Determination of sound speed in biological tissues based on frequency analysis of pulse response

Hiroyuki Hachiya and Shigeo Ohtsuki
Precision and Intelligence Laboratory, Tokyo Institute of Technology, Nagatsuta, Midori-ku, Yokohama 227, Japan

Motonao Tanaka
Research Institute for Chest Diseases and Cancer, Tohoku University, Sendai 980, Japan

Floyd Dunn
Bioacoustics Research Laboratory, University of Illinois, Urbana, Illinois 61801

(Received 28 October 1991; accepted for publication 6 May 1992)

The sound speed in biological tissues provides important diagnostic and treatment planning information. Conventional methods of sound-speed determination generally require that transducers make physical contact with specimens in order to measure thickness and travel time in the time domain. The physical contact may cause deformation and affect blood flow and the measurement of travel time in the time domain may be sensitive to waveform distortion due to tissue inhomogeneity and surface roughness. A method for determination of the sound speed is proposed in which the sound travel time in the sample and the difference in total travel time from the transducer to the rigid reflector due to the presence of the sample are estimated in the frequency domain and which does not require physical contact of ultrasonic probes to living or freshly excised tissue specimens. Ultrasonic speed measurements in silicone rubber and acrylic resin specimens verified the method validity. The standard deviation of the measurements over a 10-$\times$10-mm area is less than 4 m/s. Sound-speed distribution measurements of porcine muscle are in agreement with previously published results.

PACS numbers: 43.35.Wa, 43.80.Ev, 43.80.Cs

INTRODUCTION

The spatial distribution of sound speed is an important acoustic parameter for quantitative characterization of living tissues because it is fundamentally associated with the medium scattering behavior, and is therefore the interaction mostly observed in clincial diagnosis, and because it affects all other ultrasonic parameters (Dunn *et al.*, 1969). Conventional techniques for measuring sound speed require knowledge of the thickness of the tissue speciment and of the travel time of the sound traversing the tissue (Dunn and Goss, 1986). The mechanical contact required in making the thickness measurement causes tissue deformation and affects the blood flow of living tissue, making it difficult to determine the sound speed in tissues with high precision (Goss *et al.*, 1978, 1980). Also, measurement of the travel time in the time domain is further complicated by waveform distortion due to the inhomogeneity of tissue and to roughness of the interface, which reduces the accuracy of the estimate.

In this paper, a new noncontact method for measuring the sound-speed distribution in tissues is proposed. Herein, both the reflected ultrasonic wave from the tissue specimen, placed in water, and the reflected signals passing through the propagation medium of known sound speed are analyzed in the frequency domain, viz., the travel time through the tissue and the travel time difference due to the placement of the specimen on an agar stage are estimated. The sound speed in the specimen is then determined without mechanical contact to the specimen, and thus without effect upon the thickness of the specimen. A description of the principle of this method and results of measurements follow.

I. THEORY

A. Determination of sound speed without mechanical contact

The tissue sample is placed on an agar stage in a liquid medium having sound speed c_0. The agar stage, as shown in Fig. 1, is assembled upon a rigid reflector surface. Transmitted ultrasound reflections occur at the front and rear faces of the sample and at the rigid reflector surface. The agar concentration of the gel stage is very low, of the order of 1% by weight, and its acoustic properties are very nearly that of water. Thus reflection at the water/agar interface is negligible. Here, t_{sd} is the travel time between the front and rear interfaces of the sample; that is, the travel time of sound passing through the thickness d of the sample, and t_{wd} is the travel time of sound passing through the distance d without the sample present. The thickness d of the sample is, therefore, given by

$$d = ct_{sd} = c_0 t_{wd} = c_0(t_{sd} - \Delta t), \tag{1}$$

where

 0001-4966/92/091564-05$00.80

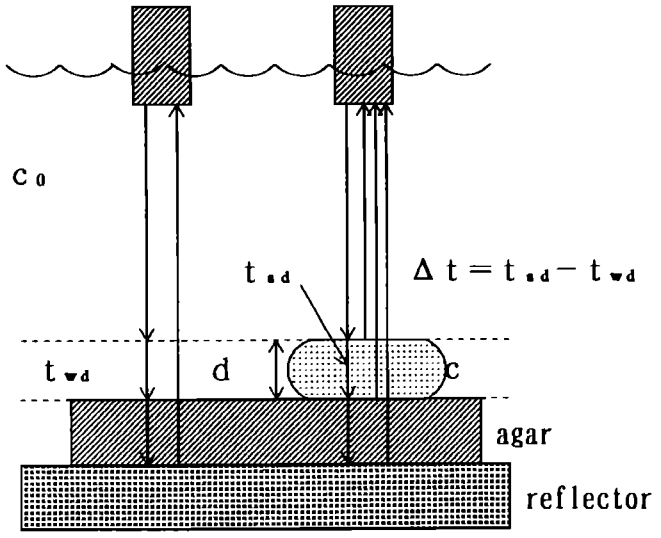


FIG. 1. Principle of measurement.

$$\Delta t \equiv t_{sd} - t_{wd} \tag{2}$$

is the difference in the travel time from the transducer to the reflector due to the placement of the sample on the agar stage.

The sound speed c in the sample is

$$c = c_0(1 - \Delta t / t_{sd}). \tag{3}$$

From (1) and (3), d and c can be determined using measured values of Δt, t_{sd} and the known value of c_0. This calculation procedure is similar to the method proposed by Kuo *et al.* (1990). The sound speed c_0 of the coupling medium, which is usually water or saline, can be determined by moving the ultrasound transmitter/receiver transducer to known positions and determining the travel time differences.

B. Estimation of travel time in the frequency domain

Travel time is often measured in the time domain. But, as waveform distortion due to tissue inhomogeneity and surface roughness limits the accuracy of the estimate, for the proposed method, travel time t_{sd} and travel time difference Δt are estimated in the frequency domain.

Travel time t_{sd} and Δt are estimated by analysis in the frequency domain using fast Fourier transform (FFT) techniques. A pulse wave with center angular frequency ω is transmitted from the transducer and reflected waves are received by the same transducer. The reflected wave amplitude without the sample present, which consists of only the wave reflected from reflector surface, $R_w(t)$, is given by

$$R_w(t) = A_w R(t - 2t_w), \tag{4}$$

where t_w is the travel time from the transducer to the agar/reflector interface without the sample present and $R(t)$ is the waveform of the transmitted signal from the transducer [Figs. 2(a) and 3(a)]. Here, A_w is a factor involving signal attenuation and a reflection coefficient. Frequency-dependent attenuation and sound-speed dispersion of tissues are not included in order to simplify the formulation.

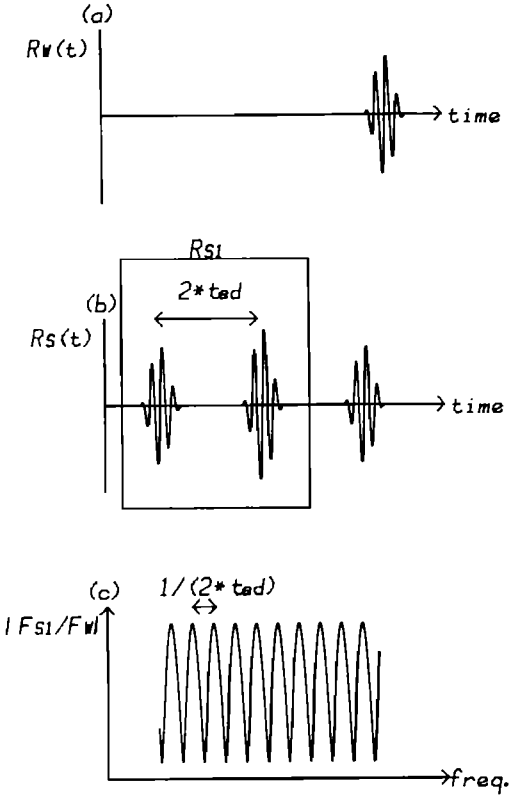


FIG. 2. The estimation of travel time t_{sd}.

As shown in Figs. 2(b) and 3(b), the reflected wave with the sample present on the agar stage, $R_s(t)$, is given by

$$R_s(t) = R_{s1}(t) + R_{s2}(t), \tag{5}$$

$$R_{s1}(t) = A_s R(t - 2t_s) + B_s R(t - 2(t_s + t_{sd})), \tag{6}$$

$$R_{s2}(t) = C_s R(t - 2(t_w - \Delta t)), \tag{7}$$

where t_s is the travel time from the transducer to the water/sample interface, A_s and B_s are the amplitudes of reflected waves from the front and rear sample faces, and C_s is the amplitude of the wave reflected at the agar/reflector interface. Here, $R(t)$ is the transmitted signal and R_s is comprised of two parts, R_{s1} and R_{s2}. R_{s1} consists of waves reflected from the front and rear faces of the sample and R_{s2} consists of waves reflected from the reflector/agar interface. Travel time t_{sd} is estimated using Fourier transforms of R_{s1} and R_w, and the travel time difference Δt is estimated using Fourier transforms of R_{s2} and R_w. Since the reflector is located beyond the agar stage with sufficient distance from the sample, R_s can be resolved into R_{s1} and R_{s2}.

The Fourier transforms of R_{s1} and R_{s2}, viz. F_{s1} and F_{s2}, respectively, are given by

$$\begin{aligned} F_{s1}(\omega) &= A_s F(\omega)\exp(-j\omega 2t_s) \\ &\quad + B_s F(\omega)\exp[-j\omega 2(t_s + t_{sd})] \\ &= F(\omega)\exp(-j\omega 2t_s) \\ &\quad \times [A_s + B_s \exp(-j\omega 2t_{sd})], \end{aligned} \tag{8}$$

$$F_{s2}(\omega) = C_s F(\omega)\exp[-j\omega 2(t_w - \Delta t)], \tag{9}$$

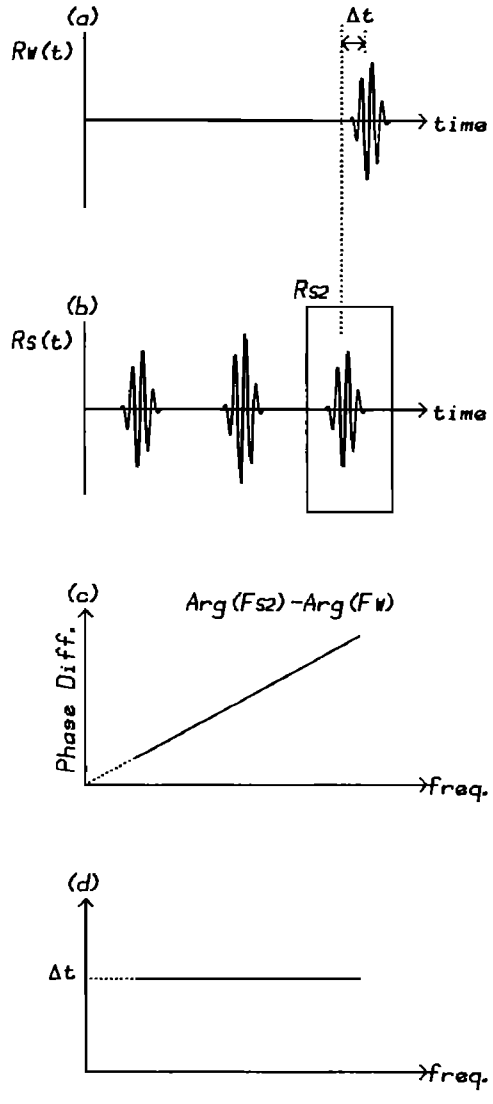


FIG. 3. The estimation of the time difference Δt.

where $F(\omega)$ is the Fourier transform of the transmitted signal $R(t)$,

$$F(\omega) = \int_{-\infty}^{\infty} R(t)\exp(-j\omega t)dt. \tag{10}$$

The Fourier transform of the reflected wave from the reflector without the sample, $F_w(\omega)$ is given by

$$F_w(\omega) = A_w F(\omega)\exp(-j\omega 2t_w), \tag{11}$$

where A_w is the amplitude of reflected wave. Using (8) and (11),

$$F_{s1}(\omega)/F_w(\omega) = (A_s/A_w)\exp[j\omega 2(t_w - t_s)] \times [1 + (B_s/A_s)\exp(-j\omega 2t_{sd})]. \tag{12}$$

Figure 4 shows the trajectory of $[1 + (B_s/A_s) \times \exp(-j\omega 2t_{sd})]$ in the complex plane. The amplitude $|F_{s1}/F_w|$ is given by

$$|F_{s1}/F_w| = \sqrt{[A_s + B_s\cos(\omega 2t_{sd})]^2 + B_s^2\sin^2(\omega 2t_{sd})}/A_w = \sqrt{A_s^2 + B_s^2 + 2A_sB_s\cos(\omega 2t_{sd})}/A_w. \tag{13}$$

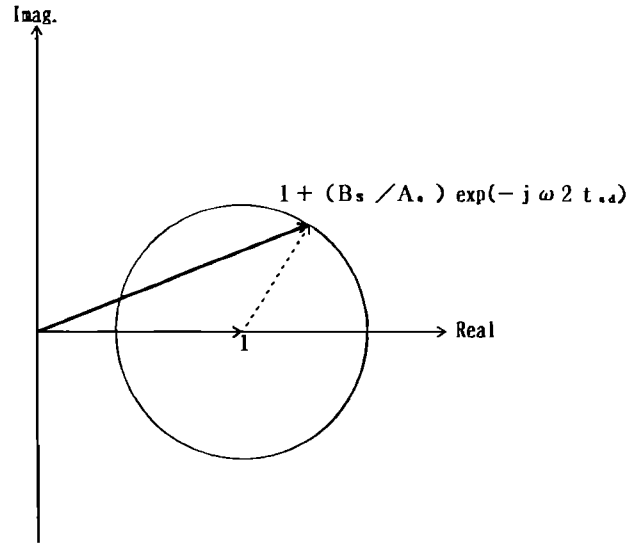


FIG. 4. The trajectory of $[1 + (B_s/A_s)\exp(-j\omega 2t_{sd})]$ in the complex plane.

As shown in Fig. 2(c), $|F_{s1}/F_w|$ exhibits periodic variation with frequency and takes a local maximum at the point of

$$\omega 2t_{sd} = 2\pi k \quad (k = 0,1,...),$$

that is,

$$f2t_{sd} = k \quad (k = 0,1,...).$$

The frequency difference Δf between neighboring maximum positions of $|F_{s1}/F_w|$ corresponds to travel time t_{sd} as given by

$$\Delta f = 1/2t_{sd}. \tag{14}$$

Since R_{s1} involves reflections from internal structures of tissue, F_{s1} contains some periodic components other than the directing component. Then t_{sd} is obtained as a maximum of the inverse Fourier transform of $|F_{s1}/F_w|$ over the transducer's band to separate the effect of reflections from internal structures of tissue.

The travel time difference Δt is estimated using F_{s2} and F_w as illustrated in Fig. 3. The phase difference between F_{s2} and F_w is given by

$$\arg(F_{s2}) - \arg(F_w) = \arg(F_{s2}/F_w) = -2\omega\Delta t \tag{15}$$

as shown in Fig. 3(c).

The travel time difference Δt, as given by

$$\Delta t = [\arg(F_{s2}) - \arg(F_w)]/(-2\omega), \tag{16}$$

is shown in Fig. 3(d). This relation is well known and can be used to measure phase velocity (Sachse *et al.*, 1978). Eliminating the effect of multipath propagation in inhomogeneous tissue, Δt is estimated as a gradient of the regression line through zero by the least-square method over the transducer's bandwidth using Eq. (15).

The travel time t_{sd} and the time difference Δt are estimated in the frequency domain.

II. EXPERIMENTAL RESULTS

The sound speeds of materials of known properties with thicknesses of several millimeters were measured by this method in order to evaluate the technique. Silicone rubber (Shinetsu silicone KE108) and acrylic resin samples were placed in a water tank 28 cm long, 28 cm wide, and 21 cm deep. Water at 25.1 ± 0.1 °C was used as the bath (coupling) medium. An ultrasound pulse was transmitted from the transducer to the sample and a brass reflector, beyond the sample. The reflected wave was received by same transducer. The received signal was captured by a Hewlett Packard 5180 waveform recorder at a 20-MHz sampling rate and transferred, via an HP-IB interface, to a computer for the time difference determination. The transducer used had a 3.5-MHz center frequency, was 13 mm in diameter, and had a 50-mm focal length. The − 3-dB signal bandwidth was 2 MHz (2.5 to 4.5 MHz). The trigger clock for the pulser was generated by dividing the 20-MHz sampling rate of the waveform recorder for completely synchronized operation.

The sound speed of the liquid medium was determined by moving the transducer known distances, with accuracy ± 5 μm, and estimating the time differences by analyzing the wave reflected from the brass reflector, in the frequency domain. Figure 5 shows the measured sound speed, as a function of the temperature, for distilled water (open circles) and 0.9% saline (open triangles). The dotted line indicates the calculated value using Greenspan–Tschiegg's empirical equation (Greenspan and Tschiegg, 1959). The measured values agree well with Greenspan's equation within ± 3 m/s (± 1.5 m/s over a range between 20 and 40 °C).

The results of measurement of the silicone rubber and acrylic resin plate samples are shown in Table I. The thickness of the samples was also measured with a micrometer. The table entries (means ± standard deviations) are the averages at 25 measuring points uniformly distributed over a 10-× 10-mm area. It is seen that the ultrasonically measured values of thickness agree well with the micrometer determinations.

TABLE I. Results of measurements of the silicone rubber and acrylic resin plate samples.

	This method		Thickness measured by micrometer (mm)
	Sound speed (m/s)	Thickness (mm)	
Silicone rubber (1)	1008.0 ± 4.6	4.37 ± 0.03	4.39 ± 0.01
Silicone rubber (2)	1008.9 ± 3.9	6.36 ± 0.03	6.35 ± 0.01
Acrylic resin	2758.3 ± 4.9	10.27 ± 0.02	10.30 ± 0.01

The temperature dependence of sound speed of silicone rubber was determined for 4-mm-thick specimens and shown in Fig. 6. The deviation of the sound-speed measurements is less than 4 m/s. The dotted line is a regression line obtained by the least-squares method.

In the measurements of the acrylic resin and silicone rubber samples, the estimated maximum errors of time difference Δt and travel time t_{sd} were, respectively, 15 and 50 ns. For a 5-mm sample of tissue, with an assumed sound speed of 1600 m/s, the maximum error in sound-speed estimation is calculated to be about 8 m/s; an average error should be smaller.

Figure 7(b) shows the two-dimensional sound-speed distribution in a sample of porcine muscle [Fig. 7(a)]. The distribution was obtained for 121 measured points by scanning a 20-×20-mm area at 2-mm intervals. The contour interval is 25 m/s. The sound speeds were found to be 1521.2 ± 12.0 m/s in the fatty tissues and 1585.2 ± 17.1 m/s in the muscle tissues. These values compare favorably with those published by other investigators (Goss *et al.*, 1978, 1980).

III. DISCUSSION

Determination of the two-dimensional sound-speed distribution in tissues is important in the evaluation of the rela-

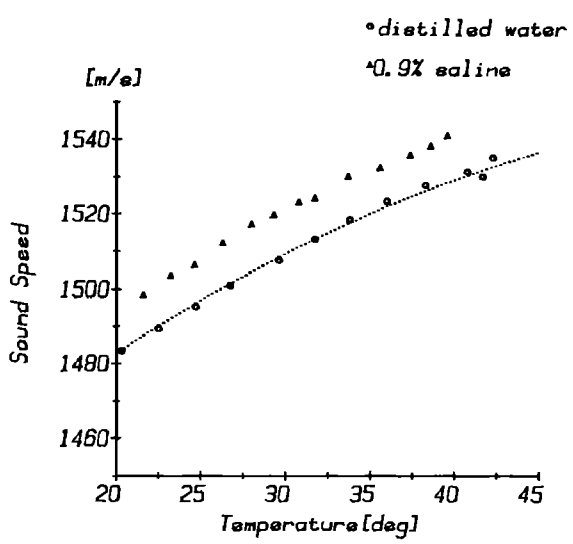


FIG. 5. The measured sound speed for distilled water (open circles) and 0.9% saline (open triangles). The dotted line indicates the calculated value using Greenspan–Tschiegg's empirical equation.

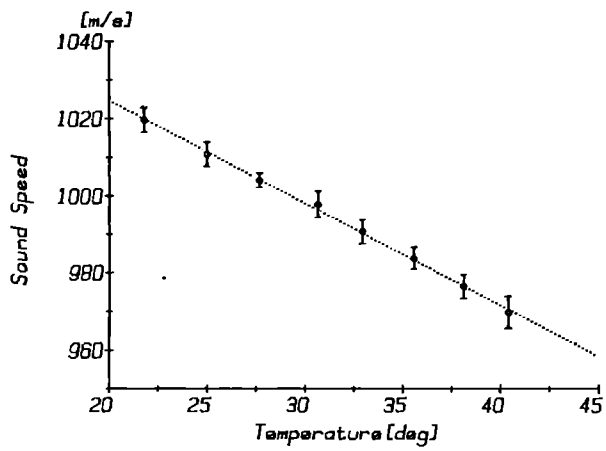
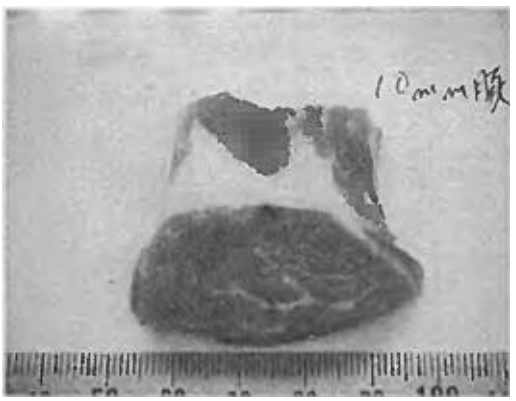
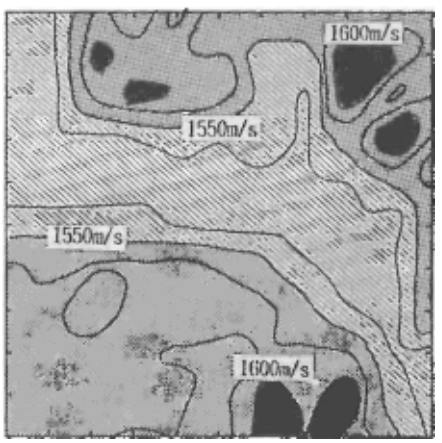


FIG. 6. The temperature dependence of the sound speed of silicone rubber. The error bars represent the standard deviation.



(a)



(b)

FIG. 7. (a) A sample of porcine muscle. (b) The two-dimensional sound-speed distribution in a sample of porcine muscle.

tionship of acoustic characteristics and physiological state in normal and diseased tissues since this parameter involves both the inertial and elastic properties. The published literature contains many reports of such measurements (Goss *et al.*, 1978, 1980). However, measurement methods requiring physical contact of, for example, the transducer to the tissue, introduce errors as the readily deformed soft tissues contravene the possibility of a unique sample thickness. As the proposed method does not require physical contact by a rigid object and thereby eliminates the need for measuring specimen thickness, normal blood flow can continue while the two-dimensional sound-speed distribution is determined by scanning the area of interest normal to the direction of wave propagation.

This method requires determination of the sound travel time in the sample, t_{sd}, and the difference in the travel time due to the presence of the sample, Δt. For a 5-mm sample of tissue, with an assumed sound speed of 1600 m/s, a 10-ns error of Δt results in a 5-m/s error of sound speed, while a 10-ns error of t_{sd} results in a 0.2-m/s error of sound speed. So the measurement of Δt is more important than the measurement of t_{sd}. For precise measurement, Δt is estimated from the gradient of the regression line through zero in the phase difference of stable reflected waves from the rigid surface as a function of frequency. By using the least-square method over the transducer's bandwidth, the estimation result is the propagation time of the principal path in multipaths through inhomogeneous or dispersive media like tissues. This procedure is formally a cross-correlation technique, but it is easy to get the time resolution shorter than the time interval of sampling without interpolation in the time domain using a function like $\sin(x)/x$.

Arguments of F_{s2} and F_{w} take 2π jumps since the argument is in the range $+\pi$ to $-\pi$. But it is normally easy to follow because tissues have a sound speed relatively close to that of water. In the case of very dispersive tissues or inhomogeneous tissues in which sound propagates along many paths, the slope of the phase may not be straight, so it may not be easy to trace the phase.

The estimation of t_{sd} also utilizes all the information contained in the waveform, by the analysis of the received signal in the frequency domain, estimation results are largely independent of waveform distortion due to the roughness of surface and internal structure, allowing the sound-speed distribution in thin specimens to be determined. Since estimation of travel time in the frequency domain is carried out using FFT's, the sound-speed distribution can be determined in nearly real-time.

The basic principle of sound-speed estimation in the frequency domain is based on the assumption of plane-wave propagation. However, the experiments reported here were carried out using very weakly focused waves, suggesting that errors so introduced are usually negligible.

Dunn, F., Edmonds, P. D., and Fry, W. J. (**1969**). "Absorption and Dispersion of Ultrasound in Biological Media, in *Biological Engineering*, edited by H. P. Schwan (McGraw-Hill, New York), Chap. 3, pp. 205–332.

Dunn, F., and Goss, S. A. (**1986**). "Definition of Terms and Measurements of Acoustical Quantities," in *Tissue Characterization with Ultrasound*, edited by J. P. Greenleaf (CRC Press, Boca Raton), Chap. 1, pp. 1–13.

Goss, S. A., Johnson, R. L., and Dunn, F. (**1978**). "Compilation of empirical ultrasonic properties of mammalian tissues," J. Acoust. Soc. Am. **64**, 423–457.

Goss, S. A., Johnson, R. L., and Dunn, F. (**1980**). "Compilation of empirical ultrasonic properties of mammalian tissues II," J. Acoust. Soc. Am. **68**, 93–108.

Greenspan, M., and Tschiegg, C. E. (**1959**). "Tables of the speed of sound in water," J. Acoust. Soc. Am. **31**, 75–76.

Kuo, I. Y., Hete, B., and Shung, K. K. (**1990**). "A novel method for the measurement of acoustic speed," J. Acoust. Soc. Am. **88**, 1679–1682.

Sachse, W., and Pao, Y. (**1978**). "On the determination of phase and group velocities of dispersive wave in solids," J. Appl. Phys. **49**, 4320–4327.