Interlaboratory Comparison of Ultrasonic Backscatter, Attenuation, and Speed Measurements

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ABBREVIATIONS

TM, Tissue mimicking; UWLMP, University of Wisconsin Laboratory Measurement Procedure; RF, Radio frequency; SD, Standard deviation; CDRH, Center for Devices and Radiological Health

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In a study involving 10 different sites, independent results of measurements of ultrasonic properties on equivalent tissue-mimicking samples are reported and compared. The properties measured were propagation speed, attenuation coefficients, and backscatter coefficients. Reasonably good agreement exists for attenuation coefficients, but less satisfactory results were found for propagation speeds. As anticipated, agreement was not impressive in the case of backscatter coefficients. Results for four sites agreed rather well in both absolute values and frequency dependence, and results from other sites were lower by as much as an order of magnitude. The study is valuable for laboratories doing quantitative studies. KEY WORDS: Measurements; Speed; Attenuation; Backscatter; Interlaboratory comparison.

In 1986 an article was published to compare measurements made of ultrasonic attenuation coefficients and propagation speeds in TM phantom materials produced at the University of Wisconsin and sent to participating laboratories.[1] To assess stability of ultrasonic properties during the study, measurements were done on those phantoms at the University of Wisconsin laboratories before and after the measurements were made at other laboratories. The same type of study, involving 10 laboratories, has been carried out and is reported in this paper. The important difference from the previous study is that backscatter coefficients have been added to the parameters reported. The inclusion of backscatter measurements is very important because the range of values reported in the literature for a given tissue parenchyma can vary considerably. An extreme example involves measurements on the seemingly homogeneous tissue parenchyma, human blood; the ratio of backscatter coefficients reported by Nassiri and Hill[2] and by Shung and colleagues[3] for human blood, while stirring, is about 26 (14 dB).

In the study reported here, two types of phantom materials were produced, one differing from the other in backscatter, attenuation, and propagation speed. A sample of each material was sent to each participating laboratory. The implication was made to each of the participants by the study coordinator (E.L.M.) that its pair of samples might not have the same properties as the pairs sent to other participants. Thus, possibly prejudicial comparisons of measured values between participants before reporting their results were discouraged. Laboratories measured ultrasonic properties of samples and reported values when samples were returned.

The following procedure was established for monitoring the stability of ultrasonic properties during the study. Before the samples were sent to the various sites, measurements of ultrasonic properties for all 20 samples were made using methods of measurement that are routinely used to characterize phantom materials at the University of Wisconsin. Using the same methods, properties were again measured after all samples had been returned.

TM MATERIALS AND PHANTOMS

The component materials were 18 MΩ deionized water, Difco Bacto agar (Difco Laboratories, Detroit, MI), n-propanol, finely powdered graphite (Type No. 9039, Superior Graphite, Chicago, IL), and 45 to 53 μm diameter glass bead scatterers (Potters Industries, Valley Forge, PA). Two types of TM materials with different compositions, Type A and Type B, were prepared, and 10 cylindrical samples were made from each. The right circular cylindrical samples were 5 cm thick and 7.6 cm in diameter, being bounded on the curved surface by a 6 mm thick acrylic wall and on the parallel flat surfaces by 25 μm thick Saran Wrap plastic film (Dow Chemical, Midland, MI). The Saran Wrap serves as a window for transmission of ultrasound pulses between the TM material and surrounding medium (presumably water).

The details of production of the TM materials have been published elsewhere.[4,5] Quantitative compositions of the TM materials are given in Table 1. Note that Type A has a lower glass bead concentration as well as a lower powdered graphite concentration than Type B. The result of these lower concentrations is that Type A has lower backscatter coefficients, and lower attenuation and propagation speed, than Type B.

DISTRIBUTION OF SAMPLES AND INFORMATION

The 10 sites participating in the study were selected either by direct invitation, based on the laboratory's reputation for accurate measurements of ultrasonic properties, or by general invitation through announcements at meetings of the American Institute of Ultrasound in Medicine Technical Standards Committee. After measurements of ultrasonic properties via the UWLMP (see next section), each site was sent one each of the Type A and Type B sample cylinders. Each of the 20 samples was distinguished from the others by a unique number, and the specific pair of samples received by any site was kept on record (by E.L.M.). Included with the samples was a listing of the ultrasonic properties to be measured at 22°C, a tabulation of amplitude transmission coefficients from 1 through 10 MHz for the Saran Wrap windows on the sample cylinders, and a request that participants exchange neither samples nor data with one another. Participants were asked via e-mail to return their samples after completing their measurements so that repeat measurements on all samples could be made with the UWLMP.

Table 1: Weight Percent Composition of the Two Types of TM Materials Used in the Study*

Component	Type A Material (Weight Percent)	Type B Material (Weight Percent)
Distilled water	86.2	84.5
n-propanol	6.3	6.3
Powdered agar	3.5	3.5
Powdered graphite	3.7	5.0
Glass beads	0.3	0.7

*The powdered graphite provides primarily absorption,[6] and the glass beads provide primarily backscatter. The n-propanol affects the propagation speed.

UWLMP

Propagation Speed

Propagation speed c was measured using displacement of water and through-transmission of a 2.5 MHz tone burst pulse. The time shift at a zero crossing was monitored when the sample was inserted in the ultrasound beam, and the following widely used straightforward relation was used to compute c:[7] $c = c_w[1 + c_w\Delta t / d]^{-1}$, where $c_w = 1489$ m/s is the propagation speed in water at 22°C, Δt is the time shift, and d is the thickness of the sample (test cylinder). Dispersion was minimal in the TM materials, the increase that occurred as the frequency was changed from 2.5 to 8.0 MHz being 1.4 ± 0.5 m/s for the Type A material and 2.0 ± 0.5 m/s for the Type B material.

Attenuation Coefficients

Attenuation coefficients at four discrete frequencies (2.50, 4.50, 6.20, and 8.00 MHz) were measured using a through-transmission water displacement technique, with tone burst amplitudes monitored before and after insertion of the sample. The attenuation coefficient (dB per unit length) in TM material at frequency f is given by the formula $\alpha(f) = (20/d) \log_{10}[A_o/(AT_{total})]$, where d is the sample thickness, A_o is the peak-to-peak signal amplitude in the absence of the sample, and A is that with the beam passing along the axis of the sample. The factor T_{total} is the total amplitude transmission coefficient through both bounding Saran Wrap layers. All measurements of attenuation coefficients at each frequency using the above method were accompanied by measurements on a laboratory grade castor oil sample used as a standard (Sigma Chemical, St. Louis, MO). If the castor oil differed from tabulated values[8] by more than 5% (a rare occurrence), the measurement apparatus and procedure were inspected for the source of the discrepancy; almost always a discrepancy has involved a new person learning the measurement technique. The same sample of castor oil has been in use for at least 3 years, including the duration of this study.

Determination of T_{total} was done at 22°C and was based on the assumption of a three-layered medium (namely, water and TM material separated by Saran Wrap). T_{total} has the form[9]

$$T_{total} = 4\{2 + (r_3/r_1 + r_1/r_3)\cos^2(2\pi f \rho_2 L/r_2) + [r_2^2/(r_1 r_3) + r_1 r_3/r_2^2]\sin^2(2\pi f \rho_2 L/r_2)\}^{-1} \tag{1}$$

where r_1 is the acoustic impedance (density times propagation speed) of water, r_2 is the acoustic impedance for the Saran Wrap, r_3 is the acoustic impedance for the TM material between the Saran Wrap windows, f is the frequency, ρ_2 is the Saran Wrap density, and L is the Saran Wrap thickness (25 μm). The density ρ_2 of Saran Wrap was supplied by the manufacturer. (Note that Equation 1 above is Equation 6.13 of Kinsler and coworkers,[9] which is the intensity transmission coefficient for three media for transmission through a single Saran Wrap layer. Equation 6.13 of Kinsler and coworkers can be shown to be equal to the total amplitude transmission coefficient for transmission from water through Saran Wrap into TM material through the second layer of Saran Wrap and back into water, no attenuation occurring in the TM material.)

The following experimental procedure was used for determining T_{total}. First, a test cylinder having two Saran Wrap windows and containing degassed distilled water was inserted in a tone burst beam between transmitter and receiver. The decrease in amplitude was used to compute the Saran Wrap acoustic impedance using the above three-layer transmission equation, with $r_1 = r_3$ = acoustic impedance of water. The attenuation coefficient of water was assumed to be negligible. Using this technique the total amplitude transmission coefficient through both Saran Wrap layers, $T_{Saran,water}$, was determined at a set of discrete frequencies between 1 and 10 MHz. The acoustic impedance for Saran Wrap (r_2) was chosen so that the three-layer theory yielded the values of $T_{Saran,water}$ found experimentally. Using the Saran Wrap acoustic impedance determined, the acoustic impedances of degassed distilled water (r_1) and of the TM material (r_3), and the thickness L of the Saran Wrap as determined with a micrometer, the total amplitude transmission coefficient T_{total} is given by Equation 1 above. The total transmission coefficients

Table 2: Total Amplitude Transmission Coefficients T_{total} Through the Saran Wrap Windows From 1 Through 10 MHz

Frequency (MHz)	1	2	3	4	5	6	7	8	9	10
T_{total}	0.9928	0.9757	0.9493	0.9151	0.8759	0.8338	0.7910	0.7491	0.7093	0.6724

T_{total} for each of the two types of TM material are given in Table 2. That this method for determining T_{total} is accurate has been tested by measuring the attenuation coefficients of castor oil contained in a test cylinder and comparing the values obtained with values in the literature.[8] Using the T_{total} described, castor oil attenuation coefficients have been consistently in agreement within 5% with tabulated values over the past 10 years. (The castor oil check is always done immediately [minutes] before measurements of attenuation coefficients at a given frequency.)

Backscatter Coefficients

The measurement of backscatter coefficients was done using the method of Chen and associates,[10] in which time-gated echoes resulting from broadband source pulses were analyzed by comparison with the echo from a plane reflector. Echo data were acquired from the sample in a tank of degassed and distilled water. An externally triggered function generator (FG 5010 Programmable 20 MHz, Tektronix, Beaverton, OR) created one-cycle sinusoidal pulses with carrier frequency near the nominal frequency of the transducer to be driven. These pulses were then amplified with a broadband RF power amplifier (Model 240L, EIN, Rochester, NY) and used to drive one of two broadband transducers (KB-Aerotech, Lewistown, PA). One transducer had a nominal frequency of 3.5 MHz, an active element radius of curvature of 9.7 cm, and a 6 dB bandwidth from 2.5 to 5.0 MHz; the other had a nominal frequency of 5.0 MHz, a radius of curvature of 8.5 cm, and a 6 dB bandwidth from 3.0 to 7.0 MHz. Echo signals received from the sample were amplified with a Panametrics 5052UA pulser/receiver (Waltham, MA). For each echo signal, a 10 µs interval was digitized at 100 megasamples per second with 8 bit resolution using a digital oscilloscope (LeCroy 9310A, Switzerland) and stored in a personal computer for off-line analysis. Signals were recorded for 100 statistically independent locations, realized by translating the sample perpendicularly to the beam axis. Amplitudes of the voltage pulses driving the transducers were kept low enough so that nonlinear propagation effects were negligible. Beam profiles over the ranges of frequencies involved were accounted for in the data reduction, as were the transmission coefficients for the Saran Wrap layer and the attenuation coefficients of the TM material.

MEASUREMENT PROCEDURES AT OTHER LABORATORIES

Nine pairs of samples were sent to laboratories at institutions other than the University of Wisconsin-Madison. A tenth pair was used in making measurements at the University of Wisconsin using techniques (called the University of Wisconsin Scanner Reference method) other than the UWLMP. The various measurement procedures are described briefly in this section. Further details are available in the literature cited.

University of Kansas

The thickness of each sample was measured using standard machinist's calipers on the cylindrical acrylic wall. The sound speed and attenuation were measured using standard narrowband pulse, through-transmission substitution techniques[7] in deionized degassed water at 22°C. Two methods were used for measuring the acoustic backscatter coefficient. Both are broadband substitution methods in which the signal from an unknown medium is compared to a reference signal. In Method I,[11] the reference signal is that from a planar reflector. Assumptions in the data analysis restrict the application of this method to the focal zone of the transducer. This method is convenient for use with single element transducers, or when both the magnitude and phase of the power spectrum are needed. A 2.25 MHz and a 10 MHz transducer, each with more than 100% bandwidth, were used. At least 100 independent A-lines were recorded from each sample using 10 µs time gates.

Method II[12] is a modified version of the Reference Phantom Technique.[13] In this method the reference echo signal is that from an agar phantom, containing powdered graphite and glass bead scatterers, with well characterized acoustic properties. Backscatter coefficients for the reference phantom were measured using Method I. This method is convenient when using imaging systems that employ array transducers, since it allows comparison of signals over a large region of interest. A Siemens Medical Systems Q2000 (San Ramon, CA) with three array transducers (3, 5, and 7.5 MHz) was used to acquire over 100 uncorrelated A-lines with a 10 µs time gate.

CDRH/Georgetown University

An ATL (Advanced Technology Laboratories, Bothell, WA) Ultramark VIII ultrasonic scanner, with a 3.5 MHz annular array transducer, was used. RF data were acquired and digitized (11 bit dynamic range) at 12.0 MHz. Measurements were performed with the test phantom placed in a water tank in the transmit focal zone (approximately 7 cm). Three regions of interest (approximately 25 A-lines by 3.5 cm) were obtained, rotating the phantom between acquisitions to interrogate different planes. A second set of measurements was performed on a reference phantom with known frequency dependent attenuation and backscattering characteristics. The test and reference phantom RF data were software-gated to identify regions of interest corresponding to the phantom interiors, excluding the specular reflections at the front surfaces. The same gate position and gain settings were used for both test phantom and reference phantom measurements.

Attenuation coefficients were measured using a substitution logarithmic spectral difference technique. A “near gate” and a “far gate” were applied to the gated RF for both the test and reference phantom data to isolate proximal and distal regions within the phantoms. The logarithmic spectral difference between the ratio of the near test phantom power spectrum to the near reference phantom power spectrum and the ratio of the far test phantom power spectrum to the far reference phantom power spectrum is proportional to the difference of the two attenuation coefficients as a function of frequency.

Backscatter coefficients were measured using a phantom reference method.[14,15] This method has previously been shown to exhibit good agreement between measurements and theoretical predictions, based on Faran’s theory of scattering,[16] for phantoms consisting of spheres embedded in agar.[17]

University of Illinois

All measurements were performed in distilled degassed water at 21 ± 1°C. The attenuation coefficient and propagation speed values were estimated in through-transmission using the insertion loss and the arrival time difference (via a correlation method) techniques, respectively. The backscatter coefficient values were estimated according to the method of Insana and Hall,[11,18] in which the power spectra of reflected RF waveforms (10 μs time gate) were compared to the spectrum of a plane reflector at the same axial position, after compensating for attenuation loss through the medium; a correction for the diffraction of the transducer beam has also been included. All measurements were compensated for the transmission coefficient through the two surfaces of the samples. The transmission coefficient was determined using measurements of the reflection coefficient of the cylindrical sample; the reflection coefficient was taken to be equal to the echo amplitude from that window divided by the echo amplitude from a water-to-air interface.

Two spherically focused transducers were used for this study: one with a 3.7 MHz center frequency (Panametrics V3680, 2.0 cm diameter, 10 cm radius of curvature), the other with a 5.5 MHz center frequency (Panametrics V309, 1.27 cm diameter, 5.08 cm radius of curvature). Both these transducers functioned as the source transducer for the attenuation coefficient and propagation speed estimates and also for the pulse-echo backscatter coefficient estimates. The receiving transducer for the attenuation coefficient and propagation speed estimates was a 1 mm spot size polyvinylidene difluoride hydrophone (Sonic Technologies Model 804-010, Hatboro, PA).

CIRS

Both speed of sound and attenuation measurements were made with the same experimental setup. An unfocused, 5.0 MHz, 13 mm diameter, broadband transducer was driven in pulse-echo mode by a Panametrics 5800 pulser/receiver. Signals were received by a Tektronix TDS 320 oscilloscope. The transducer was mounted in a water filled tank at 20.3°C and positioned 12.75 cm from a stainless steel plate.

A substitution technique[19] was used to compute the speed of sound in the two samples provided. In this method, reception times of signals reflected from a stainless steel plate with and without the sample interposed were measured and the time shift used to compute the speed of sound in the material. Each reception time corresponded to the 50% value of the pulse intensity integral.

A substitution technique[20] was also used to measure the attenuation within each sample. The peak-to-peak amplitude of the reflected signal with the sample in the path and with a water filled sample holder (with Saran Wrap membranes) in the path was measured. The water filled sample holder was used to compensate for the effects of the Saran Wrap membrane.

Indiana University

Measurements were made with two 8 mm diameter transducers attached rigidly on a calipers such that their faces were parallel. The transducer's operating frequency was from 2 to 4 MHz. The transmitter transducer was driven by a burst of RF signal from a Tektronix function generator. The burst gate length and RF amplitude were sufficient to make proper peak-to-peak voltage measurements on the received signals by the receiving transducer. The receiver transducer was connected directly to a wideband (200 MHz) Tektronix oscilloscope. The phantom thickness was measured directly on the calipers with a resolution of 0.1 mm. The data were recorded with and without the phantom in the degassed water at room temperature. The attenuation coefficient and the speed of sound were calculated from these results. Multiple sites (at least three) on the same phantom were used to collect the data. To make frequency dependent measurements, the driving RF signal frequency was varied within the operating frequency range of the transducers.

University of Wisconsin Scanner Reference Method

A reference phantom method was applied to measure backscatter and attenuation coefficients using a clinical scanner.[13] A Siemens Sonoline SL-1 sector scanner equipped with 5 and 7.5 MHz mechanical transducers and modified to provide RF echo signals was used to acquire echo data from the two test sample cylinders and from a calibrated reference phantom. The ultrasonic properties of the material in the reference phantom had been measured 2 years earlier using the UWLMP on test cylinders made with TM material from the same batch as that used to make the phantom. Echo signals were digitized at 64 megasamples per second with 8 bit precision. After acquisition, off-line analysis was performed. A 4 μs Blackman-Harris window was modulated by cos ($\omega_o t$) and sin ($\omega_o t$), where ω_o is the analysis frequency and t is the echo arrival time. Signals from the test cylinders were convolved by each set of quadrature bandpass coefficients, the bandwidth of which was determined by the window duration.[21] The filtered echo signals in each quadrature channel were then squared and the two waveforms added, producing a single time dependent waveform. Averaging over all the independent waveforms resulted in an averaged and filtered signal intensity versus depth for each test cylinder at the analysis frequency. The analysis for the 5 MHz transducer was performed at 10 frequencies, from 3.75 MHz through 5.75 MHz in 0.25 MHz steps, and at seven frequencies for the 7.5 MHz transducer, from 6 MHz through 7.5 MHz in 0.25 MHz steps. The same analysis was applied to the signals from the reference phantom.

Depth dependent ratios of filtered echo signal intensities from the test cylinders to intensities from the reference phantom then were obtained. The logarithm of the intensity ratio plotted versus depth forms a straight line. The slope of this line is proportional to the difference between the attenuation coefficient of the test cylinder and that of the reference phantom. Because the latter is known, the attenuation in the test cylinder can be deduced. The ratio can then be compensated for attenuation losses versus depth. The average of this compensated ratio versus depth can be multiplied by the backscatter coefficient of the reference phantom to yield the backscatter coefficient for the test cylinder.

Pennsylvania State University

The acoustic speed, attenuation coefficient, and backscatter coefficient of two phantoms were measured in a water tank filled with distilled water at 22°C. The acoustic speed and attenuation coefficient were measured by a narrowband through-transmission technique.[1] Unfocused transducers of center frequencies 2.25, 3.5, 5, and 7 MHz were used to produce 4 μs long tone bursts ranging from 2 to 7 MHz. The transmitted acoustic wave was received by a 0.5 mm diameter hydrophone, 6 cm away from the unfocused transducers. The acoustic speed and attenuation of phantoms were obtained by comparing the received signals with and without the phantom between the pair of transducers. The acoustic loss by the plastic transmission windows on the phantoms was compensated for by using the supplied data from the study coordinator (E.L.M.). The 3.5, 5, and 7 MHz unfocused transducers were also used for the backscatter coefficient measurements, in which the standard substitution method[22,23] was used. The –3 dB acoustic pressure and axial profiles of the transducers were measured; 9 μs long time-gated backscattered signal segments, which began 9 μs after the echo from the plastic window, were acquired. The reflected signal from a stainless steel reflector that was located at the identical time-gated region was also acquired. Backscatter coefficients of the phantoms were then calculated using these signals and the previously measured acoustic speed and attenuation. Measurements were made at 20 different locations of the phantoms.

Washington University

All phantom measurements were obtained in temperature controlled water tanks at 22.5 ± 0.5°C. The reported results represent the average of the values from two separate measurement systems over partially overlapping bandwidths. Data over the range of 2 to 6 MHz were obtained with a pair of 1.3 cm diameter, 10 cm focal length transducers. A pair of transducers with 1 cm diameter and 8.3 cm focal length was used to acquire data over the range of 4 to 8 MHz. Compensation for the effects of nonunity transmission coefficients arising from the Saran Wrap windows were applied where appropriate, based on the table of values supplied with the test samples by the University of Wisconsin. Propagation speed measurements were made using a narrowband, tone-burst, through-transmission technique.[24,25] Attenuation measurements were performed using a broadband, through-transmission technique referenced to a water-path-only measurement.[26] A linear fit was performed to the attenuation data as a function of frequency over the useful bandwidth. The attenuation coefficient at specific frequencies was determined from this fit. The uncertainty in attenuation coefficient values was estimated to be 0.1 dB/cm at all frequencies.

Backscatter coefficient measurements were performed using a broadband, pulse-echo technique referenced to the specular echo from a stainless steel plate.[19,27] A linear fit was performed to the backscatter coefficient versus frequency logarithmic-logarithmic plot over the useful bandwidth of the data.

University of Michigan

The backscatter properties of the given phantom materials were acquired using a pulse-echo setup in a water tank at 25.5°C. A focused 5 MHz transducer was used (Panametrics, Waltham, MA) (12.7 mm diameter, 88.9 mm focal length, 5 mm focal radius). The sample front wall was positioned 8 cm from the transducer. The sample thickness was 50 mm. A planar brass plate (170 mm from the transducer, 101.6 mm diameter, and 25.4 mm thick) was used as a reference reflector. The sample data for sound speed, attenuation, and backscatter were acquired on a 3 by 3 matrix across the surface of the sample, where the RF lines were spaced 10 mm apart in the vertical and horizontal directions. A Panametrics pulser model PR5900 served as a signal source. The pulser settings were as follows: 8 μJ pulse energy, 1 kHz high pass filter, 100 MHz low pass filter, X dB attenuator, 54 dB gain, where X is 10 dB for recording the attenuated reference reflector (sample in the path), 30 dB for the unattenuated reference reflector (no sample in the path), and 0 dB to record the range gates within the sample. The speed of sound was calculated by recording the time of flight to the sample's front and back wall, as well as to the reference reflector surface with and without the sample in place. The attenuation in the form of a logarithmic spectral difference was computed by a substitution method measuring the power spectrum of the echo from the brass plate with and without the sample in place with corrections for the Saran Wrap window material. The data for the computation of the backscatter were acquired as range gated RF lines within the sample. Five consecutive range gates were used, each 5 μs long, starting at 2.5 μs from the front wall of the sample. The power spectrum of the range gates from the same depth within the sample were averaged. The backscatter was calculated using the method of Chen and associates.[10]

Riverside Research Institute

RF echo signals were sampled at 25 MHz. The Panametrics single element transducer had a center frequency of 5.5 MHz, an aperture of 10 mm, and a focal length of 35 mm. At this site 128 lines of RF data were acquired, with spacing of approximately 0.8 mm. The phantom temperature was 22°C.

For estimating propagation speed, the number of samples between the top surface of the phantom and the top of its acrylic wall was determined to estimate the thickness of the TM material. The same procedure was used to estimate the distance between the glass plate and the bottom of the phantom. The difference between these two distances allowed computation of the phantom thickness. The propagation speed was then estimated using time of flight and thickness.

For estimating attenuation, two methods were used. First, linear regression analysis was applied to the calibrated backscattered power spectrum of RF data to derive the rate of change of spectral slope for a series of regions of interest spanning the phantom. The attenuation coefficient slope in dB/(MHz-cm) was computed as half the average spatial rate of change in slope. Second, several frequency bands were specified within the transducer bandwidth, a parameter image showing the amplitude of the regression line at the center of each band was generated (i.e., the midband value), the average midband value was plotted as a function of range for each band, and the attenuation coefficient was computed from the spatial rate of change of average midband value for each band.

For estimating the backscatter coefficient, the equation $\mu(f) = S(f)/(\Omega D)$ $(\text{sr-cm})^{-1}$ was derived, where S(f) is the calibrated power spectrum amplitude at frequency f, Ω is the solid angle subtended by the transducer, and D is the depth of the insonated volume; $\Omega D = 0.006$ was calculated from the transducer geometry and the properties of the Hamming analysis window. $\mu(f)$ was computed from the attenuation corrected amplitude of the calibrated spectrum at 5.5 MHz.

RESULTS

UWLMP

Since the UWLMP was used on all samples before and after measurements were made by other means, these are presented first to address the degree of stability of the ultrasonic properties over the 12 month period of the study. Results are presented in terms of means and sample SDs for each of the two sets of 10 samples. Table 3 shows values for the propagation speeds. The measured means for Type A and Type B decreased about 1 m/s during the 12 month period. A possible explanation is that the specified accuracy of the laboratory thermometers used is only ±0.5°C, and the temperature coefficient for the TM materials is 1.7 m/s/°C.[5]

Table 4 shows means and sample SDs of attenuation coefficients at four discrete frequencies for Types A and B as measured with the UWLMP at 22°C before and after dispersal of the samples. Each value in the table (e.g., 1.06 on the upper left) equals the mean of 10 values, one for each of 10 samples, while the number in parentheses to the right of each value in the table is the (sample) SD of the 10 values giving rise to the mean. Differences in before and after means were typically less than 1%.

Table 5 shows means and sample SDs for backscatter coefficients at four discrete frequencies. The percentage changes in mean values over the 12 month period are greater than in the case of attenuation coefficients, the means tending to rise with time. The greatest increase was about 18% for the 5.0 MHz values of the Type B samples. Note that the temperature dependence of backscatter coefficients is small.*

For easier grasp of the data, graphic renditions of the results given in Tables 3 to 5 are given in Figures 1 to 3. Figure 1 shows the ranges of propagation speeds for Type A and Type B before and after distribution, and Figure 2 shows attenuation coefficient values and ranges corresponding to Table 4. Figure 3 shows the Table 5 results in graphic form, with ranges of backscatter coefficients both before and after distribution to other sites.

Methods Other Than the UWLMP

Propagation Speeds

All measured propagation speeds are shown in Figure 4. The range of speeds for all 10 Type A and all 10 Type B samples determined with the UWLMP are repeated in the first two columns of the figure for comparison purposes. Note that two sites (Riverside Research Institute and the University of Michigan) found the speed for Type A to be higher than for Type B. Also note that the values from CIRS were measured at 20°C instead of 22°C; the lower values from CIRS are influenced by the lower temperature involved, since the propagation speed in the samples decreases at 1.7 m/s/°C drop.[5]

Attenuation Coefficients

Attenuation coefficients are shown in Figure 5. Type A results are given in Figure 5A and B and Type B results in Figure 5C and D. Ranges of values for all 10 Type A samples, measured with the UWLMP and corresponding to Figure 2A and the tabulation in Table 4, are reproduced in these figures. Note that two laboratories reported values at a single frequency: CDRH/Georgetown at 3.5 MHz and Riverside Research Institute at 5.5 MHz. Values from all labo-

Table 3: Mean Propagation Speeds and Sample SDs for 10 Type A and 10 Type B Samples at 22°C Measured Using the UWLMP Before and After Distribution of the Samples to Other Laboratories (One Measurement per Sample)

Material	Mean Propagation Speed (m/s) at 22°C	Sample SD (m/s)
Type A before sending to other laboratories	1535.9	0.9
Type A after return from other laboratories	1534.4	0.9
Type B before sending to other laboratories	1540.4	0.7
Type B after return from other laboratories	1539.6	0.8

*Measurements of backscatter coefficients using the UWLMP between 4.0 and 6.0 MHz on a Type B sample at 21.1°C and then at 22.2°C resulted in a mean change of +1.5% (± 5.6%), where the quantity in parentheses is the SD.

Table 4: Mean Attenuation Coefficients and Sample SDs for 10 Type A and 10 Type B Samples Measured with UWLMP

	Mean Attenuation Coefficients (dB/cm) and Sample SDs (in Parentheses)			
Material	2.50 MHz	4.50 MHz	6.20 MHz	8.00 MHz
Type A before	1.06 (± 0.00)	2.01 (± 0.02)	2.89 (± 0.02)	3.92 (± 0.03)
Type A after	1.06 (± 0.01)	2.01 (± 0.02)	2.90 (± 0.04)	3.93 (± 0.05)
Type B before	1.46 (± 0.01)	2.68 (± 0.02)	3.85 (± 0.03)	5.26 (± 0.06)
Type B after	1.43 (± 0.02)	2.67 (± 0.03)	3.89 (± 0.05)	5.31 (± 0.08)

Table 5: Mean and Sample SDs at 22°C for Backscatter Coefficients Measured with the UWLMP (10 Type A and 10 Type B Samples)

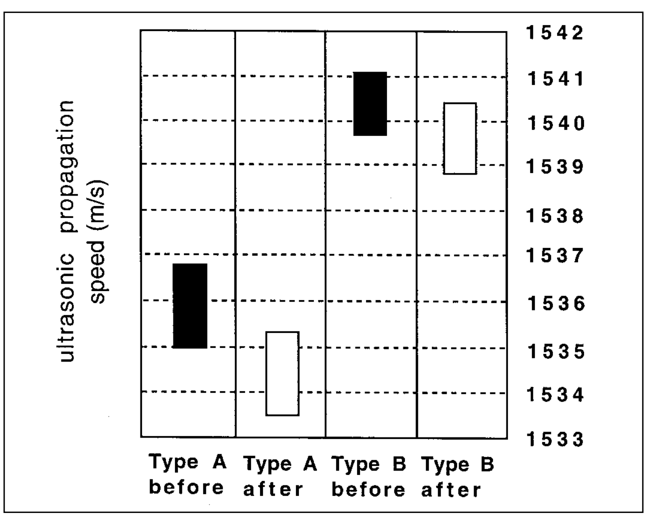
	Mean Backscatter Coefficients × 10^3 ($sr^{-1}cm^{-1}$) and Sample SDs × 10^3 (in Parentheses)			
Material	2.50 MHz	3.50 MHz	5.00 MHz	6.50 MHz
Type A before	0.22 (± 0.04)	0.77 (± 0.08)	2.6 (± 0.2)	5.9 (± 0.3)
Type A after	0.22 (± 0.01)	0.80 (± 0.09)	2.9 (± 0.3)	6.5 (± 0.5)
Type B before	0.31 (± 0.01)	1.21 (± 0.05)	4.5 (± 0.2)	11.1 (± 0.5)
Type B after	0.34 (± 0.02)	1.30 (± 0.06)	5.3 (± 0.2)	12.7 (± 0.6)

ratories appear to agree reasonably well with one another, except the values at 7.32 MHz from CIRS (solid triangles in Fig. 5D).

Backscatter Coefficients

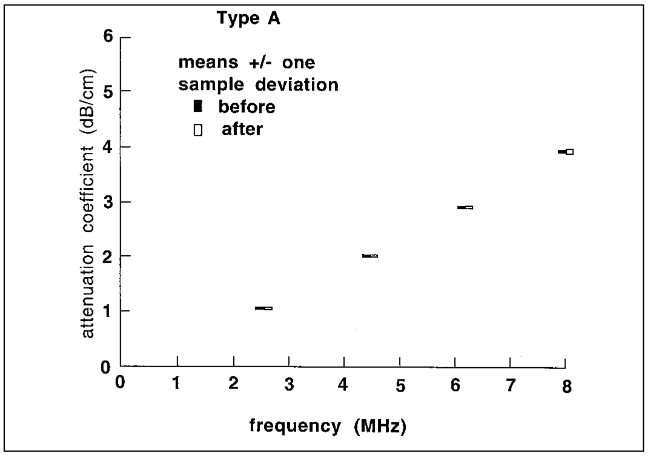
Backscatter coefficients are shown in Figures 6 to 15. As anticipated, the level of agreement of results between laboratories is not nearly as good as in the case of attenuation coefficients. Note that values were not reported by CIRS or by Indiana University. Corresponding to the results for each of the eight sites reporting, Figures 6 to 13 show, successively, results for each site, along with the before and after values determined with the UWLMP for the particular Type A and Type B samples sent to the site; particular values are given because of the possible significant spread in backscatter coefficient values among each

Figure 1 Ultrasonic propagation speeds measured at 22°C with the UWLMP for all 10 Type A samples and all 10 Type B samples before distribution to and after return by other sites. The vertical center of each bar is the mean for the 10 samples, and the vertical length of each bar is 2 SDs for the 10 samples.

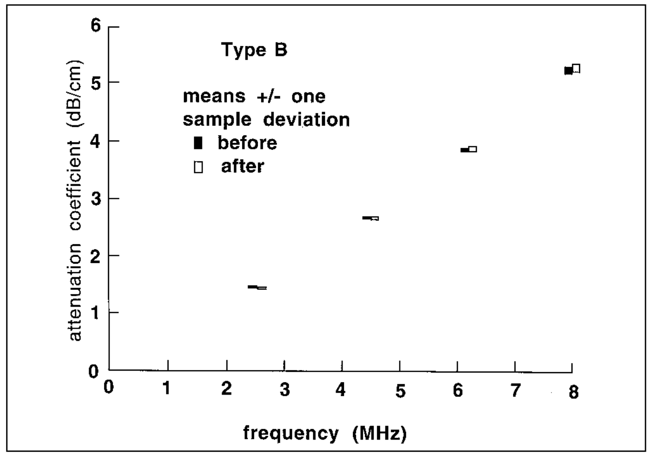


set of 10 samples (see Table 5 and Figure 3). Excellent agreement with the UWLMP exists for three cases: the University of Kansas substitution method, the University of Wisconsin Scanner Reference method, and the Washington University method. In fact, measurements of all three parameters (speed, attenuation, and backscatter) from Washington University (and the University of Kansas, excluding the reference phantom method for backscatter measurement) are in excellent agreement with those found using the UWLMP, even in backscatter over the broad range of frequency from 2.5 through 7 MHz. Those values that differ from determinations using the UWLMP tend to be lower by as much as 10 dB. The backscatter results from Pennsylvania State University showed a considerably greater increase of backscatter coefficient with frequency than others, while results from the Universities of Illinois and Michigan showed a lower rate of increase with frequency.

Figures 14 and 15 may be the most illuminating regarding comparison of backscatter results. The ranges of values for all sites and methods are demonstrated. Rather good agreement over at least a 4 MHz frequency range is demonstrated for a “cluster of four” site or method cases (namely, UWLMP, Washington University, University of Wisconsin Scanner Reference method, and the University of Kansas substitution method). The frequency dependence of the University of Kansas reference phantom method agrees well with the cluster of four, but all values are about 5 dB lower than those of the cluster. A fifth site, CDRH/Georgetown, also agrees rather well with the cluster, but measurements were made at only one frequency. The Pennsylvania State values show a noticeably elevated rate of increase with frequency relative to the case for all other sites, and values are generally much lower than the cluster of four values. The University of Illinois and University of Michigan values show a lesser rate of increase with frequency than the cluster of four and are generally lower by about an order of



A

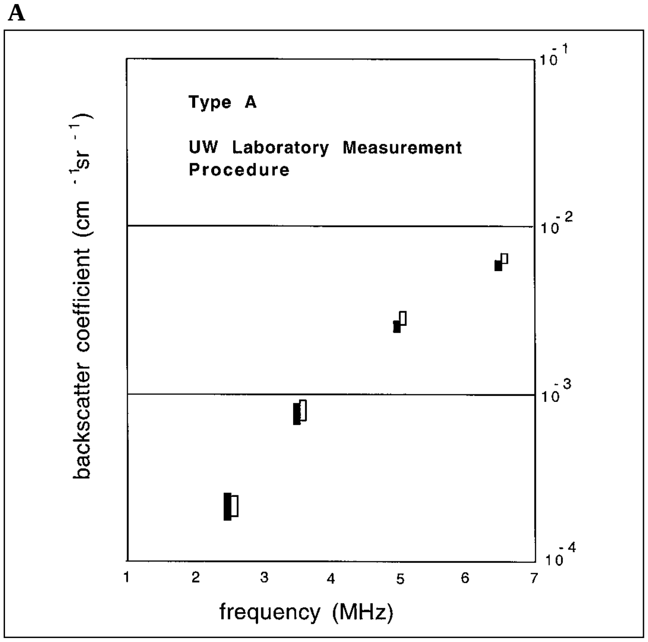


B

Figure 2 A, UWLMP means ± 1 SD at four different frequencies for attenuation coefficients for all 10 Type A samples before distribution to (solid rectangles) and after return by (open rectangles) other sites. The vertical center of each bar is the mean for the 10 samples, and the vertical length of each bar is 2 SDS for the 10 samples. For a given frequency, the before rectangle is on the left and the after rectangle is immediately to the right. **B**, UWLMP means ± 1 SD at four different frequencies for attenuation coefficients for all 10 Type B samples before distribution to (solid rectangles) and after return by (open rectangles) other sites. The vertical center of each bar is the mean for the 10 samples, and the vertical length of each bar is 2 SDs for the 10 samples. For a given frequency, the before rectangle is on the left and the after rectangle is immediately to the right.

Figure 3 A, UWLMP means ± 1 SD at four different frequencies for backscatter coefficients for all 10 Type A samples before distribution to (solid rectangles) and after return by (open rectangles) other sites. The vertical center of each bar is the mean for the 10 samples, and the vertical length of each bar is 2 SDs for the 10 samples. For a given frequency, the before rectangle is on the left and the after rectangle is immediately to the right. **B**, UWLMP means ± 1 SD at four different frequencies for backscatter coefficients for all 10 Type B samples before distribution to (solid rectangles) and after return by (open rectangles) other sites. The vertical center of each bar is the mean for the 10 samples, and the vertical length of each bar is 2 SDs for the 10 samples. For a given frequency, the before rectangle is on the left and the after rectangle is immediately to the right.

A



B

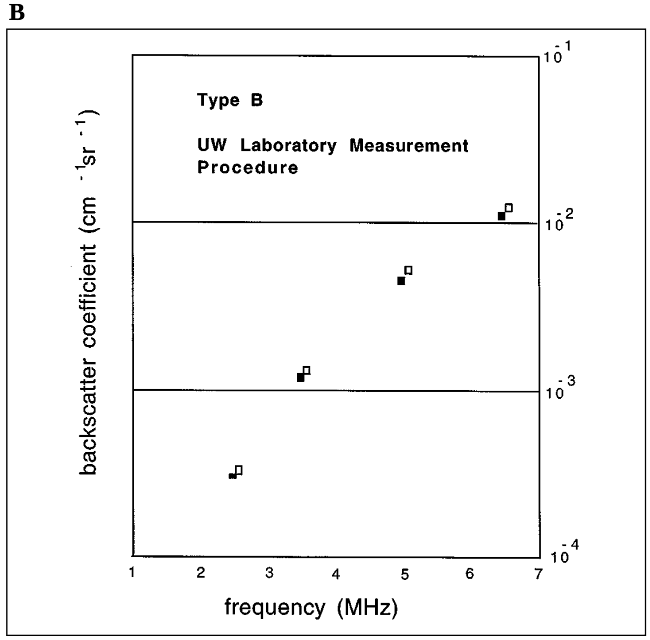


Figure 4 (right) Comparison of ultrasonic propagation speeds (measured at 22°C except as noted) with the UWLMP (Type A, solid rectangle; Type B, open rectangle) and at 10 other sites (solid dot, Type A; open dot, Type B). The horizontal extent of the rectangles corresponds to 2 SDs for the 10 samples involved, and the central value is the mean.

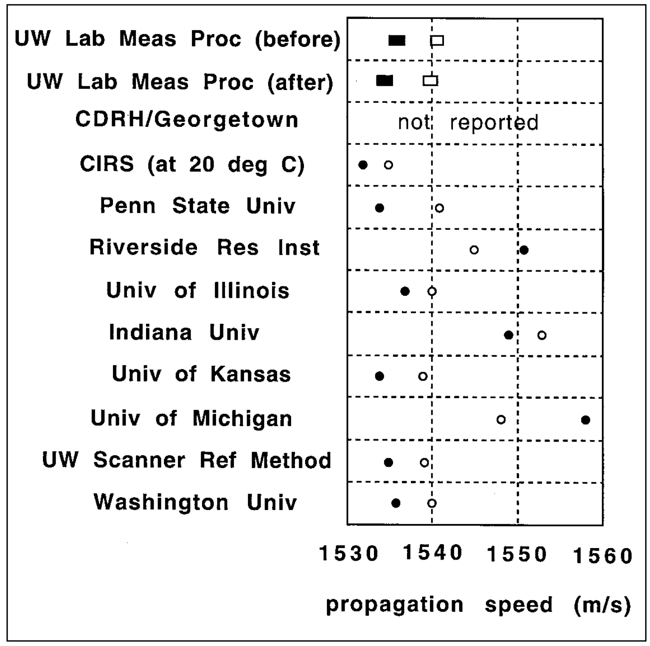
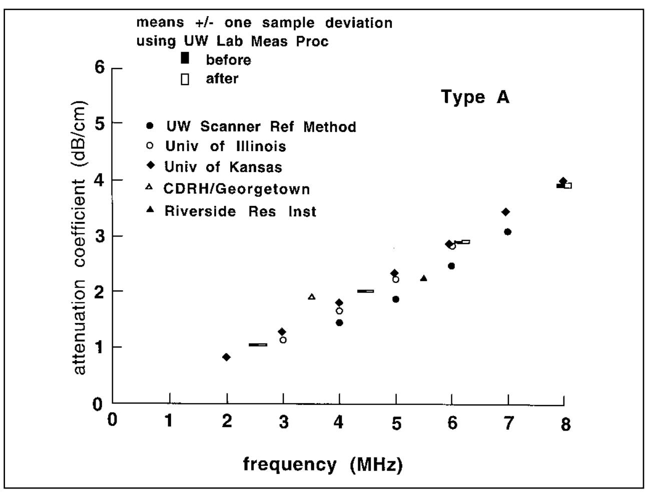
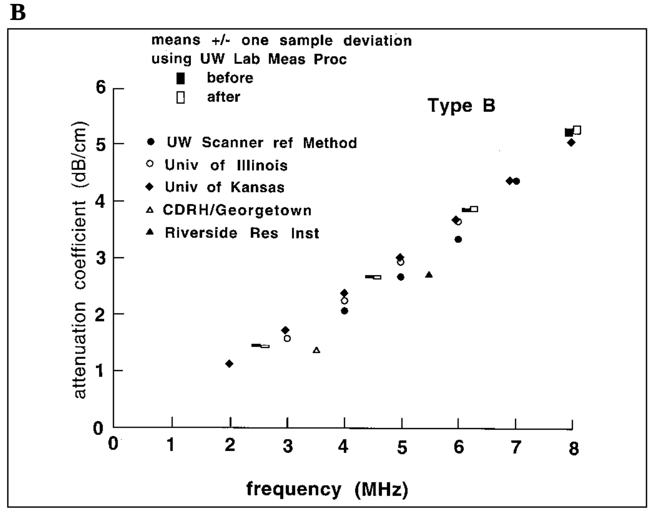


Figure 5 (below) **A**, Comparison of ultrasonic attenuation coefficients for the Type A material measured at 22°C using the UWLMP (reproduced from Fig. 2A) and measured at five of 10 other sites (see key on figure). **B**, Comparison of ultrasonic attenuation coefficients for the Type B material measured at 22°C using the UWLMP (reproduced from Fig. 2B) and measured at five of 10 other sites (see key on figure). **C**, Comparison of ultrasonic attenuation coefficients for the Type A material measured at 22°C using the UWLMP (reproduced from Fig. 2A) and measured at the remaining five of 10 other sites (see key on figure). **D**, Comparison of ultrasonic attenuation coefficients for the Type B material measured at 22°C using the UWLMP (reproduced from Fig. 2B) and measured at the remaining five of 10 other sites (see key on figure).

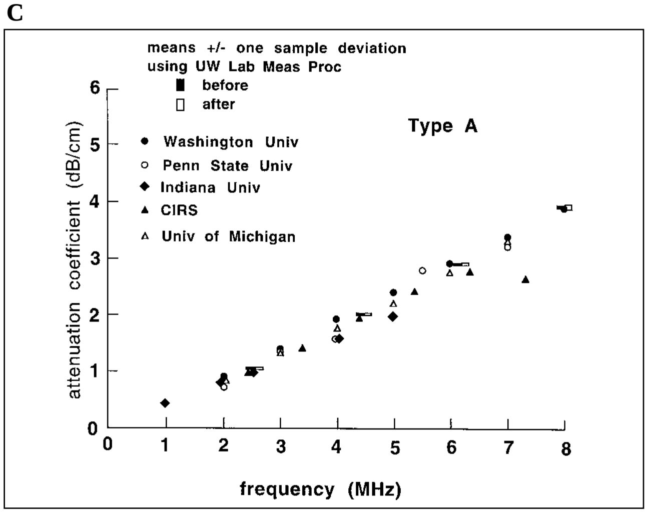
A



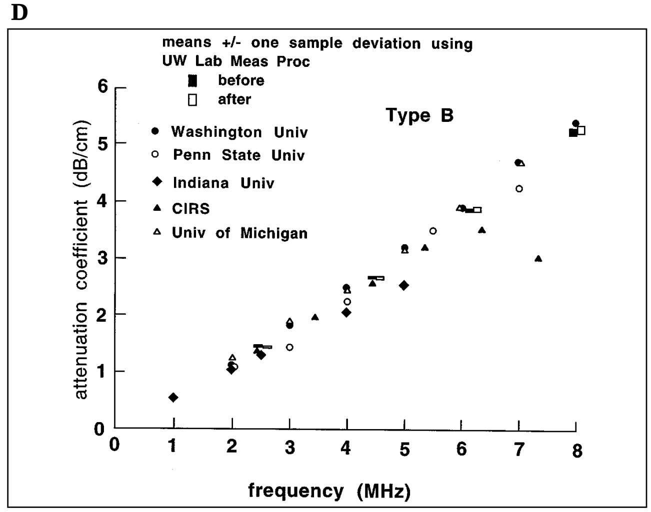
B



C



D



magnitude. The Riverside Research Institute values at 5.5 MHz are about 3 dB below those for the cluster of four for both Types A and B.

DISCUSSION AND SUMMARY

Two sets of 10 samples of TM material were made at the University of Wisconsin, each set made from the same batch of material. The propagation speed, attenuation coefficients, and backscatter coefficients for all samples were measured at 22°C using long standing measurement techniques at the University of Wisconsin (the UWLMP). Then one of each set was sent to each participating laboratory for measurements of propagation speed, attenuation coefficients, and backscatter coefficients at 22°C. With return of the samples to the University of Wisconsin, parameters were remeasured for all 20 samples to assess any change of properties over the period of the study. The greatest change was in backscatter coefficients, for which the mean increased as much as 18%. (See 5.0 MHz values for Type B in Table 5.) An unexpectedly large range of propagation speeds was reported from the various sites for each of the two types of material, the spread being from 1532 through 1558 m / s for Type A and from 1534 through 1553 m / s for Type B. Agreement between sites in attenuation coefficient values was very good.

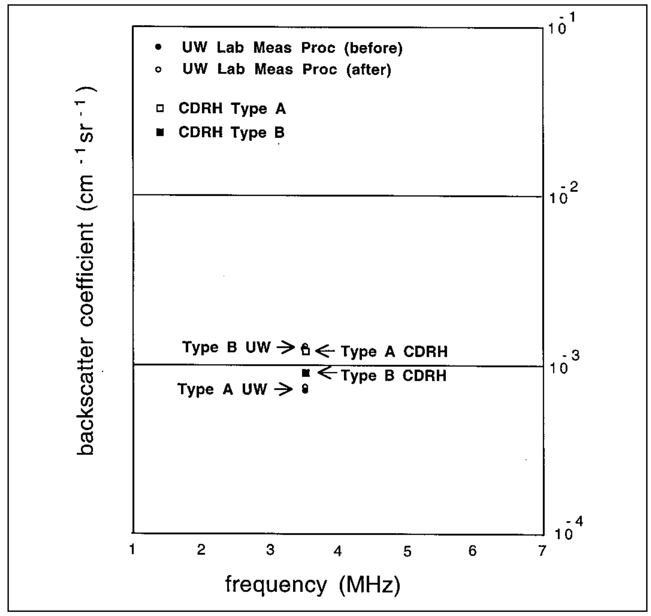
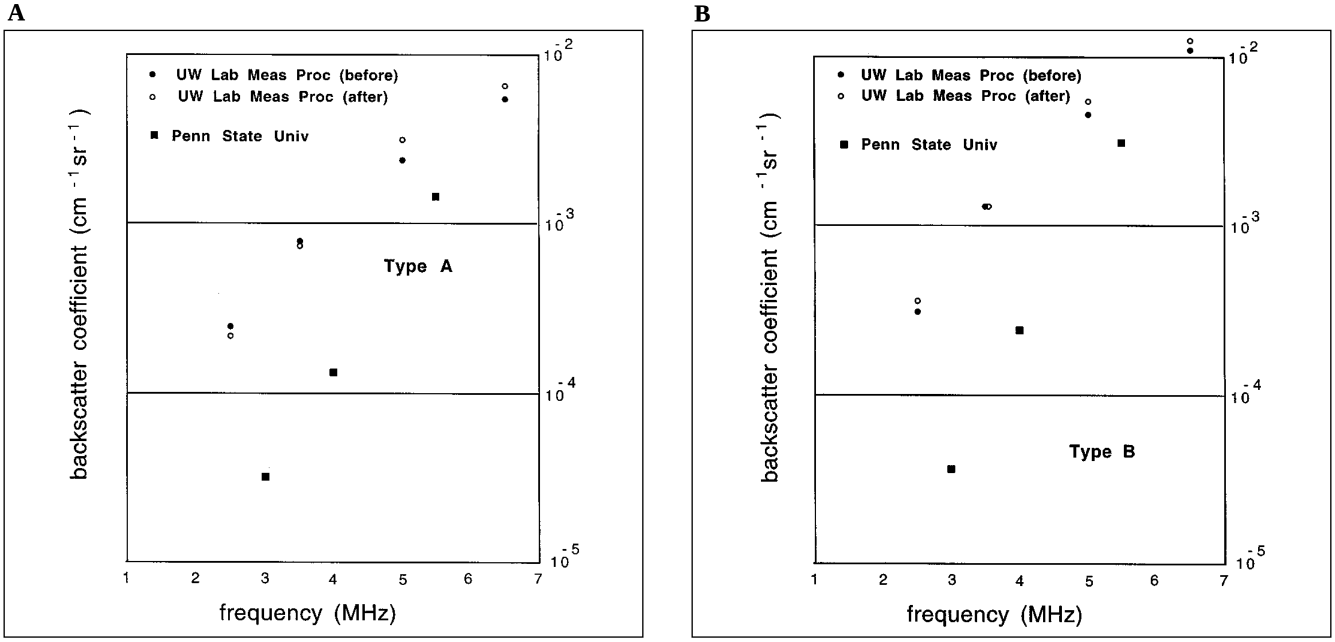


Figure 6 Measured values of the backscatter coefficients for the specific Type A and Type B samples sent to CDRH (Type A, open square; Type B, solid square) and values measured with UWLMP for the same specific samples (before sending, solid dot; after return, open dot). Values were obtained only at 3.5 MHz by CDRH.

Figure 7 A, Measured values of backscatter coefficients for the specific Type A sample sent to Pennsylvania State University (solid square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot). **B**, Measured values of backscatter coefficients for the specific Type B sample sent to Pennsylvania State University (solid square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot).

A **B**



As expected, considerable disagreement occurred in backscatter coefficient values for the eight reporting sites. Four site or measurement procedures produced very good agreement, however: the UWLMP, Washington University's method, the University of Wisconsin Scanner Reference method, and the substitution method used at the University of Kansas. A fifth site (CDRH/Georgetown) also agreed rather well with the above four, but measurements were made at only one frequency. Results from other sites were lower than the above five, often by more than an order of magnitude.

Note that attenuation and backscatter measurements using the CDRH/Georgetown method and the University of Wisconsin alternative method relied on analysis of pulse-echo data using clinical sector scanners (CDRH, phased array; and University of Wisconsin, mechanical) and reference phantoms with known attenuation and backscatter properties. Contrary to the more commonly used through-transmission methods, the CDRH/Georgetown method, the reference phantom method of the University of Kansas, and the University of Wisconsin Scanner Reference method have the distinction that they are well suited for in vivo determinations.

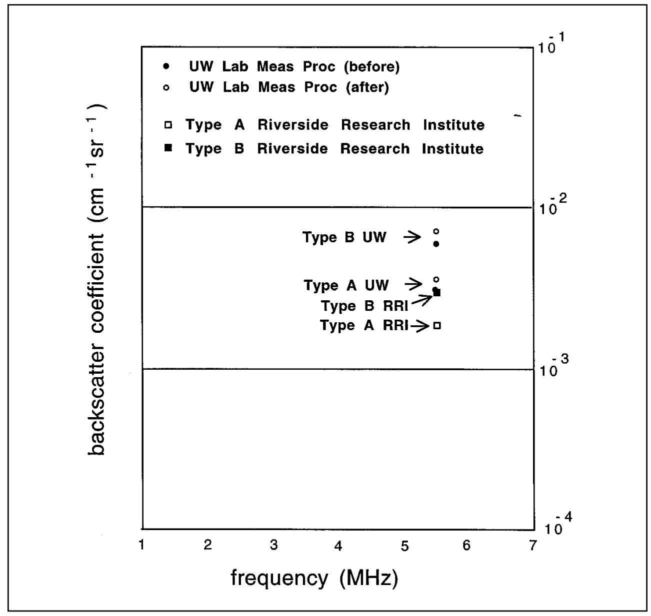
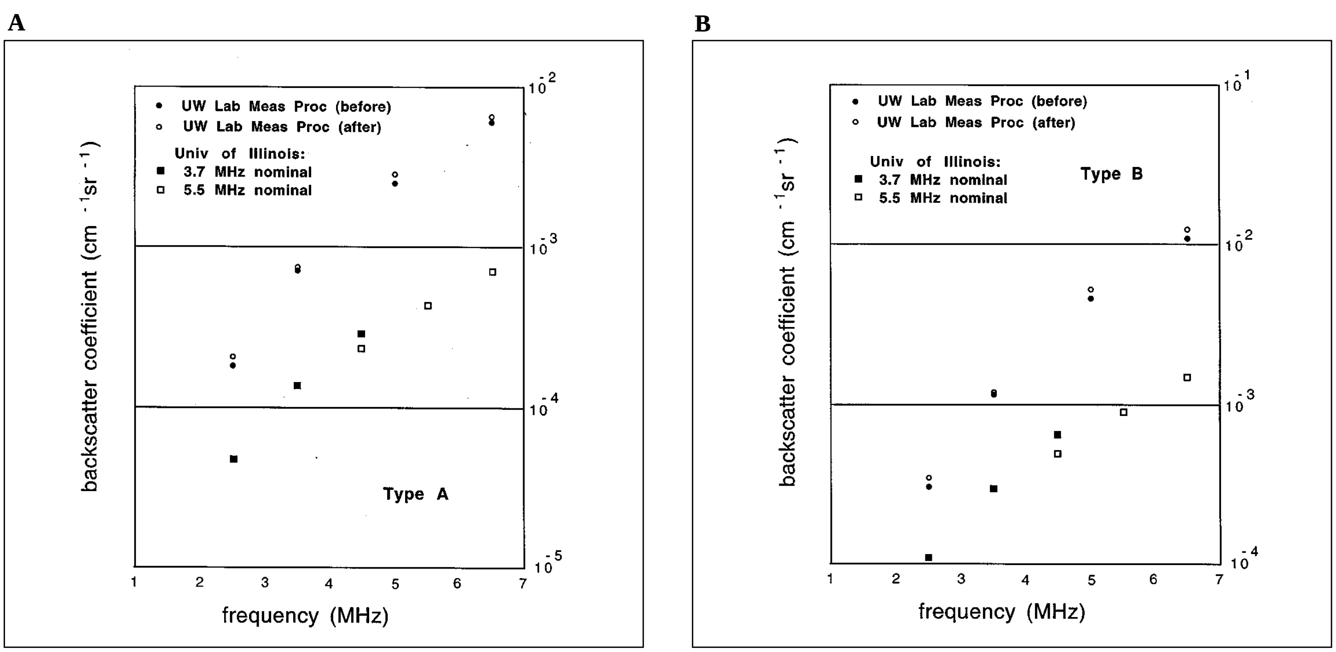
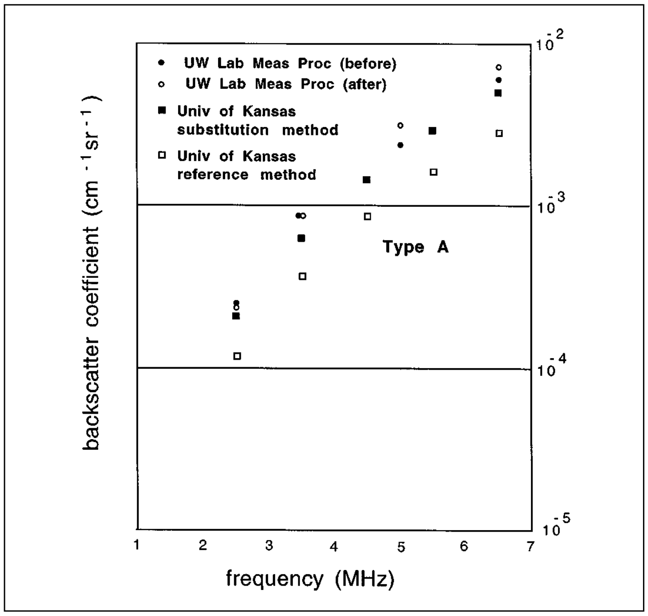
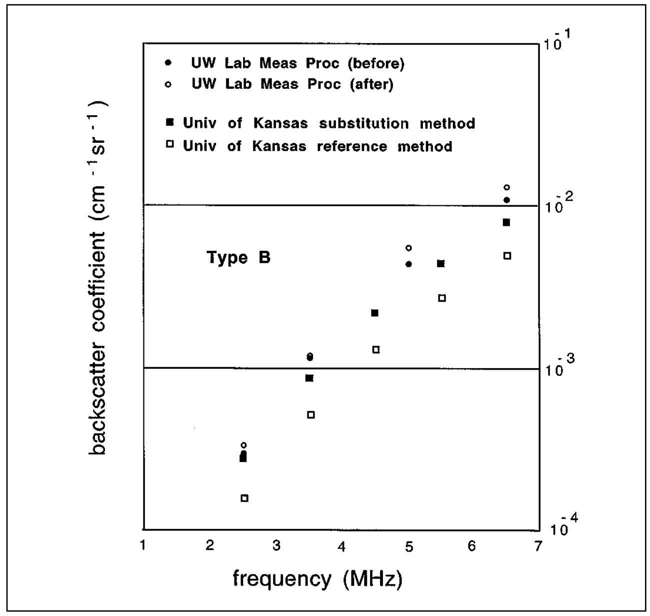


Figure 8 Measured values of the backscatter coefficients for the specific Type A and Type B samples sent to Riverside Research Institute (Type A, open square; Type B, solid square) and values measured with UWLMP for the same specific samples (before sending, solid dot; after return, open dot). Values were obtained only at 5.5 MHz by Riverside Research Institute.

Figure 9 A, Measured values of backscatter coefficients for the specific Type A sample sent to the University of Illinois using a nominal 3.7 MHz transducer (solid square) and a nominal 5.5 MHz transducer (open square). Values measured with UWLMP for the same specific sample are also shown (before sending, solid dot; after return, open dot). **B**, Measured values of backscatter coefficients for the specific Type B sample sent to the University of Illinois using a nominal 3.7 MHz transducer (solid square) and a nominal 5.5 MHz transducer (open square). Values measured with UWLMP for the same specific sample are also shown (before sending, solid dot; after return, open dot).





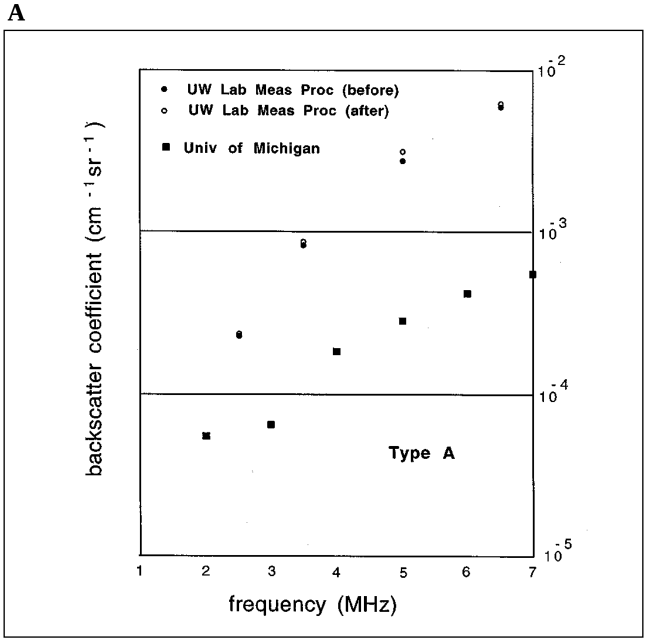


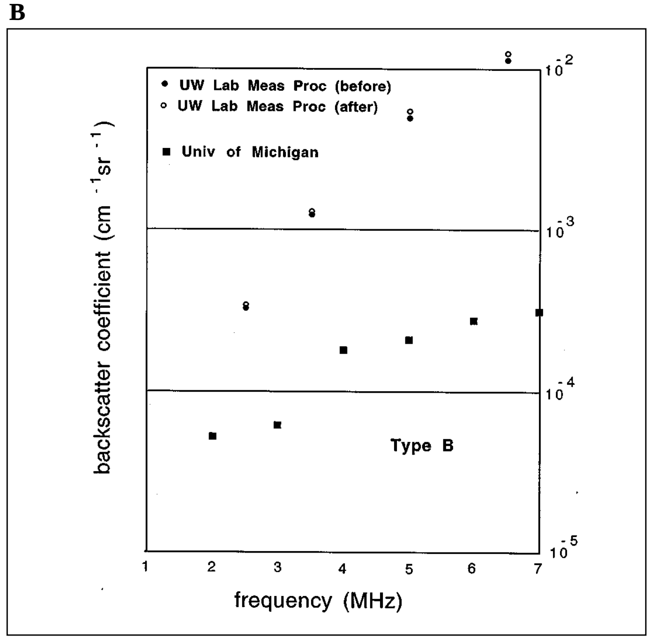
A **B**

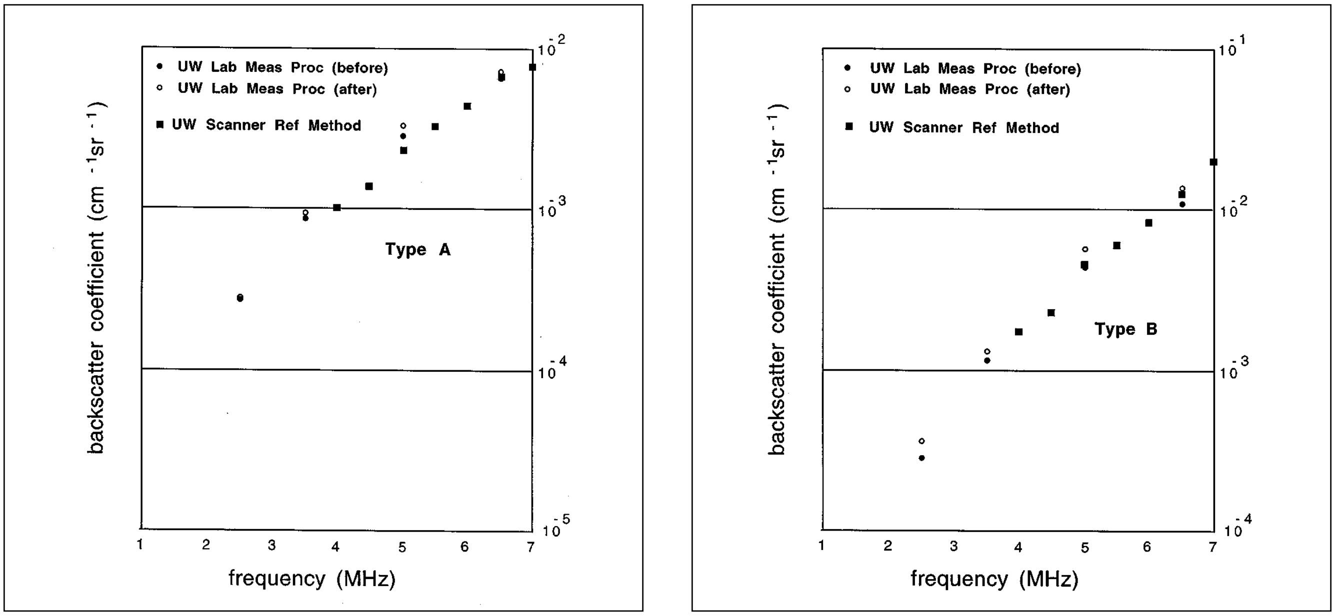
Figure 10 A, Measured values of backscatter coefficients for the specific Type A sample sent to the University of Kansas using the substitution method (solid square) and the reference phantom method (open square). Values measured with UWLMP for the same specific sample are also shown (before sending, solid dot; after return, open dot). **B**, Measured values of backscatter coefficients for the specific Type B sample sent to the University of Kansas using the substitution method (solid square) and the reference phantom method (open square). Values measured with UWLMP for the same specific sample are also shown (before sending, solid dot; after return, open dot).

Figure 11 A, Measured values of backscatter coefficients for the specific Type A sample sent to the University of Michigan (solid square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot). **B**, Measured values of backscatter coefficients for the specific Type B sample sent to the University of Michigan (solid square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot).

A **B**





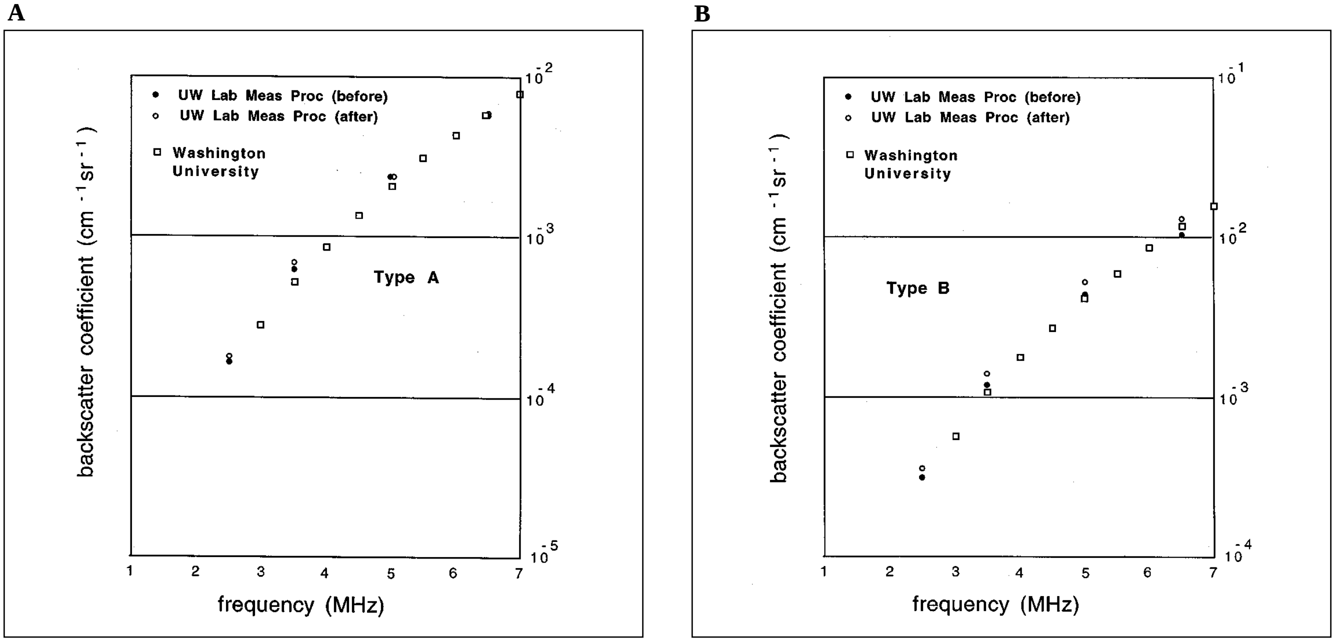


A **B**

Figure 12 A, Measured values of backscatter coefficients for the specific Type A sample using the University of Wisconsin scanner reference method (solid square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot). **B**, Measured values of backscatter coefficients for the specific Type B sample using the University of Wisconsin scanner reference method (solid square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot).

Figure 13 A, Measured values of backscatter coefficients for the specific Type A sample sent to Washington University (open square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot). **B**, Measured values of backscatter coefficients for the specific Type B sample sent to Washington University (open square) and values measured with UWLMP for the same specific sample (before sending, solid dot; after return, open dot).

A **B**



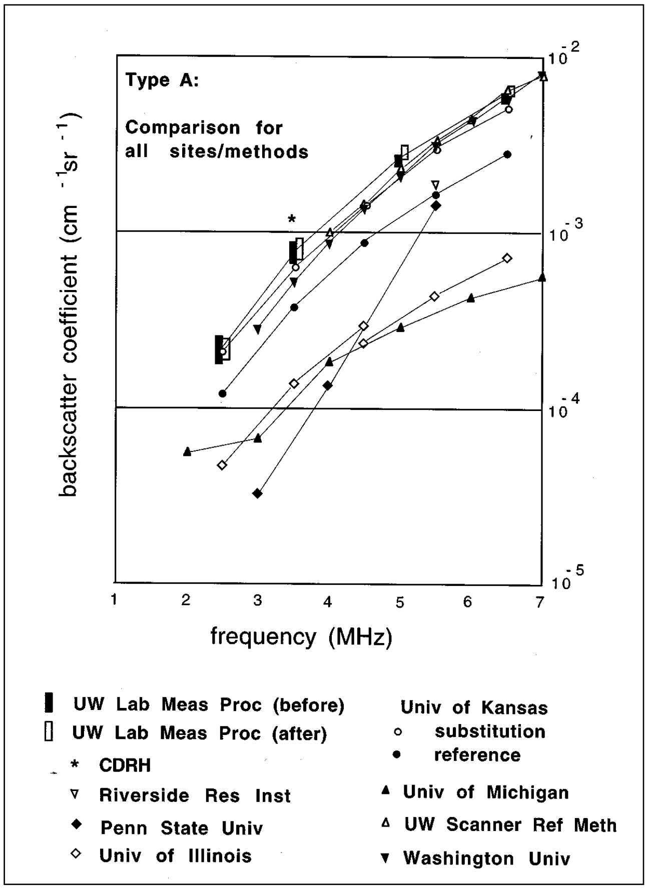


Figure 14 Display of all backscatter measurements made in the study for the Type A material. The rectangles representing the UWLMP are reproduced from Figure 3A. See the key below the graph identifying the different participating sites. For each site or method, lines connect values at successive frequencies.

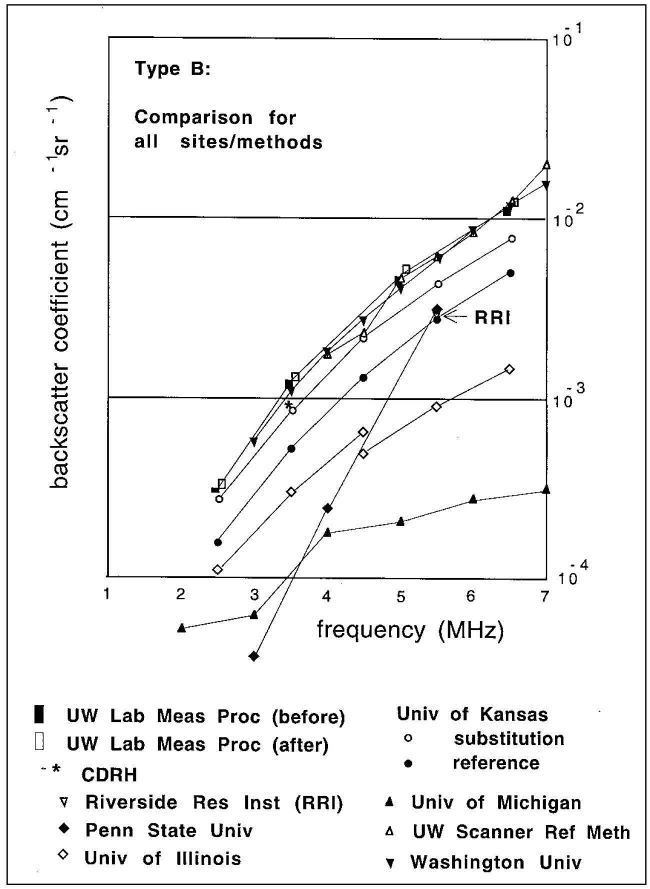


Figure 15 Display of all backscatter measurements made in the study for the Type B material. The rectangles representing the UWLMP are reproduced from Figure 3B. See the key below the graph identifying the different participating sites. For each site or method, lines connect values at successive frequencies.

The major conclusion from this study is that uniformity does not exist among laboratories in terms of determination of fundamental ultrasonic properties in tissuelike media. The results should be valuable for the various sites in assessing their measurement techniques. The study has shown that attenuation coefficient measurement is perhaps the most reliable, with little variation between sites. A surprise is the degree of variation in propagation speeds from site to site. Regarding backscatter coefficients, if it is assumed that the good agreement between four sites or procedures indicates that those results are likely the most correct, then the tendency is for sites to underestimate the backscatter coefficient, but not much worse than by 10 dB. Perhaps agreement among laboratories in backscatter coefficient measurements would improve if a reference standard were used to check measurements.

A comparison may be of interest of overall results of the present study with those of the previous interlaboratory study.[1] It should be noted first, however, that the earlier study involved about half the number of sites as that in the present study. Regarding propagation speed values, the level of agreement in the earlier study was much better, the range being from 1559 to 1564 m/s (0.3%). For the current study, the range for Type A was from 1532 to 1558 m/s (1.7%) and for Type B from 1535 to 1553 m/s (1.2%). In the case of attenuation coefficients, the level of agreement between sites is comparable when the spreads in values in Figure 5 are compared with the corresponding figure in the previous report.

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