Tissue mimicking materials for ultrasound phantoms

Ernest L. Madsen, James A. Zagzebski, Richard A. Banjavie, and Ronald E. Jutila

Departments of Radiology and Human Oncology, University of Wisconsin, Madison, Wisconsin 53706

(Received 19 September 1977; accepted for publication 19 May 1978)

Up until now, no material has been found whose attenuation and speed of sound properties not only mimic those of human soft tissue, but are controllable in magnitude. We have discovered such a material in the form of water-based pharmaceutical gels containing uniform distributions of graphite powder and known concentrations of alcohol. The magnitude of the attenuation coefficient can be controlled easily between 0.2 and 1.5 dB/cm at 1 MHz, by varying the concentration of graphite. These attenuation coefficients are nearly proportional to the frequency. The speed of sound varies between 1520 and 1650 m/s at room temperature, depending primarily upon the concentration of alcohol. Bacterial invasion has been prevented by sterilization procedures and the introduction of appropriate preservatives. The ultrasonic properties exhibit temporal stability and change little over the range of room temperatures.

I. INTRODUCTION

In the field of diagnostic ultrasound there are test objects presently available for assessing the depth calibration and electromechanical alignment of ultrasound scanners. Such test objects consist of rods or wires in a liquid whose speed of sound is matched to that in tissue but which provides no absorption or scattering of the ultrasound beam. A material which more closely mimics soft tissues is desirable for use in advanced test objects and phantoms including gray scale test objects, phantoms for carrying out performance checks of transducers, and ultrasonic training phantoms for use by student technologists.

An *ideal* material for constructing ultrasound phantoms should have the same ranges of speeds of sound, attenuation coefficients, and scattering coefficients as soft tissue. These three parameters should be controllable in the manufacturing process of the phantom material, and their variation within the range of room temperatures should be small. Also, the material should exhibit temporal stability and ease of storage.

Speeds of sound in mammalian soft tissues vary over a fairly small range with an average value of about 1540 m/s. The speed of sound in fat is thought to be about 1470 m/s, while for other tissues the speed ranges from 1570 m/s in liver to 1600 m/s along the direction of the fibers in muscle.[1]

The amplitude attenuation coefficients appear to vary over the range from 0.4 dB/cm to about 2 dB/cm at a frequency of 1 MHz in these tissues.[1] Chivers and Hill[2] have examined the dependence of the attenuation coefficients on frequency for some typical soft tissues. In almost all cases reported, the attenuation coefficient is approximately proportional to the ultrasonic frequency.

Various substances are being investigated in attempts to produce such a phantom material. These include soft plastics, either plastisols[3] or urethane polymers,[4] pharmaceutical gels,[5–8] and a polymer marketed by the 3M Company, used for bedsore prevention pads.[4,8]

Many of these materials possess some ultrasonic properties which are approximately soft-tissue-equivalent over a limited frequency range. Our measurements of speed of sound and attenuation coefficient in the case of the 3M material indicate that the speed of sound can be varied over the range from 1468 m/s to 1524 m/s, a reasonable range especially for mimicking fat. Our recent measurements on a sample at 18.9 °C yielded a speed of sound of 1493 m/s; the attenuation coefficients at 1.14, 3.14, and 5.20 MHz were 1.05, 4.3, and 10.1 dB/cm, respectively. Corrections for reflections at the interfaces were negligible. Assuming a functional form for the attenuation coefficient α to be $\alpha = \alpha_0 f^n$, where α_0 and n are constants and f is the frequency, a least-squares fitting yields $\alpha_0 = 0.846$ dB cm^{-1} MHz$^{-1.48}$ and $n = 1.48 \approx 3/2$; the correlation coefficient was 0.999. Thus, assuming an attenuation coefficient for fat which is proportional to the frequency and is described by 0.6 dB/cm/MHz,[9] the 3M material is not appropriate for use as fat. Because of the low speed of sound and $n \approx 3/2$ (instead of 1), use of this material to mimick tissue other than fat is not desirable. An additional disadvantage of the 3M material is that no ultrasonic scattering has been detectable and, hence, addition of appropriate scatterers for tissue mimicking will necessarily drive the attenuation coefficient even higher.

The soft plastic materials can be made to exhibit speeds of sound in the correct range, but difficulty has apparently been encountered in attempts to reduce the attenuation coefficient to acceptable values, especially at room temperature, while maintaining the desired range for speed of sound.[3,4]

Water-based gelatins containing suspensions of solid particles, including acetate fibers and glass spheres, are being investigated as possible ultrasonic tissue phantom materials by Edmonds *et al.*[7] Although the attenuation of a simple gel mixture is too low for correctly matching soft tissues, additives can be employed to bring the attenuation coefficient within a useful range.

Our group has also been working on acoustical properties of water-based gelatins (derived from animal hides). We have found that both the speed of sound and the ultrasonic at-

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tenuation properties can be simultaneously controlled in gels in order to match those of most soft tissues. Very importantly, we have been able consistently to achieve proportionality of the attenuation coefficient and the ultrasonic frequency. This proportionality is important not only so that a specific piece of phantom material can mimic soft tissues at any clinically important ultrasonic frequency, but so that the broad-band nature of clinical ultrasound pulses can be correctly taken into account (Beam hardening is mimicked.).

Our work on pharmaceutical gels is the subject of the remainder of this report.

II. MATERIALS AND METHODS OF PRODUCTION OF THE GEL SAMPLES

Initially a mixture of dry gelatin, distilled water, n-propanol, and preservatives is prepared at room temperature. The ratio of dry gelatin to water–alcohol preservative is $1/5$. Heating clarifies the mixture, after which powdered graphite is added. The concentration of n-propanol determines the speed of sound in the final sample, and the concentration of graphite determines the attenuation coefficient and the nature of ultrasonic scattering produced in the sample. The graphite grains are irregularly shaped and include all sizes which will pass through a sieve with openings of 43 by 43 μm. The average particle diameter, however, is only about 6 μm, with a standard deviation of 4 μm. Fay *et al.*[5] have worked with gels, studying scattering by suspended 0.5-mm plastic spheres as well as the effects of interfaces between gels having different speeds of sound and acoustic impedances. Their inclusion of concentrations of ethanol and glycerin presumably was to control the speed of sound. We have employed concentrations of n-propanol instead of ethanol to take advantage of its higher boiling point and lower vapor pressure (compared to ethanol), thus avoiding difficulties maintaining the desired alcohol concentration.

The final hot mixture is poured into plastic molds so that the gel is formed into right circular cylinders of 7.5-cm diameter and 2.55-cm height. During congealing, which takes a few hours, the samples are rotated to defeat any development of gradients in the concentration of the graphite particles. The final samples have 0.05-mm-thick layers of plastic covering the parallel flat surfaces; this plastic has a very low diffusion constant for water thus greatly discouraging desiccation of the gel.

III. METHODS OF MEASURING ACOUSTIC PARAMETERS

So far we have concentrated our efforts on developing materials exhibiting the same speed of sound and attenuation coefficient as soft tissue. Thus, good quantitative measurements of scattering parameters have yet to be made.

The apparatus used to make our measurements is shown in Fig. 1. Gel samples are placed between the transmitting transducer and the receiving hydrophone with the parallel faces of the sample maintained perpendicular to the ultrasonic beam direction. Narrow band pulses are produced by the Arenberg pulsed oscillator. The diameter of the piezoelectric crystal in the hydrophone is about 1 mm, thus minimizing phase cancellation effects.[10] The bathing medium is distilled water.

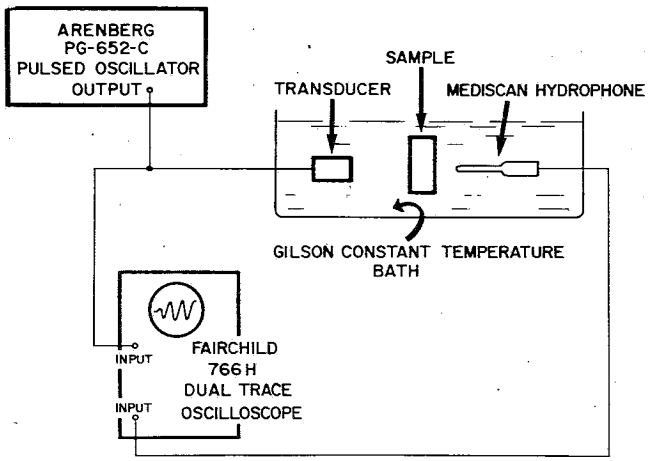

Fig. 1. Apparatus used in measuring the speed of sound and attenuation coefficient.

Speed of sound is measured by noting the difference in pulse arrival time for the two cases in which the sample is present or absent between the sending transducer and hydrophone. The speed of sound in the sample can then be calculated relative to the speed of sound in the distilled water. Using this method, agreement has been obtained with published values for three different ethanol–water concentrations to within 0.2%. A precision of $\pm 0.1\%$ is easily attainable.

Attenuation coefficients at discrete ultrasonic frequencies are measured with the same experimental setup. The attenuation coefficient for a sample can be calculated by noting the pulse amplitude before and after insertion of the sample in the ultrasound beam. Corrections for the nonzero thickness of thin plastic layers over the parallel sample faces are significant for frequencies above about 2 MHz and are included in the data reduction.[6]

IV. RESULTS

The pure congealed gelatin-water-alcohol mixture exhibits an attenuation coefficient per MHz in the range 0.2–0.3 dB $cm^{-1}MHz^{-1}$. By adding uniform concentrations of powdered graphite, this value can be raised to anything between 0.2 and 1.5 dB $cm^{-1}MHz^{-1}$, and probably higher. Figure 2 shows the attenuation coefficient in several gel samples as a function of frequency and graphite concentration. The attenuation coefficients were measured at 24.5 °C for all cases except those at 4.6 MHz, which were measured at 22 °C. Graphite concentrations for the samples shown in Fig. 2 are found in Table I. The data show the very important fact that any value of the attenuation coefficient can be obtained by choosing the appropriate graphite concentration.

To determine the frequency dependence of the attenuation coefficient of our samples, a least-squares fitting of these attenuation data was done for each graphite concentration, assuming that the attenuation coefficient is proportional to the nth power of the frequency, i.e., we assumed $\alpha = \alpha_0 f^n$ where α_0 is the constant of proportionality and is numerically equal to the attenuation coefficient at 1 MHz and n is the

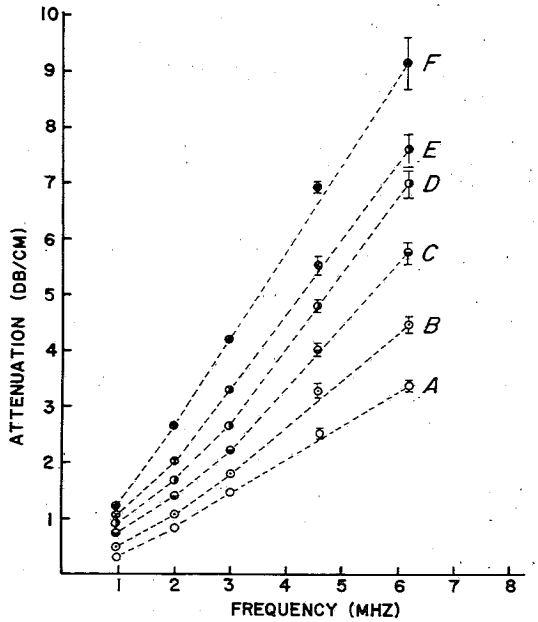

Fig. 2. Attenuation coefficient as a function of frequency, for the six different graphite concentrations listed in Table I.

power to which the frequency f, in MHz, is raised. Values of α_0 and n (as well as the speed of sound) as functions of graphite concentration are given in Table 1, corresponding to the data plotted in Fig. 2. As can be seen from the values of n, the attenuation coefficient is approximately proportional to the frequency as is the case for soft tissues.

The speed of sound in the material appears to be in the soft tissue range. The speeds of sound in various samples have been found to be as low as 1520 m/s and as high as 1650 m/s, at room temperature, depending on the concentration of n-propanol. The values in Table I were measured at 25.0 °C and show little dependence on graphite concentration. These samples contain a 5% concentration of n-propanol by weight. In another set of samples we found that the speed of sound increased monotonically with n-propanol concentration, from 1550 m/s at 0% to 1650 m/s at 21%. Thus, a speed of sound range of at least 100 m/s is available.

Measurements of attenuation coefficient and speed of sound were repeated about two months later at temperatures of 16.0, 19.7, 24.0, and 28.0 °C, incorporating a reasonable range of room temperatures. The results of these measurements are presented in Figs 3 and 4. Reported here are the results for the sample of intermediate graphite concentration, viz., 0.124 g/cm^3.

TABLE I. Values of α_0, n and speed of sound for samples differing only in graphite concentration. The attenuation coefficient α is assumed to have the form $\alpha = \alpha_0 f^n$, where f is the frequency.

Gel sample code	Graphite concentration (g/cm^3)	Speed of sound (m/s)	α_0 (dB cm^{-1}MHz^{-n})	n
A	0.049	1579	0.368	1.24
B	0.073	1579	0.491	1.21
C	0.097	1580	0.730	1.09
D	0.124	1578	0.915	1.07
E	0.142	1578	1.058	1.06
F	0.187	1576	1.453	0.99

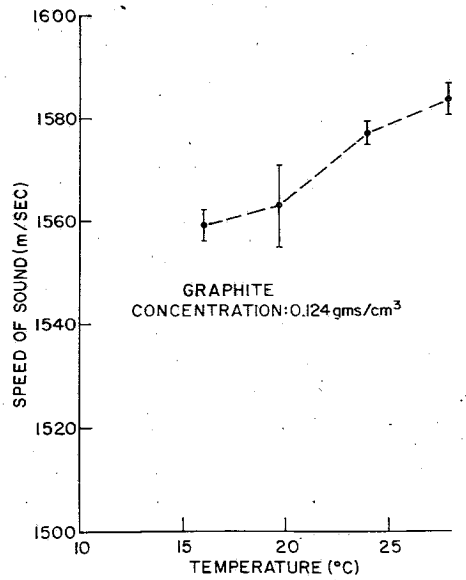

Fig. 3. Speed of sound as a function of temperature.

The data displayed in Fig. 3 indicate that the speed of sound in this sample shows only about 1.5% increase as the temperature rises from 16.0 to 28.0 °C. As indicated by the lengths of the error bars, we neglected to obtain the best available precision from our apparatus for this sample. A speed of sound measured two months before these data were taken lies right on this curve, indicating a stable speed of sound.

Figure 4 shows the attenuation coefficient as a function of frequency and temperature. Again, proportionality of the

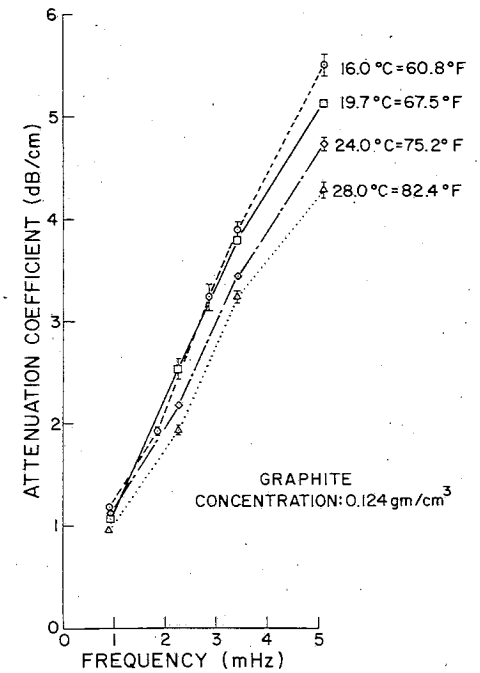

Fig. 4. Attenuation coefficient versus frequency for different temperatures-graphite concentration, 0.124 g/cm^3.

attenuation coefficient and frequency is strongly indicated. A reasonable room temperature range might by 19.7 °C = 67.5 °F to 24 °C = 75.2 °F. Curve fitting at these temperatures shows a drop of 8.6% in the attenuation coefficient at 3 MHz with the temperature rise.

At 22 °C and 4.6 MHz the attenuation coefficient measured initially was 4.57 dB/cm. Analysis of measurements on the same sample made two months later gives 4.56 dB/cm for the same temperature and frequency—the same value within our precision limits.

V. CONCLUSIONS AND CONTINUING WORK

We have discovered a combination of materials and manufacturing techniques which will allow all the abdominal and lower chest parenchymal tissues to be simulated in terms of independently controllable speeds of sound and attenuation coefficients. Methods are being investigated for reaching lower speeds of sound so that fat can be stimulated. The properties of the material exhibit temporal stability and change little over the range of room temperature. The samples reported here have remained unchanged in shape, size, and acoustic parameters through the time of this writing, a period of over four months. To help in discouraging desiccation these samples have been stored in a closed container above a layer of distilled water. Bacterial invasion had been a problem with earlier samples until appropriate preservatives were introduced. We are now using p-methyl and p-propyl benzoic acids as preservatives.

Work is in progress to characterize ultrasonic scattering from gel-graphite mixtures. In preliminary work, ultrasonic *B*-scans of samples of large volume have been taken using sensitivity and swept gain parameters as employed for adult living *B*-scans. Gray scale patterns obtained with such scans indicate a lower level of scatter occurs from within the sample than occurs from liver parenchyma. The attenuation coefficient of the gel sample was 0.75 dB $cm^{-1}MHz^{-1}$. Additional work is required to quantify accurately the scatter and to learn the effects on scatter due to various concentrations, sizes, and shapes of particles suspended in the gels.

Besides continuing to study the gels and further develop their capabilities, we are constructing anthropomorphic phantoms and test objects for studying ultrasonic transducer beam profiles and axial resolution as a function of depth. Furthermore, because of the relative ease of manufacturing this phantom material and ease of controlling acoustic parameters (speed of sound and attenuation coefficient) over significantly large ranges, gelatin phantoms represent a useful laboratory tool for use in the development of *in vivo* techniques for ultrasonic tissue characterization.

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