ULTRASONIC IMAGING 9, 132-145 (1987)

A PRELIMINARY STUDY ON THE ANGULAR DISTRIBUTION OF SCATTERED ULTRASOUND FROM BOVINE LIVER AND MYOCARDIUM

Thomas M. Burke[1], Ernest L. Madsen, and James A. Zagzebski

Department of Medical Physics
University of Wisconsin
Madison, WI 53706

Measurements were performed on freshly-excised bovine liver and myocardium to determine the ultrasonic scattering nature of the tissues under a variety of experimental conditions. Results for the angular distribution of the differential scattering cross section per unit volume of tissue are reported for scattering angles spanning 170 to 44 degrees for interrogating frequencies of 1.0, 2.25, 3.5 and 5.0 MHz. Fresh and aged tissues, some with abnormally high connective tissue content were analyzed. The results are compared to previously-published works.

Key words: Bovine; differential scattering cross section; liver; myocardium; ultrasound.

I. INTRODUCTION

In the last decade, a number of investigators have suggested that quantitative ultrasonic scatter measurements may be used to characterize the state of various soft tissues [1-12]. One fundamental means of quantifying the scatter nature of a material is by measuring the frequency (f) and scattering angle (θ) dependence of the average differential scattering cross section per unit volume, $\sigma_{vol}(f,\theta)$. Mathematically, $\sigma_{vol}(f,\theta)$ may be related to the incident plane wave intensity $I_o(f)$ and mean scattered intensity $\langle I_s(f,\theta)\rangle$ by

$$\sigma_{vol}(f,\theta) = \langle I_s(f,\theta)\rangle \, r^2 \, / \, I_o(f) \cdot V, \qquad (1)$$

where the brackets, $\langle \ldots \rangle$, designate mean value and r is the distance from the scattering target (of volume V) to the point of measurement of $I_s(f,\theta)$. The units of $\sigma_{vol}(f,\theta)$ are $cm^{-1}\ sr^{-1}$.

This paper presents experimental results from a series of preliminary studies on quantifying the scattering nature of two

[1] Present address: General Electric Medical Systems, 3920 Security Park Drive, Rancho Cordova, CA 95670.

0161-7346/87 $3.00

bovine tissues. The tissues were freshly-excised bovine liver and myocardium. Values of $\sigma_{vol}(f,\theta)$, measured with four discrete insonifying frequencies spanning 1.0 to 5.0 MHz for scattering angles between 170 and 44 degrees, are reported. These experimental values have been corrected for tissue attenuation effects. Data are shown that point to possible dependencies of $\sigma_{vol}(f,\theta)$ on connective tissue content as well as on tissue handling techniques.

II. EXPERIMENTAL METHODS

A. Data Collection System

The scattering targets consisted of small (~4 ml) samples of tissue positioned in a specially-constructed agar cylinder for scatter measurements [12,13] (Fig. 1). The agar cylinder acted as a support for the tissue and surrounded the tissue with a scatter-free material whose bulk acoustic properties closely match those of the surrounding water. (The density of the agar is 1.0 g/ml and the speed of sound is 1503 m/s at 22 degrees centigrade [12].) Similar agar cylinders have been previously used to investigate the scattering properties of ultrasonically tissue mimicking materials [12,13,17].

The target cylinder was positioned in the experimental apparatus as shown in figure 2. In this configuration, the tissue was constrained to lie in the same horizontal plane as the source and receiver transducers. The target is rotated about an axis through its center to allow scattering measurements to be performed for 150 target volume orientations for each scattering angle. Averaging over these target orientations

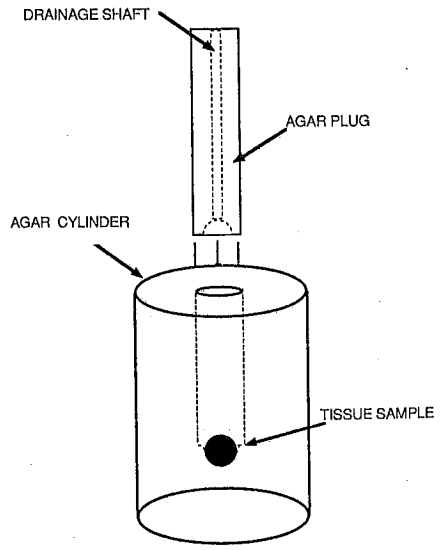

Fig.1 Diagram of an agar target cylinder showing the relationship between the agar plug, target tissue and target cylinder.

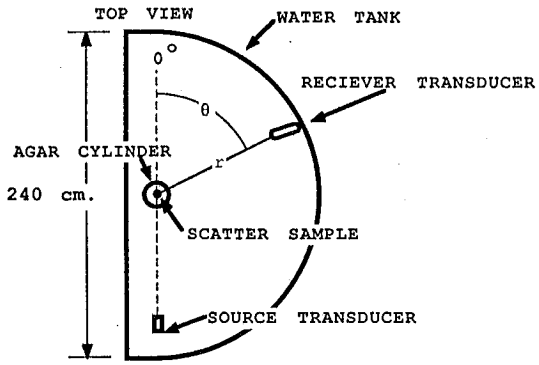

Fig.2 Diagram of the experimental scatter geometry.

yields a scattering cross section that should be free of orientation-related dependencies.

The transducers used were manufactured by KB Aerotech (Lewistown,PA). These were in the form of matched narrowband piezoelectric disc transducers with center frequencies of 1.0, 2.25, 3.5 and 5.0 MHz. Table I lists the relevant information calculated for the transducers used in this study.

In order to approximate incident plane wave intensities, I_o, at the target and to minimize phase cancellation effects at the receiver, large source to target and target to receiver distances (≈60 cm respectively) were used in conjunction with sufficiently long gated continuous wave tone bursts. The tone bursts are produced by gating 40 microsecond long signal segments from a sinewave generator and running the gated sinusoid into a broadband power amplifier before routing the amplified signal to the source transducer (Fig. 3).A burst length of 40 microseconds was chosen to ensure that the entire target volume was completely enveloped within the interrogating burst.

Table I. Relevant parameters for the source (S) and receiver (R) transducers.

Transducer	Frequency (MHz)	Diameter (cm)	L axial max (calc) (cm)	Distance (cm)
S	1.0	2.86	13.6	60
R	1.0	1.27	2.7	60
S	2.25	2.54	24.2	65
R	2.25	0.64	1.51	60
S	3.5	1.91	21.2	65
R	3.5	0.64	2.35	60
S	5.0	1.27	13.44	75
R	5.0	0.64	3.36	65

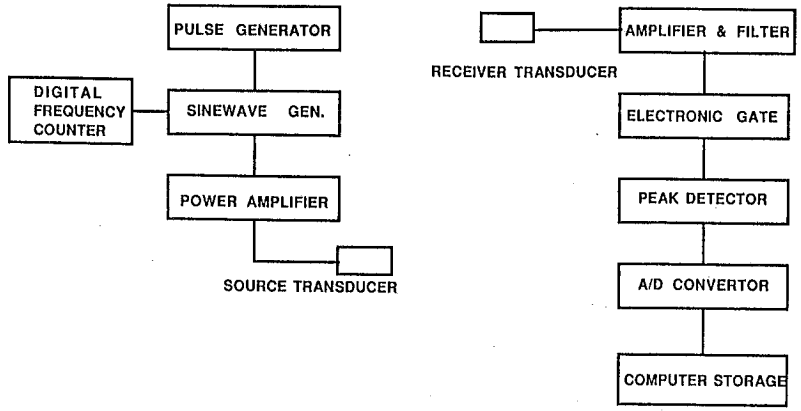

Fig.3 Block diagram of the scatter systems electronics.

Scattered waves were monitored with the receiver transducer for scattering angles ranging from 170 to 44 degrees in 3.6 degree increments. At smaller scattering angles, there was contamination by the primary beam and, in the backward direction, ($\theta > 170°$) transmit and receive assemblies overlap. For these measurements, the receiving transducer was constrained to move on a circular arc centered on the target volume. The received scatter signals were amplified and bandpass filtered prior to the extraction of a 15 microsecond long segment from the center of the 40 microsecond long waveform for analysis(Fig.3). This segment corresponded to continuous wave scattering and possessed constant amplitude for each fixed position of the scattering sphere and receiver. The latter was accomplished by an electronic gate which isolated the desired 15 microsecond long waveform and routed it first to a peak detector and then to a 12-bit A/D converter. The resulting data consisted of a 12-bit digital word stored on a DEC (Maynard, MA) PDP 8/I computer that represented the scattered wave amplitude for a particular orientation of the target volume for each scattering angle and interrogating frequency.

The scattered wave signal amplitude was normalized to values representing the amplitude of the incident acoustic beam. The incident pressure wave amplitude was measured by placing the receiver transducer at the location of the target volume (after removing the target) with the incident signal being processed in a manner similar to the procedure used to process the scattered wave signals. An attenuator was inserted into the signal path between the receiving transducer and the amplifier in the case of the incident amplitude measurement. This was done to avoid saturation of the receiver electronics due to the large signal amplitude for the incident beam compared to that for the scattered waves.

B. Data Processing

The goals of the data processing were to evaluate $\sigma_{vol}(f,\theta)$ using Eq.(1). Due to interference effects, averages

over 150 target volume orientations were obtained for each scattering angle θ and frequency f. Also, attenuation of the incident and scattered waves was accounted for by calculation, using measured values for attenuation coefficients for the tissues interrogated.

The attenuation correction factor (see appendix A) used in this study accounted for the loss of acoustic energy as the incident beam traveled from the surface of the target sphere to each differential scattering element within the target sphere as well as the loss as the scattered wave traveled from the element out of the target volume to the receiver transducer for each scattering angle. Thus, the attenuation correction factor was a function of the diameter of the target sphere, the measured attenuation coefficient of the target material and the scattering angle.

Notice the ratio of intensities in Eq.(1) can be expressed as the ratio of squares of signal amplitudes, since intensity = $p^2/2\rho c$ = A v^2, where the constant A depends on the receiver transfer function and receiver area. Assuming a linear response, A is independent of the intensity (p is the pressure amplitude and v is the corresponding signal amplitude, above.) Thus, $\langle I_s\rangle/I_o = \langle v^2_s\rangle/v^2_o$ and Eq. (1) becomes

$$\sigma_{vol}(f,\theta) = r^2 \langle v^2_s(f,\theta)\rangle/(V\, v^2_o). \qquad (2)$$

The mean value, $\langle v_s^2\rangle$, for each scattering angle appears in Eq.(2) because interference effects, specific to each particular realization of the (presumably) randomly-distributed scattering sites in the tissue sample, cause v_s^2 to vary greatly with sample orientation. It is the mean value of v^2 that is proportional to V for a sufficiently large number of statistically-independent sample orientations.In our measurements the number of statistically independent orientations was 150; i.e.,

$$\sigma_{vol}(f,\theta) = r^2\langle v_s^2(f,\theta)\rangle/(V\, v_o^2) = r^2\Sigma(v_{si}^2/v_o^2)/(V*150) \qquad (3)$$

where the subscript i in the summation runs from 1 to 150 orientations.

C. Tissue Preparation

Fresh bovine heart and liver tissues were obtained from a local slaughter house and ultrasonic scattering measurements were performed the same day. For either tissue, the entire organ was secured and packed in a plastic bag on ice for transport to the laboratory within 30 minutes of the death of the animal.

Next, a roughly spherical volume was formed out of the tissue. This was accomplished by first cutting a 2.0 cm diameter cylindrical plug of tissue from the intact organ with a sharp cork-borer type tool. A spherical volume was then fashioned by cutting the cylindrical plug with surgical scissors. This technique produced target volumes of 3-4 ml. The volume of the target sample was determined by the amount of

normal saline solution displaced when the sample was submerged in a graduated cylinder. The sample surface was then quickly dried on an absorbent paper to remove excess saline prior to measurement of the samples mass for eventual calculation of its density. The sample volume was then placed in the agar target cylinder for measurements, taking care to eliminate air bubbles from the target volume. When the tissue was not being scanned, it was kept at 4 degrees centigrade in degassed normal saline solution to retard decay processes [2].(Degassing was accomplished by boiling and cooling.) Throughout the tissue handling phase, surgical gloves were used to protect both investigators and samples from needless contact.

III. RESULTS

The results from three different experimental situations are presented in this section for each type of bovine tissue. The first situation deals with the measurement of $\sigma_{vol}(f,\theta)$ for tissue specimens minutes after the tissue sample had been removed from the donor organ. This situation is referred to as "fresh tissue". The second situation deals with the previously-defined "fresh tissue" specimen except that the tissue samples exhibited connective tissue marbling as seen by the naked eye. Lastly, the term "aged tissue" is used to refer to tissue specimens that were kept in degassed normal saline solution for 30 minutes to 24 hours before scattering measurements were performed.

A. Bovine Liver

Livers obtained from four different animals were used in this study. The results to be presented represent the average measurements for three tissue samples, each taken from a different animal. (The result for bovine liver with connective-tissue marbling is an exception, with only one measurement being reported at 2.25 MHz.) The error bars shown in the experimental results represent standard errors of the means. The angular distribution of $\sigma_{vol}(f,\theta)$ for the specimens of bovine liver are plotted in figures 4 a,b,c,d, for each interrogating frequency respectively. The results are plotted for fresh tissue and for tissue that shows the effects of keeping the tissue samples at 22 degrees centigrade in degassed normal saline solution from 3 to 10 hours prior to the repeat of the scatter measurements. Figure 4b is an exception in that results for liver with elevated levels of collagen are also reported. Lastly, figure 5 shows results for $\sigma_{vol}(f,\theta)$ measured at 170 degrees compared to previously-reported results [2] for the backscatter coefficient $\eta(f)$ as a function of interrogating frequency where $\eta(f)$ is defined as $\sigma_{vol}(f,180°)$.

B. Bovine Heart

The studies performed on bovine heart were similar to those just reported for bovine liver. An exception to the earlier procedure was in regard to the nature of the aging of the tissue; viz,the tissue was kept 4 degrees centigrade for 24 hours in degassed normal saline solution. It had been reported

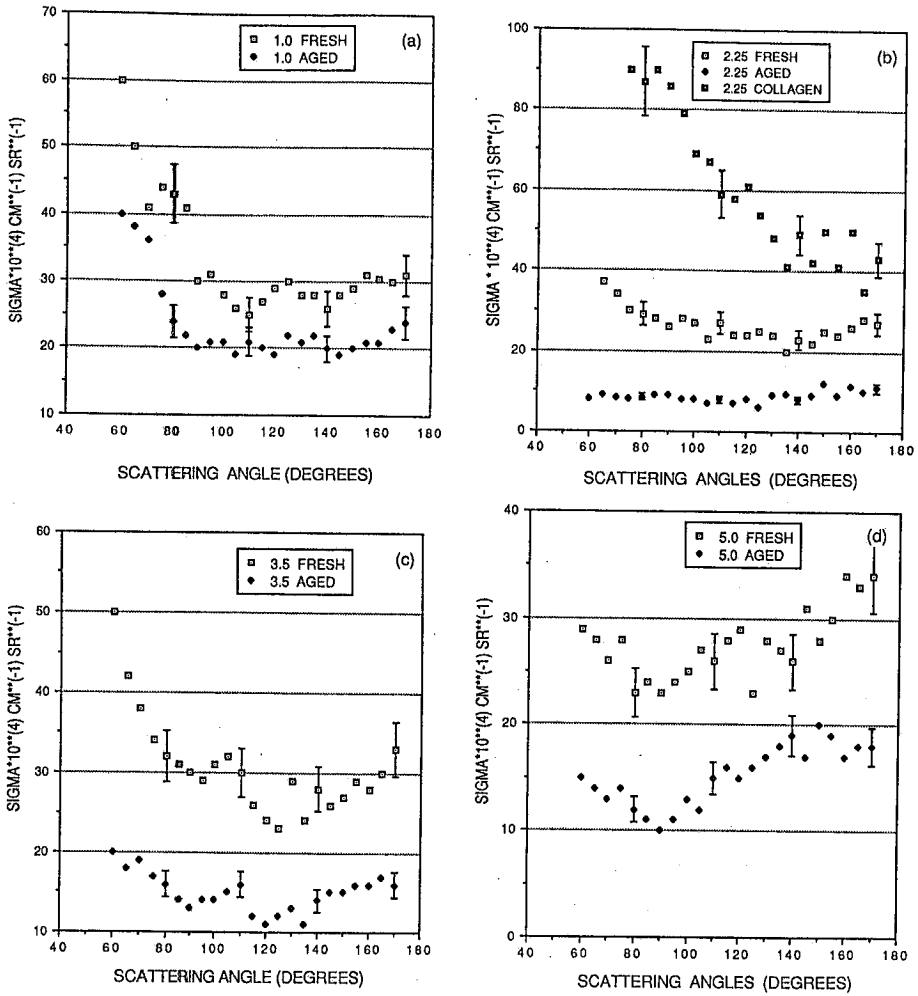

Fig.4 Plots of $\sigma_{vol}(f,\theta)$ for bovine liver tissue in fresh, aged and with-collagen states plotted vs. scatter angle for (a) 1.0, (b) 2.25, (c) 3.5, and (d) 5.0 MHz.

that storage at 4 degrees centigrade inhibits time-dependent variations in the scattering properties of excised tissue [2]. Our purpose was to test this idea. In all, two separate hearts were used. Each set of data represents the results of one tissue sample from a specific donor organ. The error bars reported correspond to standard errors of the mean.

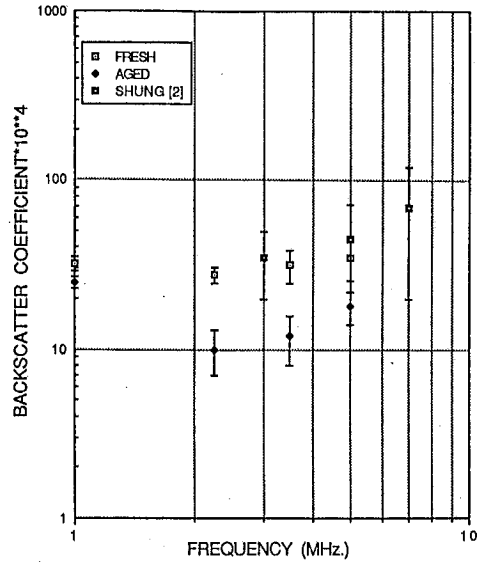

Fig.5 Backscatter coefficient $\eta(f)$ plotted vs. frequency for bovine liver in fresh, aged, and with collagen state. Results from Shung [2] are shown for comparison.

The angular distribution of $\sigma_{vol}(f,\theta)$ obtained from fresh and aged samples of bovine heart tissue are plotted in figure 6 for each interrogating frequency. Figure 6 a,b,c also include data corresponding to tissues with connective tissue marbling

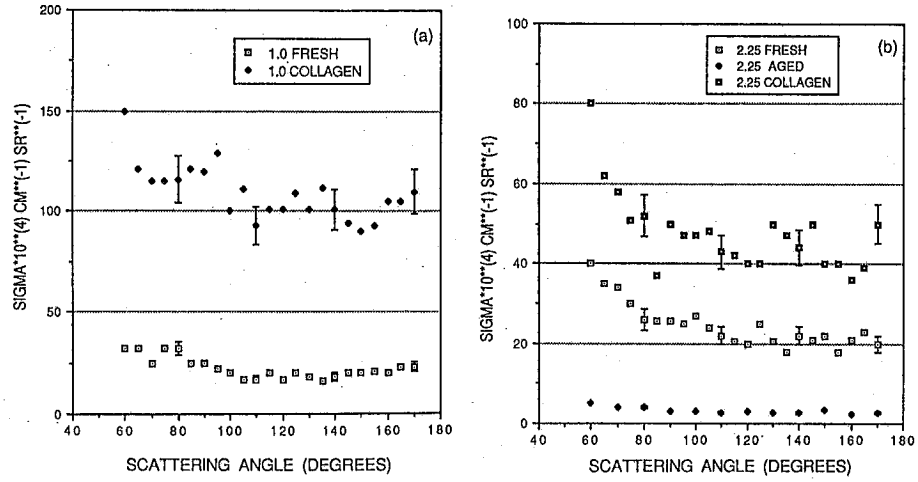

Fig.6 Plots of $\sigma_{vol}(f,\theta)$ bovine myocardium in fresh, aged and with collagen state plotted vs. scatter angle for (a) 1.0, (b) 2.25, (c) 3.5, and (d) 5.0 MHz.

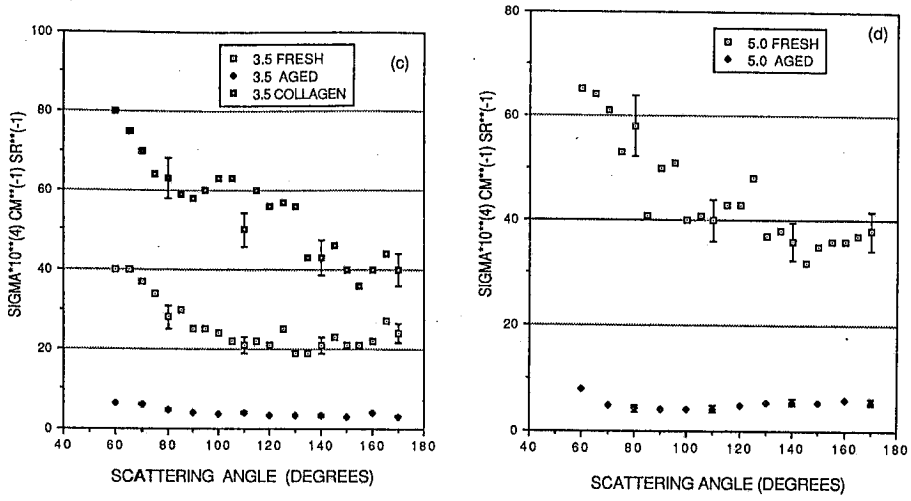

Fig. 6 — *Continued*.

present in the scattering volume. Figure 7 compares $\eta(f)$ for bovine myocardium taken from previous studies [2,16] to results from this study measured at θ equal to 170 degrees; again, some of the data correspond to tissue specimens containing connective tissue marbling. The latter results were taken from data plotted in figure 6 a,b,c.

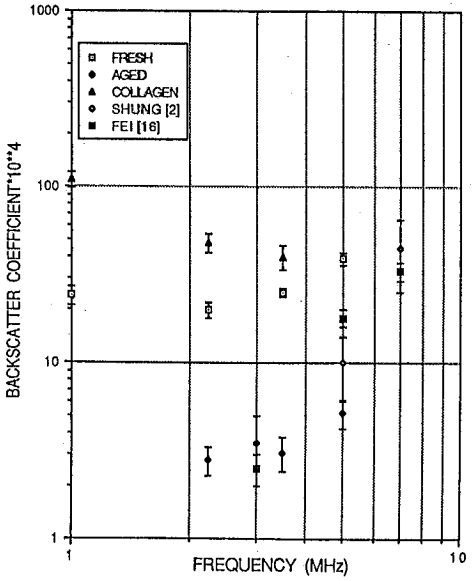

Fig.7 Backscatter coefficient $\eta(f)$ plotted vs. frequency for bovine myocardium in fresh, aged, and with collagen state. Results from Shung [2] and Fei [16] are shown for comparison.

IV. DISCUSSION

A. Liver

As shown in figure 5, the scattering results at about 180° for fresh liver agree reasonably well with previously-published data on the backscattering properties of excised liver tissue [2]. Whether the two methods would agree so well using materials with identical backscatter coefficients has not been established, however.

Figures 4 and 5 show that keeping the tissue samples at 22 degrees centigrade for up to 10 hours in degassed normal saline solution consistently lowers $\sigma_{vol}(f,\theta)$ by a factor of about one half at all scattering angles. Notice, however, that the angular distribution of $\sigma_{vol}(f,\theta)$ remained almost the same as in the case of fresh tissue results.

A possible explanation for the lowering of $\sigma_{vol}(f,\theta)$ with time is that bacterial action caused degradation of connective tissue accompanied by absorption of adjacent fluids. This absorption of the surrounding saline solution might lessen variations in density and speed of sound encountered in the tissue sample.

Lastly, a perhaps expected feature of this study was the large increase in the $\sigma_{vol}(f,\theta)$ for the liver specimen with connective tissue marbling present in the target volume. This effect has been reported previously [15].Note in figure 4b the particularly large increase in $\sigma_{vol}(f,\theta)$ for scattering angles less than 90 degrees. This increase in forward scattering resembles scattering associated with phantom materials that were composed of scatterers whose dimensions were on the order of the interrogating wavelength [12,13].

B. Myocardium

Two trends become apparent after comparing $\sigma_{vol}(f,\theta)$ measured for bovine liver to results measured for bovine myocardium at the same interrogating frequency. These are: 1) both tissues have a small frequency dependence for large scattering angles and interrogating frequencies less than or equal to 5.0 MHz; and 2) myocardium appears more sensitive to aging effects than liver tissue(compare figures 4 a,b,c,d with figures 6 a,b,c,d).

Figure 7 compares results for $\sigma_{vol}(f,170)$ taken from this study to previously-published results of $\eta(f)$ [2,16]. The results for fresh tissue from this study show larger values of $\sigma_{vol}(f,\theta)$ when compared to results both from Shung [2] as well as Fei [16].However, our "aged" tissue results were comparable with both previous studies. It is important to note that the results reported in [2] were for measurements taken 24 hours after the death of the animal just as in the case of our "aged"

tissue. The results from Fei [16] were for tissue stored up to two hours in normal saline solution at four degrees centigrade.

An important point should be emphasized, however, regarding aging effects for bovine heart tissue. No decrease in scatter level was observed if the target volume was removed from the intact organ (which had been kept on ice) just prior to measurement. This was true even if the measurements were done 24 hours after the death of the animal. Thus, it may be that the time after the death of the animal is not as important in influencing the levels of scattering as the environment in which the tissue exists prior to measurement.

The effect of large collagenous structures in the target volume is shown in the plots of the angular distribution of $\sigma_{vol}(f,\theta)$ (Figs. 6 a,b,c). These results were obtained with interrogating frequencies of 1.0, 2.25, and 3.5 MHz. Once more, the effect of the collagen is to elevate the scatter levels for all frequencies and at all angles when compared to results for pure heart tissue.

V. SUMMARY

Multiple specimens of tissue taken from intact bovine heart and liver organs were studied to determine their ultrasonic scattering characteristics. Measurements were performed on tissue specimens with interrogating frequencies ranging from 1.0 to 5.0 MHz and for scattering angles from 170 to 40 degrees. For each tissue type (i.e., liver or heart), three different experimental situations were investigated in a preliminary fashion. The first situation consisted of measuring the scatter characteristics from specimens of tissue removed from the donor organ just minutes prior to measurement. These specimens are referred to as "fresh tissue". The second situation dealt with the use of "fresh tissue" that had elevated levels of connective tissue present in the sample. The last situation dealt with the effect of separating the small target sample for the donor organ for an extended period of time prior to scatter measurements.

The results for fresh normal liver tissue agreed reasonably well with previously-published data for $\eta(f,180)$ [2]. The results obtained for fresh normal heart, however, were consistently higher for all frequencies when compared to previously-published data. The results for aged bovine heart tissue were comparable to previous results [2,16].We found that the effect of separating the target volume from the donor organ and holding the tissue in normal saline solution for an extended period of time prior to scatter measurements was to consistently lower the magnitude of the scattering cross section at all measured frequencies while preserving the overall frequency and angle dependencies. Lastly, the effect of having elevated levels of connective tissue (collagen) in the target volume was to elevate consistently the level of the measured scatter cross sections for all frequencies. This latter effect has also been observed by other investigators [15].

ACKNOWLEDGMENT

This work was supported in part by DHEW Grant 2 R01 25634.

Appendix A

For each determination of $\sigma_{vol}(f,\theta)$ in our study, it was necessary to account for attenuation of incident and scattered waves in the tissue sample itself. Attenuation coefficients of each sample at the frequencies of interest were determined using tissues taken from the same organ. A narrowband through-transmission technique was employed [18].

The correction factor involves three basic assumptions. The first is that, for each volume element dv = dxdydz containing scatterers, the incident beam is attenuated in the tissue along the straight line connecting dv with the source; the source is approximated to be an infinite distance away from the sample, and attenuation occurs only along that part of the straight line lying in the tissue sample. The second assumption is that the wave scattered by the scatterers in dv is attenuated in the tissue sample in the same fashion as in the case of the is that the wave scattered by the scatterers in dv is attenuated in the tissue sample in the same fashion as in the case of the incident beam along that line connecting dv with the receiver. The receiver is simultaneously approximated to be an infinite distance away. The third assumption is that the scattering is incoherent, meaning that the total intensity at the receiver for any scattering angle is the sum of scattered intensities from each volume element.

The resulting correction factor, taking the origin of the coordinate system to be at the center of the spherical tissue sample, the z axis to be in the direction of propagation of the incident beam, and the receiving transducer to lie in the x-z plane, is

$$C_A(\alpha,\theta)=\frac{1}{(4/3)\pi a^3}\iiint_{\text{volume}} e^{-\alpha(Do+Ds)}\,dxdydz. \qquad (A1)$$

In this expression, $Do \equiv (a^2-x^2-y^2)^{1/2}+ z$, corresponds to the incident wave path in the sample volume, and $Ds \equiv (a^2-x_s^2-y^2)^{1/2} - z_s$, corresponds to the scattered wave path. Also, $x_s \equiv -z\sin(\theta) + x\cos(\theta)$ and $z_s \equiv z\cos(\theta) + x\sin(\theta)$. $\alpha=\alpha(f)$ is the intensity attenuation coefficient of the tissue at frequency f, and a is the radius of the scattering tissue sample.

REFERENCES

[1] Sigelmann,R.A. and Reid,J.M., Analysis and measurement of ultrasound backscattering from an ensemble of scatterers excited by sine wavebursts ,*J. Acoust. Soc. Am. 53*, 1351-1355 (1973).

[2] Shung,K.K. and Reid,J.M., Ultrasonic Scattering from Tissues, in 1977 IEEE *Ultrasonics Symposium Proceedings*, p.203 *(IEEE Cat. No. 77 CH1264-ISU)*.

[3] O'Donnell,M. and Miller,J.G., Quantitative broadband ultrasonic backscatter: an approach to nondestructive evaluation in acoustically inhomogeneous materials, *J. Acoust. Soc. Am. 52*, 1056-1065 (1981).

[4] Nicholas,D.,*Recent Advances in Ultrasound in Medicine*, 29-54, (Research Studies, New York, NY, 1977).

[5] Bamber,C. and Hill,C. R., Acoustic properties of normal and cancerous human liver I-dependence on pathological conditions, *Ultrasound Med. Biol. 7*, 121-133 (1981).

[6] Nicholas, D., Hill,C.R., and Nassiri,D.K., Evaluation of backscattering coefficients for excised human tissues: principles and techniques, *Ultrasound Med. Biol. 8* , 7-15 (1982).

[7] Campbell,J.A. and Waag,R.C., Normalization of ultrasonic scattering measurements to obtain average differential scattering cross sections for tissue, *J. Acoust. Soc. Am. 74* , 393-399 (1983).

[8] Chivers,R.C. and Hill,C.R. A spectral approach to ultrasonic scattering from human tissues: methods, objectives and backscattering measurements, *Phys. Med. Biol. 20*, 799-815 (1975).

[9] Shung,K.K., An alternative approach for formulating the backscattering equation in Sigelmann and Reid's method, *J.Acoust. Soc. Am. 73*, 1384-1386 (1983).

[10] Shung,K.K., On the ultrasound scattering from blood as a function of hematocrit, *IEEE Trans. Sonics. Ultrason. SU-29*, 327-330 (1982).

[11] Insana,M.F., Zagzebski,J.A., and Madsen,E.L., Acoustic backscattering from ultrasonically tissue-like media, *Med Phys. 9*, 848-855 (1982).

[12] Burke,T.M., Quantitative Characterization of the Ultrasonic Scattering Nature of Tissue and Tissue Mimicking Materials, *Ph.D. Thesis* (University of Wisconsin, 1983).

[13] Madsen,E.L., Zagzebski,J.A. ,Insana,M.F., Burke,T.M., and Frank,G., Ultrasonic tissue-mimicking liver including the frequency dependence of backscatter, *Med. Phys.9*, 703-710 (1982).

[14] Madsen,E.L., Zagzebski,J.A., Banjavic,R.A., and Jutila,R.E., Tissue mimicking materials for ultrasound phantoms, *Med. Phys. 5*, 391-394 (1978).

[15] Mimbs,J.W., Bauwens,D., Cohen,R.D., O'Donnell,M., Miller,J.G., and Sobel,B.E., Effects of myocardial ischemia on quantitative ultrasonic backscatter and

identification of responsible determinants, *Circulation Research 49*, 89-96 (1981).

[16] Fei,D.Y., Shung,K.K. and Wilson,T.M., Ultrasonic backscatter from bovine tissues: variation with pathology, *J. Acoust. Soc. Am. 81*, 166-172 (1987).

[17] Burke, T.M.,Goodsitt, M.M., Madsen, E.L., and Zagzebski,J.A., Angular distribution of scattered ultrasound from a single steel sphere in agar gelatin: a comparison between theory and experiment, *Ultrasonic Imaging 6*, 342-347 (1984).

[18] Madsen,E.L., Zagzebski,J.A., Frank,G.R., Oil-in-gelatin dispersions for use as ultrasonically tissue-mimicking materials,*Ultrasound Med. Biol. 8*, 277-287 (1982).