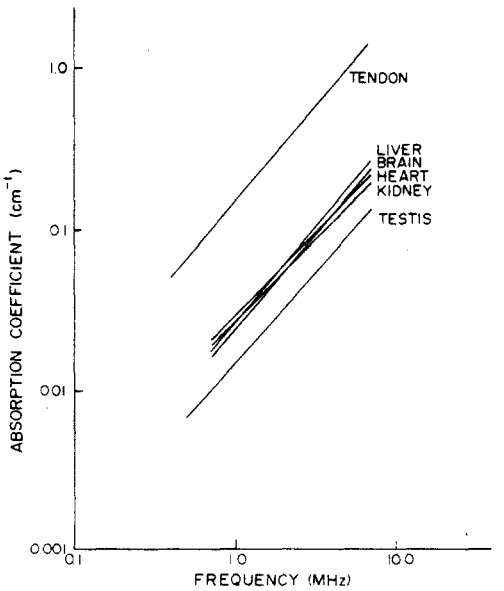

Fig. 1. Summary of frequency dependence of ultrasonic absorption in various tissues at 37°C. See Table 1 for data points, ranges, and standard deviations.

Table 1. Ultrasonic absorption in biological tissues at 37°C (±std. dev.)

Tissue	Absorption (neper/cm) Frequency (MHz) 0.5	0.7	1	3	4	7	Regression analysis fit
Brain	—	0.014 ± 0.003	0.029 ± 0.004	—	—	0.23 ± 0.09	$0.024F^{1.18}$ $R = 0.993$
Heart	—	0.018 ± 0.009	0.033 ± 0.006	—	—	0.21 ± 0.03	$0.028F^{1.04}$ $R = 0.995$
Kidney	—	0.017 ± 0.007	0.033 ± 0.004	—	—	0.20 ± 0.002	$0.028F^{1.02}$ $R = 0.994$
Liver	0.010 ± 0.006	0.020 ± 0.003	0.023 ± 0.004	—	0.14 ± 0.03	0.24 ± 0.02	$0.026F^{1.17}$ $R = 0.995$
Tendon	0.050 ± 0.03	0.16 ± 0.1	0.11 ± 0.04	0.53 ± 0.2	0.75 ± 0.4	1.4 ± 0.5	$0.14F^{1.17}$ $R = 0.973$
Testis	0.0078 ± 0.002	0.0085 ± 0.001	0.015 ± 0.003	—	0.079 ± 0.02	0.12 ± 0.02	$0.015F^{1.11}$ $R = 0.995$

coefficient. At 1 MHz, kidney, liver, heart, and brain exhibit roughly the same magnitude of absorption, with tendon and testis being appreciably different. It is seen that the absorption coefficient of tendon is four to five times that of liver, while that of testis is only one-half that of liver. The constitution of these tissues may be invoked in seeking an understanding for this behavior. Referring to Table 2, it is seen that heart, liver, and kidney are all 16–18% by weight protein, and roughly 1–2% collagen. Each of these tissues also is approximately 71–76% water. Tendon, on the other hand, has a total protein content of 35–40%, some 30% of which is in the form of collagen, with water comprising only about 63% of the tissues wet weight. Testis, on the other hand, contains very little collagen, but does contain an exceptional amount of water (greater than 80%), with only about 12% of the tissue wet weight composed of protein. It appears from these data that the tissue constituents appreciably influence the ultrasonic absorption properties of these biomaterials. Though brain has a lesser protein content than do kidney, heart, and liver, its greater lipid and lesser collagen contents may combine to provide it similar absorption properties.

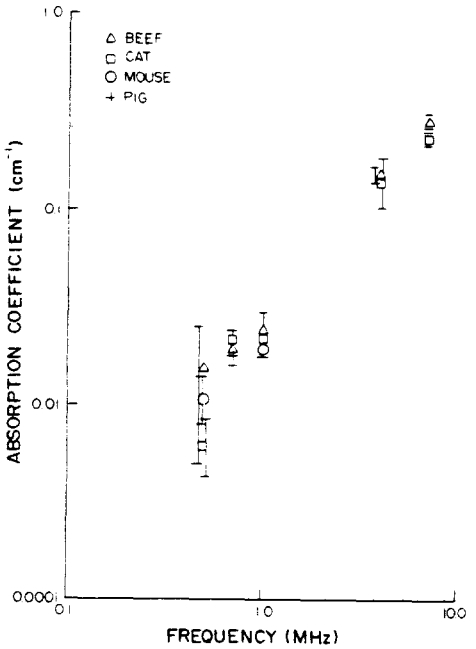

Fig. 2. Species dependence of ultrasonic absorption in liver at 37°C. Error bars represent the standard deviations.

The dependence of ultrasonic absorption on species was investigated for liver tissue of beef, pig, cat, and mouse over the frequency range from 0.5 to 7 MHz at 37°C. The results for liver tissue are shown in Fig. 2 where it is seen that with the possible exception of the data at 0.5 MHz, where some scatter possibly due to specimen variation is seen, little difference in ultrasonic absorption is observed among the four species studied, i.e. all variation is within the standard deviation of the mean value.

2. *Comparison of ultrasonic attenuation and absorption coefficient*

It is interesting to compare the magnitude and frequency dependence of attenuation in fresh tissues, as reported in the literature (Goss *et al.*, 1978b) and shown in Table 3 and the absorption coefficients obtained in the present study for these six investigated tissues.

Attenuation includes absorption and other losses such as those due to scattering, which might be expected to become more important at the higher frequencies. In Fig. 3, the best fit least squares linear regression curves to the attenuation and absorption data (Tables 3 and 1, respectively), are shown as a function of ultrasonic frequency. Clearly there is little difference in the frequency dependence of attenuation and of absorption, in the 0.5–7 MHz frequency range, for these tissues. The difference exhibited by tendon is not considered significant since the attenuation

Table 2. Principal constituents (% wet weight) of biological tissues*

Tissue	% Total protein	% Collagen	% Lipid	% Water
Brain	10(8–12)	0.16(0.05–0.28)	11(9–17)	77.4(76–78)
Heart	16.5(14–19)	1.7(1.4–2.0)	2.6(2.7–17)	72(63–83)
Kidney	17(14.7–19.3)	0.865(0.43–1.3)	5(1.8–7.2)	76(71–81)
Liver	18(16–22)	0.4(0.1–0.7)	6.9(1.1–11.5)	71(63.6–73.9)
Tendon	35–40	32	1	63
Testis	12	—	3	81

*Total protein, lipid and water content after Snyder *et al.*, 1975; Collagen content computed from dry weight percentages (Chvapil, 1967) by assuming appropriate water content.

Table 3. Ultrasonic attenuation in biological tissues at 37°C

Tissue	Attenuation (neper/cm) Frequency (MHz) 0.5	0.7	1	3	4	7	Regression analysis fit
Brain	0.032	0.047	0.07	0.24	0.34	0.64	$A = 0.07F^{1.14}$ $R = 0.822$
Heart	0.060	0.086	0.13	0.41	0.56	1.0	$A = 0.13F^{1.07}$ $R = 0.98$
Kidney	0.049	0.070	0.10	0.34	0.47	0.87	$A = 0.10F^{1.09}$ $R = 0.973$
Liver	0.038	0.055	0.08	0.29	0.40	0.75	$A = 0.08F^{1.13}$ $R = 0.934$
Tendon	0.33	0.42	0.56	1.3	1.6	2.5	$A = 0.56F^{0.763}$ $R = 0.998$

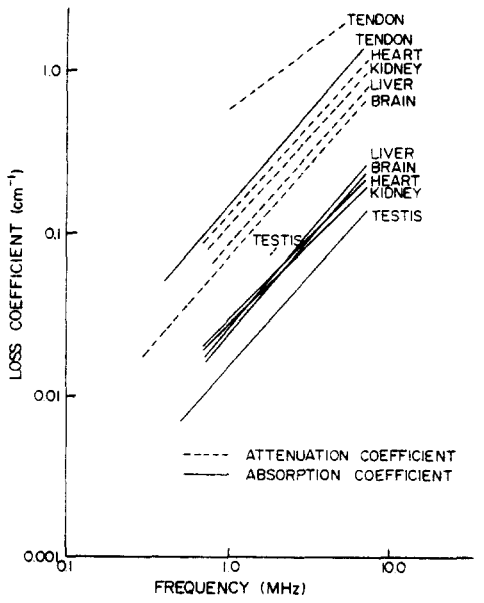

Fig. 3. Comparison of ultrasonic attenuation and absorption in various tissues as a function of frequency. See Tables 1 and 3 for data points and standard deviations.

data is that for only a single study, while the others are numerical averages of a number of studies by different investigators. Existence of differences in frequency dependence for testis cannot be determined, due to the lack of attenuation data. For all of the other tissues, however, the agreement of the frequency dependence for the attenuation and for the absorption suggests that whatever the source of the differences in magnitude between attenuation and absorption values (i.e. scattering, reflection, measurement artifact), that mechanism is also nearly linearly dependent upon frequency.

The magnitude of the attenuation (A) and absorption (α) coefficients are seen to be greatly different, however. Though the basic groupings of each loss parameter in terms of tissue constituents can be discerned for both attenuation and absorption (tendon greatest, testis least; with the loss observed in heart, kidney, liver, and brain situated between the two), there is nearly a threefold difference between the attenuation and absorption observed for each tissue type. This difference is more clearly shown in Table 4 where the ratio α/A is calculated for the six tissues in Tables 1 and 3. Here it is seen that the ratio of attenuation to absorption does not vary appreciably among these tissues, excepting testis, suggesting that tissue macrostructure and/or tissue constituents have little to do with this diversity found in the measured loss coefficient. Attenuation measurements in testis (Frizzell *et al.* 1977) were made using a phase insensitive, frequency independent radiation pressure technique, a primary method for the measurement of the second order quantities of intensity and power (Lele, 1962; Kossoff, 1965; Hill, 1970; Rooney, 1973; O'Brien, 1978). Thus, these values are much less susceptible to errors due to the phase cancellation artifacts described by Marcus and Carstensen (1975), who compared a piezoelectric receiver (phase-sensitive) with a radiation-force receiver (phase-

Table 4. Comparison of ultrasonic absorption and attenuation at 1 MHz

Tissue	Absorption α(neper/cm)	Attenuation A(neper/cm)	α/A
Brain	0.024	0.07	0.34
Heart	0.028	0.13	0.22
Kidney	0.028	0.10	0.27
Liver	0.026	0.083	0.31
Tendon	0.14	0.56	0.25
Testis	0.015	0.035*	0.43

*Extrapolated from 2 MHz data (Frizzell, 1975) assuming linear frequency dependence

insensitive), and also by Busse *et al.* (1977), who compared the piezoelectric receiver with an acoustic-electric receiver. Both these latter studies found that measurements using piezoelectric (phase-preserving) receivers yielded higher apparent attenuation values than those obtained using phase-insensitive receivers, and phase cancellation artifacts are thought to be the source of this error. In the comparison of ultrasonic absorption and attenuation values of Table 4, testis is the only tissue in which the attenuation was measured by only the radiation force technique, since the other attenuation values represent the averages of measurements obtained using a number of measurement techniques, including pulse transmission (Goss *et al.* 1979), pulse reflection (Mountford and Wells, 1972), spectrum analysis (Namery and Lele, 1972; Lele and Namery, 1974; Chivers and Hill, 1975; Bamber *et al.* 1977 and Lele and Senapati, 1977), as well as radiation pressure techniques. Measurement technique may thus, at least to some extent, be responsible for the disparity in absorption/attenuation ratios among the various tissues, and even more importantly, may serve to explain at least a portion of the observed difference in absorption and attenuation values for each tissue.

To examine the effect of measurement technique on the observed attenuation in tissues, data from the literature (Goss *et al.* 1978b) for fresh liver and brain were identified by measurement technique and the mean value for the tissue attenuation coefficient obtained by each method. These two tissues were chosen for this comparison because of the availability of data over a variety of measuring techniques. The results of this comparison, shown in Table 5, are revealing as nearly a factor of three can be obtained in the measured attenuation coefficient depending upon the method chosen. Variations in temperature, specimen preparation and other such factors, which are included by all these data, can also be expected to produce scatter in the data. For both tissues, spectrum analysis techniques yielded the greatest attenuation coefficient, with pulse transmission techniques yielding slightly lower values. Radiation pressure techniques, as suggested earlier by the testis data, yielded the lowest value of attenuation coefficient, most likely due to the phase-insensitivity characteristic of this technique.

Table 5. Ultrasonic attenuation values at 1 MHz obtained using various measurement techniques

Method of measurement	Attenuation (neper/cm)	
	Brain tissue	Liver tissue
Pulse transmission	0.088 ± 0.1	0.12 ± 0.03
Spectrum analysis	0.15 ± 0.04	0.13 ± 0.017
Radiation pressure	0.053 ± 0.03	0.077 ± 0.02

The dependence of the measured attenuation coefficient on the method by which that value was obtained, and the differences between attenuation and absorption exhibited above in Fig. 3 and Table 4, suggest that it may no longer be prudent to assign a value of ultrasonic attenuation to a particular tissue without also specifying the method by which the value was obtained and the purpose for which it will be used. For example, the "best" attenuation coefficient for a tissue is generally thought at present to be one in which measurement artifacts due to phase cancellation, reflection, or other sources are minimized. By this criterion, the "best" attenuation coefficient may be a factor of two below that determined when such artifacts are included by the measurement method. A measure of the "best" attenuation coefficient might be required in biophysical applications where the attenuation from within a particular tissue is required and losses due to measurement artifacts are undesirable. In other uses of the attenuation coefficient of biological tissues, however, as in the attenuation observed using a clinical diagnostic ultrasound instrument, the "best" attenuation coefficient would not be appropriate as it would not encompass all the encountered sources of attenuation. Thus for this example, the most appropriate "attenuation" coefficient would be only that coefficient actually measured with a specific diagnostic instrument (or by a method mimicking the functions of that instrument) and could only serve as a relative attenuation index rather than a universal ultrasonic property characteristic of any particular tissue.

In the light of the above discussion, the measurement technique which would be most appropriate to describe the attenuation from within tissues is that of radiation pressure. If radiation pressure values of attenuation are compared (Table 5) with the absorption values of the present study, the ratios of absorption to attenuation in brain and liver,

0.455 and 0.388 respectively, agrees well with that previously presented for testicle, viz. 0.433. On a gross basis then, variation in tissue constituents for these tissues does not seem to be responsible for the observed difference between this measure of attenuation and absorption. However, there is relatively little difference in collagen content between these three tissues. Collagen, the tissue constituent (other than those in bone) having the greatest velocity per unit concentration, could be expected to contribute substantially to internal scattering and ultimately to attenuation (Fields and Dunn, 1973; Goss and Dunn, 1979). The testing of this hypothesis requires that radiation pressure attenuation measurements be available in highly collagenous tissues, and since values are not presently available, further measurements will be required to define a more specific role for collagen in the explantation of the difference between attenuation and absorption.

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