Dependence of the ultrasonic scatter coefficient on collagen concentration in mammalian tissues[a)]

J. Pohlhammer and W. D. O'Brien, Jr.

Bioacoustic Research Laboratory, University of Illinois, Urbana, Illinois 61801
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The difference between literature values of ultrasonic attenuation and absorption coefficients, defined as the scatter coefficient, was related to percent wet weight collagen concentration for brain, heart, liver, kidney, and tendon, in the range of 0.7 to 7 MHz. The comparison shows that as the ultrasonic frequency increases, the scatter coefficient increases, and the dependence of scattering upon collagen concentration decreases.

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Ultrasound is being increasingly used as a means of detecting and displaying interfaces between tissues in medical imaging systems, and as a means of gaining information about the tissue pathology. However, it is usually not possible to make a quantitative diagnosis using ultrasound, principally because the relationship between acoustical propagation properties and other considerations, such as tissue constituent properties, are unknown. The overall goal of this study is the development of an algorithm to model the relationship between a tissue's constituents and acoustical properties, and thereby gain a greater understanding of the interaction between ultrasound and tissue. The discussion here deals with one aspect of this model, viz. the relationship between collagen concentration and the scatter coefficient, defined herein.

Figure 1 depicts an approach to such an algorithm. Acoustical properties, such as ultrasonic attenuation and velocity in a tissue, serve as input data to the algorithm. The output is an estimate of the wet-weight percentages of the tissue's constituents. As shown here, attenuation may be broken into subgroups including absorption, reflection, refraction, diffraction, and scattering, where scattering in this sense generally refers to back scattering as used in medical diagnostic systems, planar scattering, and the scattering seen from simple sources, such as spheres and cylinders. Phase cancellation may also contribute to attenuation depending upon the measurement method used. For our purposes, the scatter coefficient describes any phenomenon which redirects acoustic energy away from a direct path from source to receiver. Hence we have defined

$$S = A - \alpha, \tag{1}$$

where S is the scatter coefficient, and A and α are the attenuation and absorption coefficients (in nepers/cm), respectively. As such, S encompasses reflection, refraction, diffraction, and scattering as normally defined, with the exception of that portion of acoustic energy which undergoes any of these effects and is still detected by the receiver.

The relationship between collagen concentration and scatter coefficient, hereafter defined by Eq. (1), is examined because collagen, the most abundant protein in the human body,[1] is believed to play an important role in terms of echographic imaging[2] due to its widely different ultrasonic velocity and characteristic acoustic impedance values with respect to those of other tissue constituents.[3,4]

The ultrasonic absorption coefficient data used in this study were determined by Goss *et al.*,[5] using the transient thermoelectric technique in fresh biological tissues. The attenuation coefficient data utilized herein, also taken from Goss *et al.*, were originally compiled by Goss[6] by applying a linear regression analysis to selected literature values,[7] viz., only those which were classified by the original investigators as fresh tissue. This means that attenuation coefficient data cover a variety of measurement techniques over a range of temperatures. In some cases, tendon in particular, they[5] extrapolated the regression curve beyond the range of frequencies for which data were available.

The above-mentioned data, together with literature values for collagen concentration,[8-10] C (wet-weight percentage), provide the data base for relating S to C. The values of S are shown in Table I for five tissues, at 0.7, 1, 3, 4, and 7 MHz, along with the range of collagen concentrations associated with each tissue.

A linear regression curve was fit to the data shown in Table I for each of the five frequencies listed there (assuming the collagen concentration to be the midpoint of the range given). The resulting relations of scatter coefficient to collagen concentration are shown in Fig. 2.

As was also determined by Goss *et al.*,[5] a typical ratio of absorption coefficient to attenuation coefficient is about 0.3. Even when an error of ± 50% is assumed

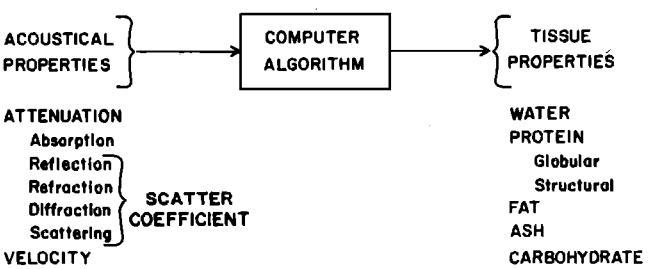

FIG. 1. Inputs to and outputs from an algorithm relating the acoustical propagation properties and constituents of a tissue.

[a)]Portions of this work presented at ASA*50, Cambridge, MA, June 1979, J. Acoust. Soc. Am. Suppl. 1 65, S3 (1979).

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TABLE I. Values of collagen concentration, C, and scatter coefficient, S, as determined by Eq. (1), for selected tissues.

Tissue	Collagen concentration (wet weight percent) range	midpoint	Scatter coefficient (cm^{-1}) $f=0.7$ MHz	1.0 MHz	3.0 MHz	4.0 MHz	7.0 MHz
Brain	0.03–0.34	0.19	0.033	0.041	0.15	0.22	0.41
Liver	0.18–1.1	0.64	0.035	0.057	0.20	0.26	0.51
Heart	0.40–2.6	1.5	0.068	0.097	0.32	0.44	0.79
Kidney	0.39–1.47	0.93	0.053	0.067	0.25	0.36	0.67
Tendon	30–31.6	30.8	0.26	0.45	0.77	0.85	1.1

for A (no uncertainties were reported for the attenuation coefficients), the ranges of $A \pm 50\%$ and $\alpha \pm \sigma$ (where σ is the reported standard deviation) do not, in most cases, overlap. For this reason it is not felt that the uncertainties of S determined in the above manner are so large as to preclude one from making the following observations. First as the ultrasonic frequency increases, the magnitude of the scatter coefficient also increases. This is to be expected since, as the ultrasonic frequency increases, the scattering sites tend to become larger compared to the wavelength, and more objects become significant as scatterers. Second, as the frequency increases, the scatter coefficient tends to approach a value which is independent of the amount of collagen present in a tissue. Table II lists the relations between the scatter coefficient and collagen concentration for the curves in Fig. 1, and numerically shows both of these trends. Combining these relations into a single formula by determining least-squares power curves for both their coefficients and exponents yields:

$$S = cC^e, \tag{2}$$

where

$$c = 0.08f^{1.05} \text{ (with } r^2 = 1.00),$$

and

$$e = 0.44f^{-0.37} \text{ (with } r^2 = 0.89),$$

which lends itself to application in the algorithm mentioned above.

It should be noted that the curves in Fig. 2 suggest that a certain amount of acoustical scattering is occurring even when the collagen concentration is negligible, i.e., 0.2% or less. This merely suggests that there are other scattering sites within these tissues, and that this simplified view of scattering is not sufficient to explain all types of scattering that take place. Fat, for example, may also contribute to scattering due to its relatively low acoustic speed.

Several other comments ought to be made concerning these results. First, there is a large gap between the data near 1% collagen concentration and that near 30%. Since the tendon data could have a marked effect on the slopes of these curves, the least squares determinations were repeated, omitting the tendon data. As shown in Table III, the same trends as mentioned above were exhibited. Second, one of the two lowest frequency curves does not appear to fit the pattern of approaching a horizontal line with increasing frequency, as exhibited by the other curves. It is not known whether this is due to errors in the literature values used to calculate these curves, or if this is due to some anomalous phenomenon occurring near 1 MHz. A suggested explanation, although not verifiable at this time, is that a greater abundance of measurements at 1 MHz by numerous investigators using a variety of techniques, provided a better measure of attenuation in these tissues at this frequency.

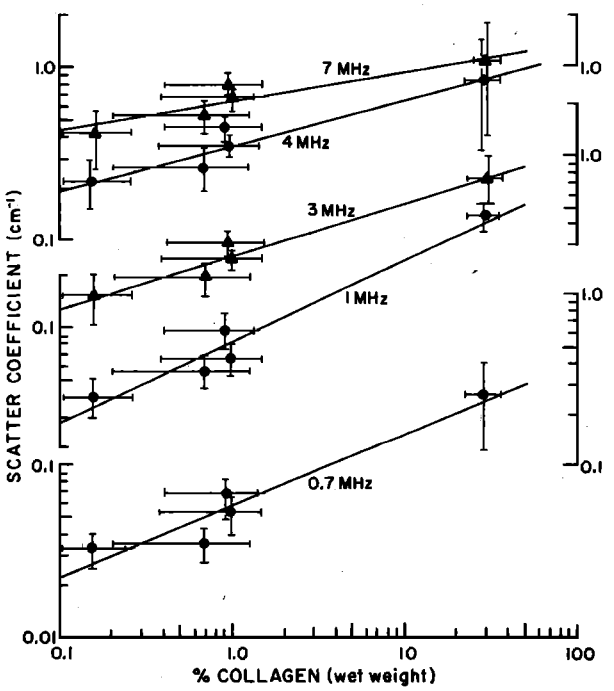

FIG. 2. Plot of scatter coefficient (attenuation coefficient–absorption coefficient) versus collagen concentration at $f = 0.7$, 1, 2, 3, and 7 MHz.

TABLE II. Relations of the collagen concentration, C, to the scatter coefficient, S, at the individual frequencies for brain, liver, heart, kidney and tendon.

f(MHz)	S(cm^{-1})	Goodness of fit parameter, r^2
0.7	$0.06\ (C)^{0.43}$	0.96
1.0	$0.08\ (C)^{0.49}$	0.98
3.0	$0.26\ (C)^{0.33}$	0.98
4.0	$0.34\ (C)^{0.27}$	0.96
7.0	$0.62\ (C)^{0.19}$	0.90

TABLE III. Relations of the collagen concentration, C, to the scatter coefficient, S, at the individual frequencies but omitting tendon.

f(MHz)	$S(\text{cm}^{-1})$	Goodness of fit parameter, r^2
0.7	$0.05\ (C)^{0.33}$	0.74
1.0	$0.07\ (C)^{0.38}$	0.92
3.0	$0.26\ (C)^{0.35}$	0.92
4.0	$0.36\ (C)^{0.33}$	0.87
7.0	$0.66\ (C)^{0.31}$	0.93

A fundamental understanding of the relationship between acoustical properties and tissue constituents is essential to the development of any quantitative diagnostic techniqe employing ultrasound as its means of interrogation. Equation (2) represents a step towards such an understanding. Similar studies concerning the dependency on other tissue constituents will help to develop this understanding further.

ACKNOWLEDGMENT

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