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OIL-IN-GELATIN DISPERSIONS FOR USE AS ULTRASONICALLY TISSUE-MIMICKING MATERIALS

ERNEST L. MADSEN, JAMES A. ZAGZEBSKI and GARY R. FRANK
Department of Medical Physics, 1530 Medical Sciences Center, 1300 University Avenue, University of Wisconsin, Madison, WI 53706, U.S.A.

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Abstract—A form of tissue-mimicking material is reported in which oil droplets are dispersed in a water-based gelatin. Broad ranges of ultrasonic parameters, including speed of sound, attenuation coefficient, density and backscatter level, exist for this material. Very important, the attenuation coefficients are nearly proportional to the frequency as in the case of mammalian tissue and the available attenuation coefficient slopes span the range of mammalian tissues. The available range of slopes is 0.1 dB/cm/MHz through at least 2.0 dB/cm/MHz. The available speeds of sound range from a minimum below that of mammalian fat (~ 1460 m/s) to a maximum above the accepted average for human tissue (1540 m/s). Densities available range from below that of fat (~ 0.92 gm/cm^3) through about 1.00 gm/cm^3. Backscatter levels are easily made negligible compared to clinical levels and compared to those exhibited in previously reported tissue-mimicking materials in which the suspended particles are solid (Madsen *et al.*, 1978; Burlew *et al.*, 1980). Addition of solid or hollow glass scatterers allows backscatter levels to be made comparable to those clinically observed.

Key words: Ultrasonics; Adipose tissue; Models, Biological; Gels.

INTRODUCTION

We previously reported on tissue-mimicking materials in which solid particles are uniformly distributed in a solid water-based gelatin matrix (Madsen, *et al.*, 1978; Burlew *et al.*, 1980). If the gelatin is derived from calf skin and is prepared as in our lab, it exhibits a reproducible minimum speed of sound of 1570 m/s at room temperature (22°C) and a maximum of about 1650 m/s; if the gelatin is in the form of 3% agar, the minimum is 1500 m/s and the maximum is about 1600 m/s at 22°C.

The agar materials have been found to be somewhat difficult to work with, particularly because of the tendency for solid particles not to be uniformly distributed. This can be ascertained by naked eye inspection of the material. If very careful control over temperature and mixing techniques are not taken during manufacture, this nonuniform distribution is likely to occcur. This results in nonuniform *B*-scan "texture patterns" when scanned with grey scale equipment as well as in large-scale nonuniformities in the attenuation coefficient (e.g. fifty percent variations within one sample).

One advantage of the agar is that its melting point is about 78°C, making it stable with respect to environmental fluctuations. Following a recent publication (Astrahan, 1979), we have developed techniques for introducing small concentrations of formaldehyde into the animal hide gel materials increasing their melting point from 32.5 to over 70°C. The animal hide gelatin is easy to work with and tissue-mimicking materials made using it always exhibit a uniform "texture pattern"; therefore, it is preferred to the agar.

These materials are preserved with paramethyl benzoic acid, *n*-propanol, and formaldehyde, and dessication is negligible for years if the materials are sealed from the atmosphere. One of the first phantoms produced is still in use after three years; no deterioration has occurred and dessication is negligible.

Of particular interest to us has been the need for a stable material with the ultrasonic properties approximating those of mammalian fat. Such a material should have a speed of sound of about 1460 ms, an attenuation coefficient proportional to the frequency with coefficient of proportionality of about 0.4 dB/cm/MHz, and a density of about 0.94 gm/cm (Wells, 1977; Goss *et al.*, 1978).

We have found that oil-in-gelatin type dispersions are capable of mimicking fat and also offer ranges of densities, speeds of sound and attenuation coefficients supplementing the ranges available for the solid-particle materials. These dispersions can be made with either animal-hide gelatin or agar,

but the animal hide is again preferred. We discuss below the materials used, the method of production of these dispersions and the ultrasonic properties of some specific preparations.

Of particular importance is the fact that TM* fat and other oil-in-gelatin dispersions can easily be made to have the desired ultrasonic properties *and* to have *n*-propanol concentrations in the gel matrix which match those in other TM gelatin materials with which they may be in direct contact, such as in an anthropomorphic phantom (Madsen *et al.*, 1980, 1982). Thus, speeds of sound, which depend on *n*-propanol concentration (as well as on oil concentration), are not altered by diffusion of *n*-propanol across boundaries between different TM materials following production of such anthropomorphic phantoms.

MATERIALS USED

In our manufacturing procedure an emulsion is first produced consisting of an oil-in-water-based molten gelatin. This is allowed to cool, with the gelatin solidifying. Applying the definition of an emulsion used in physical chemistry, the resulting material is not an emulsion, the oil droplets being suspended in an elastic (and therefore solid) gelatin matrix. To conform to this idea, we refer to the final material as an oil-in-gelatin dispersion.

A number of emulsifying agents have been tried to facilitate the emulsion process. These include commercial dishwashing detergents and emulsifiers used in making photographic emulsions. The former have been the most effective in this application. The emulsions discussed here were made with "Ivory Liquid" detergent†, the major active ingredient of which is alkyl ethoxylate sulfate, an ionic surfactant. The chemical composition of commercially available Ivory Liquid has been constant during the last three years (Griffith, 1980) which includes all of the time we have been using it. To ensure continued predictability of ultrasonic properties of TM materials in the future, a large supply of this detergent is kept in an air-tight container in our lab.

The two liquids which are combined are: (1) molten water-based gelatin (13% by weight rendered calf-skin), and (2) olive oil, castor oil or kerosene or some mixture of these three oils, which is immiscible with the molten water-based gelatin. Other oils have also been used, but, since ultrasonic properties of the above three have been tabulated (Kaye and Laby, 1973) or reported in some detail (Dunn *et al.*, 1969) and since they allow spanning of the ranges of properties needed for our purposes, we have restricted ourselves to using the above three. Kerosene has the lowest density, viscosity and speed of sound of the three oils and castor oil has the highest values for these three properties.

As in the case of the solid particle materials, the oil-in-gelatin dispersions contain sufficient concentrations of *p*-methyl benzoic acid, *n*-propanol, and formaldehyde that bacterial invasion cannot occur. Also, the amount of formaldehyde added is sufficient that the melting point of the solidified gelatin matrix is beyond 70°C.

METHOD OF PRODUCTION

The production of these oil-in-gelatin dispersions is rather easy. First a gelatin solution is produced at an elevated temperature (50–60°C). This solution contains at least 4.5% *n*-propanol and 0.2% *p*-methylbenzoic acid by weight. To this solution is added the appropriate amount of oil. The temperature of this oil is also brought to 50–60°C before the addition. Following this the detergent is added; we used Ivory Liquid such that, in most of the examples discussed below, the volume ratio of oil to detergent is 33. Emulsification is then brought about in one of two reproducible techniques, the two presumably yielding different extents of emulsification and resulting different ultrasonic properties.

In one technique the batch is vigorously stirred with a spoon until a characteristic yellowish milky appearance results, no evidence of droplets being detectable by the naked eye. The following specific spoon-stirring method results in reproducibility of resulting ultrasonic properties and allows introduction of air bubbles into the emulsion to be avoided. A teaspoon or tablespoon is used, depending on the size of the batch. The spoon used is bent at an angle of 90° where the handle meets the bowl of the spoon, and stirring is done with a rotary motion about a

*TM means "tissue-mimicking." We prefer this term to "tissue-equivalent" (TE) because no artificial material—to our knowledge—is equivalent to a tissue type in all four categories of speed of sound, attenuation coefficient, density and scattering characteristics.

†This is a product of the Proctor and Gamble Company, Cincinnati, Ohio.

horizontal axis, the bowl of the spoon being maintained in the bottom half of the emulsion. The stirring is done at 4–5 cycles per second and is continued until a milky appearance develops in which individual particles of oil are no longer resolvable with the naked eye. The duration of this stirring depends on the size of the batch, but, for a 600–1200 cm^3 batch, usually 2 min of stirring is sufficient. This stirring is done with the emulsion between 45 and 55°C.

In the other technique, the batch is put into a Hamilton Beach Model 688–4 blender and blended at the lowest speed setting until a characteristic white appearance is attained. The blending takes about two minutes for a 600 to 1200 cm^3 batch of emulsion. It has been found to be important, for assuring reproducibility of ultrasonic properties, that the mixture have a predetermined temperature at the onset of emulsification e.g. 40 ± 2°C.

Extra stirring or blending time (depending on which technique is used) has little effect on ultrasonic properties of the final TM material. The two techniques for emulsifying are considerably reproducible in terms of the ultrasonic properties of the resulting TM materials. See the section entitled *Reproducibility* for a quantitative discussion.

The spoon stirring technique results in a low scatter TM material (in comparison to the standard graphite suspension in gelatin (Madsen *et al.*, 1978)). The TM materials in which the blending technique is used for emulsifying results in scatter which is negligible compared to the standard graphite-type suspension. At present, scatter is controlled by addition of appropriate concentrations of hollow glass beads having an average diameter of 30 μm. This avails a broad range of scatter levels extending beyond that in the graphite–gel material used as TM liver (Madsen *et al.*, 1978). These scatterers are added following the emulsification and the formaldehyde is also added at this point. An amount of 13.4 cm^3 of 37% formaldehyde solution is added per liter of molten gelatin. The batch is then poured into test cylinders (See below) and appropriate molds, placed under positive gauge pressure, and rotated slowly (2 rpm) about a horizontal axis until congealing is complete. The rotation step assures homogeneity by avoiding gravitational sedimentation. A method used for checking homogeneity is described at the end of the next section.

MEASUREMENT OF ULTRASONIC PROPERTIES AND ERROR ANALYSES

(a) *Attenuation and speed of sound*

For each "batch" of TM material reported here two 7.6 cm dia. right circular test cylinders were produced, having lengths of about 5 and 2.5 cm, the precise thicknesses being individually determined with calipers. The flat boundaries of these cylinders were formed from 50 μm thick Saran Wrap film (Dow Chemical) and the curved surfaces from 0.63 cm wall thickness Lucite.

A through transmission measurement technique was employed in which distilled water was displaced by the test cylinders. See Fig. 1. Continuous wave (CW) ultrasound bursts were created by the Arenberg PG 652C pulsed oscillator driving one of a set of three, 13 mm dia. broad band, nonfocussed transmitting transducers (nominal frequencies 2.25, 5.0 and 7.5 MHz). The receiver was one of a set of six narrow band, 6.3 mm dia., nonfocussed transducers (nominal frequencies 1.0. 2.25, 3.5, 5.0, 7.0 and 10.0 MHz). The distance between the transmitting and receiving piezoelectric elements was maintained between 40 and 45 cm. The amplitude of the source beam was made small enough that the attenuated signal at the receiver was independent of the distance between the sample cylinder and the transmitter; this was assumed to assure that nonlinear effects during transmission of the pulses through the water were negligible. The pulse durations were great enough that transients were not involved and small enough that pulse overlap didn't occur between the directly transmitted pulse and those which suffered reflections at the flat boundaries between the TM material and the distilled water. Measurements were

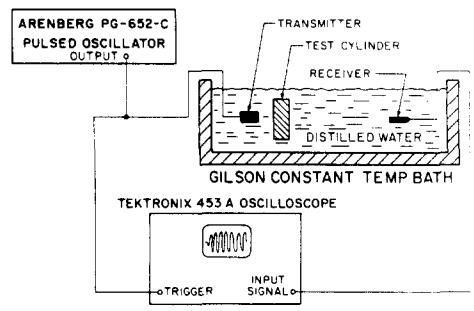

Fig. 1. Apparatus for measuring attenuation coefficients and speeds of sound. For a particular sample and frequency, the amplitudes and phases of the received signal are recorded before and after the introduction of the test cylinder between the transmitting transducer and receiving transducer.

made at a set of discrete frequencies spanning the range of diagnostic ultrasound (see Figs. 3–8). The amplitude of the signal was recorded before and after the insertion of a test cylinder. The phase shift of the CW pulse (as observed on the oscilloscope) due to the introduction of the sample was also recorded. Sufficient time (about 2 hr) was allowed for the test cylinders to reach thermal equilibrium with the water bath before these measurements were made. The temperature (either 22.0 or 34.0°C) was controlled to within 0.1°C by a Gilson constant temperature water bath. The temperature control in the bath had been verified using a mercury thermometer.

The speed of sound, c, was calculated relative to that of distilled water using the relation

$$c = \frac{c_w}{1 + c_w \frac{\Delta t}{d}}$$

where c_w is the speed of sound in the distilled water at the temperature used, d is the length of the test cylinder, and Δt is the shift in time, upon displacement of the water with the test cylinder, of a zero crossover point in the central region of the sinusoidal wave form where transients are no longer apparent. Preliminary to each such shift measurement, an approximate shift was obtained by observing the shift at the initial part of the pulse. The uncertainty in Δt was estimated to be ± 10 nanosec and that in d to be $\pm$ 0.2 mm. The uncertainty in the temperature measurement was ± 0.1°C, which results in an uncertainty in the speed of sound in water, Δc_w, of ± 0.3 m/s (Del Grosso and Mader, 1972). The uncertainty in speed of sound measurements resulting from the combined uncertainties in t, d and c_w is ± 0.6 m/s for all samples reported at both 22 and 34°C.

Measurement of the shift in time of arrival Δt_{Saran}, due to the Saran Wrap windows alone, was done at 2.5 and 3.5 MHz using test cylinders filled with distilled water only at 22 and 34°C. This shift was found to be $\Delta t_{\text{Saran}} = -6 \pm 1$ nanosec, i.e. the beam was delayed. Assuming approximately the same size shift to have occurred in the measurements in which the test cylinders were filled with TM materials (the densities and speeds of sound are all close to one another), the correction term to be added to the speeds of sound is 0.2 m/s. This is half the amplitude of the uncertainty in the speed of sound measurement; nevertheless, this was included in the speed of sound values appearing in this article.

The attenuation coefficients were calculated using measurements of the amplitudes of the received signal before and after the introduction of the test cylinder both for the short (~ 2.5 cm) cylinder and the long (~ 5 cm) cylinder. Since the cylinders were identical except for length, reflection effects at the Saran Wrap covered surfaces can be eliminated from contributing to the measured attenuation coefficients. The expression for the attenuation coefficient in dB/cm corresponding to this procedure is

$$\alpha = \frac{20}{d_l - d_s} \log_{10} \frac{A_s / A_{os}}{A_l / A_{ol}}$$

where $d_l \equiv$ length of the longer sample ($\sim$ 5 cm), $d_s \equiv$ length of the shorter sample ($\sim$ 2.5 cm), $A_{os}(A_{ol}) \equiv$ receiver signal amplitude just before introduction of the shorter (longer) test cylinder, $A_s(A_l) \equiv$ receiver signal amplitude with the shorter (longer) test cylinder interposed between transmitter and receiver.

Castor oil was used as a standard for the attenuation measurements. For each experimental set up corresponding to a specific frequency and temperature, a measurement of the attenuation coefficient on U.S.P. castor oil samples was made, the castor oil being contained in test cylinders of the same kind containing the TM materials. We have subsequently switched to using laboratory grade castor oil. At 30°C measurements on castor oil by various investigators (Dunn *et al.*, 1969) indicate that the attenuation coefficient is very nearly proportional to the frequency raised to the 5/3 power. Measured values at 1 MHz and at 10, 20, 30, 40°C... are tabulated (Dunn *et al.*, 1969). Scatter in castor oil is presumably absent, and, therefore, the attenuation coefficient equals the absorption coefficient.

All of the measurements reported here were made at our estimate of the average clinical room temperature, 22°C, and at a typical temperature of the water bath in which the breast is suspended during the ultrasonic breast imaging, 34°C. Phantoms made from our TM materials are being used in these two environments. Making the

assumption that the 5/3 power rule holds for castor oil attenuation at 22 and 34°C and interpolating to obtain the attenuation coefficient at 1 MHz for 22 and 34°C, the curves in Fig. 2 were obtained. Our measured values appear to exhibit less spread about the plotted curves than those giving rise to the curves themselves. The plotted points correspond to our own experimental measurements.

The error analysis was done in the usual way when a set of independently measured quantities determine the value of the quantity of interest (See, e.g. Bevington, 1969). In the case of the speed of sound determination, uncertainties in t, d_l and c_w were the independently measured quantities. In the case of the attenuation coefficient measurement, which is addressed in this paragraph, there are six such quantities: d_s, d_l, A_s, A_{os}, A_l and A_{ol}. The uncertainty in α can be written

$$\Delta\alpha = \left[\sum_{j=1}^{6}\left(\frac{\partial\alpha}{\partial x_j}\right)^2(\Delta x_j)^2\right]^{1/2}$$

where Δx_j is the uncertainty in the jth measured quantity, the uncertainty in the measurements of both d_s and d_l is ± 0.2 mm. The uncertainties in the remaining four peak-to-peak amplitudes, as measured using the oscilloscope display and assuming a typical peak-to-peak reading of about 5 divisions, is ± 0.15 divisions. The latter uncertainty includes the accuracy to which the oscilloscope's vertical display is maintained ($\pm 2\%$) and the precision to which the peak-to-peak amplitude can be read (± 0.1 divisions). The resulting uncertainties for typical measured values of the attenuation coefficient of 0.30, 0.50, 1.00, 2.00, 4.00, 6.00, 8.00, 10.0 and 12.00 dB/cm are, respectively, ± 0.10, ± 0.11, ± 0.11, ± 0.11, ± 0.11, ± 0.13, ± 0.14, ± 0.15, and ± 0.17 dB/cm.

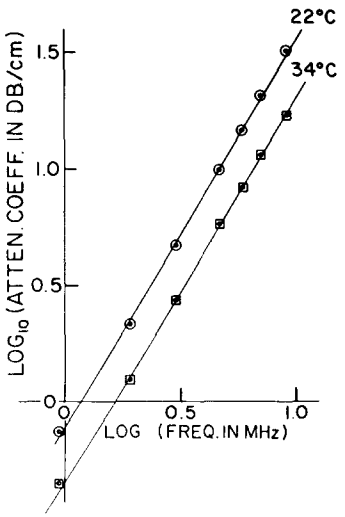

Fig. 2. Measurements made in our laboratory of attenuation coefficient of castor oil at various frequencies and at two different temperatures, viz. 22 and 34°C. The curves shown were derived from compiled data (see text).

(b) *Density*

Density determinations were made at 22°C by direct measurement of mass and volume. Sufficient quantities of TM material (approx. 150 cm^3) were used to assure a precision of about $\pm 0.5\%$. It has been found that direct measurements such as these agree within 0.5% with calculated average densities using the knowledge of the densities of the oils, the density of the congealed gelatin by itself and the percentages by volume of each of these components in the TM material.

(c) *Backscatter level*

Using a pulse-echo system and gating the echoes in the focal region of a 3.5 MHz, 13 mm dia., short internal focus transducer (about 7 μs gate duration), backscatter signal levels were measured on a spectrum analyzer at 4.0 MHz. The samples used were test cylinders described in the materials section, the Saran Wrap "window" being perpendicular to the beam direction and about 6 mm from the gated volume. Measurements were made in decibels relative to the peaked signal (at 4 MHz) from a flat 1" thick aluminum plate 6 mm below a Saran Wrap layer identical to that used in the test cylinders. All objects were in a water-filled tank. The aluminum plate was mounted on an Ardel Kinematic Rx, Ry orientation apparatus allowing any desired orientation of the reflecting surface about a fixed point on that surface. Successively peaked reflected signals from the aluminum plate were indistinguishable from one another within the limits of the experimenters' ability to read the oscilloscope display. Due to the statistical nature of scatter, it was necessary to measure a number of data points for each sample (typically sixteen). These data points were obtained as the transducer was moved in stepwise fashion in directions parallel to the Saran Wrap window (and perpendicular to the beam direction). Backscatter signals were corrected for the effect of attenuation of the beam on passing

through the attenuating TM material. The corrected data points for measurements on each test cylinder were then averaged using the following relation:

$$\bar{X} = 10 \log_{10}\left[\frac{1}{N}\sum_{i=1}^{N} 10^{(X_i/10)}\right]$$

where $\bar{X}$ is the mean backscatter level in dB relative to the flat aluminum plate, X_i is the ith corrected data point in dB relative to the aluminum plate, and N is the number of data points involved. The X_i's and $\bar{X}$ have negative values. Subsequent to the calculation of $\bar{X}$ for each TM material, an adjustment was made to make this mean value relative to a flat perfect reflector instead of to a flat aluminum reflector. The uncertainty in the mean backscatter levels was about ± 1 dB.

(d) *Homogeneity of ultrasonic properties*

One method of assessment of homogeneity is to look for receiver signal amplitude and phase changes when moving the sample 2 or 3 cm in the beam, perpendicularly to the beam direction, care being taken not to allow the beam to pass too close to the cylindrical Lucite walls (see Fig. 1.). No variations in amplitude or phase were detectable on the scope trace in any of the samples discussed in this paper.

ULTRASONIC PROPERTIES

Ultrasonic properties of five different batches of TM material are reported in this section. The different batches of emulsion are designated A, B, C, D and E. Other batches are discussed in the following section entitled *Reproducibility*. The five batches discussed in the present section were chosen to demonstrate a variety of compositions and the range of ultrasonic properties attainable with these materials.

Two of the five batches were made in which the oils contained were olive oil and castor oil in the ratio three to two. The attenuation coefficients at 22 and 34°C are shown in Fig. 3. The solid curves correspond to measurements of attenuation coefficients (α) at 22°C and the dashed curves to measurements of α at 34°C. There are four curves, the upper two corresponding to batch A in which the percentages by volume of olive oil, castor oil and gelatin matrix are 30, 20 and 50, respectively; the lower two curves correspond to batch B having percentages

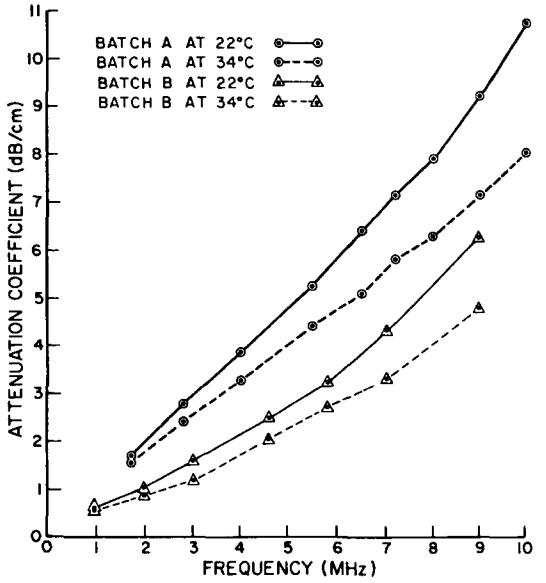

Fig. 3. Attenuation coefficients vs frequency for batches A and B at 22 and 34°C. Batch A contains 30% olive oil, 20% castor oil and 2.2% n-propanol. Batch B contains 20.4% olive oil, 13.6% castor oil and 8.8% n-propanol. The uncertainty in the measurements is about ± 0.1 dB/cm.

20.4, 13.6 and 66.0, respectively. Speeds of sound, c, measured at 22 and 34°C are shown in Tables 1 and 2. These batches were emulsified using the blender method discussed in the *Method of Production* section.

Batch C, for which the attenuation coefficients are given in Fig. 4, contains 40% olive oil and 60% gelatin matrix by volume and was emulsified using the blender method. Batches A, B and C have had no extra scatterers added; any backscatter observed is due to the oil droplets generated in the

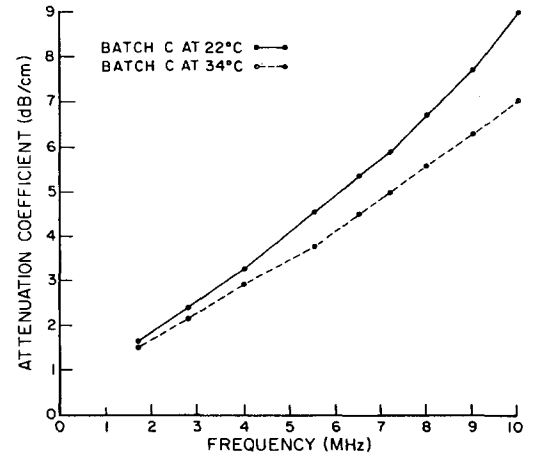

Fig. 4. Attenuation coefficients vs frequency at 22 and 34°C for batch C. Batch C contains 40% olive oil and 2.6% n-propanol. The uncertainty in the measurements is about ± 0.1 dB/cm.

Table 1. Ultrasonic properties at 22°C and description of contents of each batch *A–E*. α_o and n were obtained from data by linear regression analysis of the data assuming the relation between the attenuation coefficient, α, and frequency, f, is of the form $\alpha = \alpha_o f^n$ where α_o and n are constants

Batch Identity	Volume percent of contents except for clear gelatin which makes up the remainder	Speed of Sound c (m/s)	α_o ($dBcm^{-1}MHz^{-n}$)	n	density $\rho(gm/cm^3)$	Backscatter level (#dB below that for a flat perfect reflector at 4 MHz)
A	30% olive oil, 20% castor oil, 2.2% n-propanol	1513.2	0.97	1.02	0.97	67
B	13.6% castor oil, 20.4% olive oil, 8.8% n-propanol	1539.4	0.51	1.08	0.98	67
C	40% olive oil, 2.6% n-propanol	1512.3	0.95	0.92	0.98	66
D (TM glandular tissue for breast)	34% olive oil and 3.0% n-propanol (plus 0.11 mg/cm^3 scatterers)	1518.8	0.80	1.01	0.99	51
E (TM fat)	25% olive oil, 25% kerosene and 2.2% n-propanol (plus 0.65 mg/cm^3 scatterers)	1458.5	0.42	1.02	0.94	52

Table 2. Ultrasonic properties for batches *A–E* at 34°C

Batch Identity	Speed of Sound c (m/s)	α_o ($dBcm^{-1}MHz^{-n}$)	n
A	1495.9	0.92	0.96
B	1525.3	0.51	0.96
C	1498.2	0.90	0.87
D (TM glandular tissue for breast)	1508.5	0.73	0.98
E (TM fat)	1433.5	0.35	1.07

emulsification and/or microscopic particles* suspended in the commercial Ivory Liquid detergent. Since the backscatter levels exhibited by batches *A*, *B* and *C* are at least 15 dB below those normally used in our lab to simulate soft tissues (including backscatter level), further pursuit of the character of these particles in the Ivory Liquid has not been considered worthwhile. Batches *A* and *C* were the result of our first attempt to produce tissue-mimicking materials having speeds of sound of 1520 m/s at 22°C. This value for the speed of sound was recommended as representative of that of glandular tissue in the human breast (Greenleaf and Bahn, 1979).

Batches *D* and *E* both have had extra scatterers added in the form of the 30 μ hollow spheres discussed in the Materials section. These test cylinders were poured from batches of emulsions used in the production of an anthropomorphic breast phantom; i.e. sufficient (liquid) emulsion was made in any one batch so that part of it was poured into a breast phantom mold and part into the pair of test cylinders, gelation occurring subsequently in both cases. Batch *D* corresponds to the TM glandular material used in this phantom. This was produced using the blender method of emulsification and contains 34% olive oil and 66% gelatin matrix by volume. 0.11 mg/cm^3 of scatterers were added following the blending. Attenuation coefficients are shown in Fig. 5.

Batch *E* (TM fat) was emulsified by the alternative to the blender method, i.e. vigorous stirring with a spoon. It contains 25% olive oil, 25% kerosene and 50% gelatin matrix by volume. It also contains 0.065 mg/cm^3 of hollow scatterers. Attenuation coefficients are shown in Fig. 6.

A summary of the ultrasonic properties of the five batches at 22°C, including speed of sound, density, backscatter level and α_o and n, are given in Table 1. α_o and n were obtained by least squares fitting to the attenuation coefficient vs frequency curves assuming a relation of attenuation coefficient,

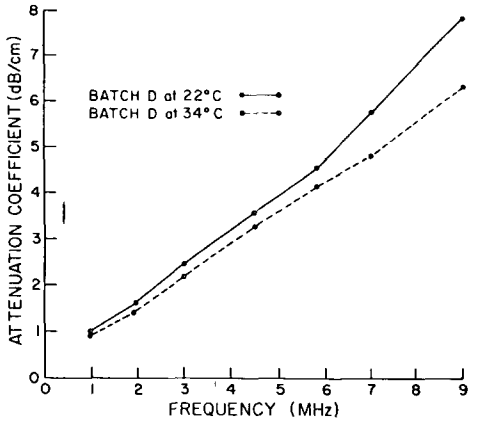

Fig. 5. Attenuation coefficients vs frequency at 22 and 34°C for batch *D* corresponding to a version of tissue-mimicking breast glandular material. This batch contains 34% olive oil, 3.0% *n*-propanol and 0.11 mg/cm^3 of hollow scatterers. The uncertainty in the measurements is about ±0.1 dB/cm.

α, to frequency, f, given by $\alpha = \alpha_o f^n$ where α_o and n are constants for each batch. Table 2 exhibits, for 34°C, the above information excluding density and backscatter level. The density, for each of the samples discussed, should decrease by about 1% as the temperature is raised from 22 to 34°C if thermal expansion properties for the various component materials are employed. Backscatter level was not measured at 34°C.

REPRODUCIBILITY

In the *Ultrasonic Properties* section various oil-in-gelatin dispersions were described, a major purpose of that section being to indicate the variety of compositions and ultrasonic properties which these TM materials can possess. In the present section

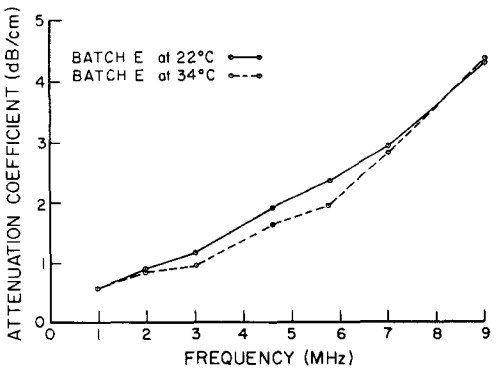

Fig. 6. Attenuation coefficients vs frequency at 22 and 34°C for batch *E* corresponding to tissue-mimicking fat. Batch *E* contains 25% olive oil, 25% kerosene, 2.2% *n*-propanol and 0.065 mg/cm^3 hollow scatterers. The uncertainty in the measurements is about ±0.1 dB/cm.

*These particles are composed of fatty acid esters having molecular weights of "a few hundred" (Griffith, 1981). The specific gravity of such a material probably lies between 0.94 and 1.01 (*Handbook of Chemistry and Physics*, 1958). It is not unreasonable to expect the speed of sound in this material to be in the range of common materials consisting of fatty acid esters; e.g. the speed of sound in olive oil at 22°C is 1440 m/s (Kaye and Laby, 1973).

the reproducibility of production of these materials, regarding their ultrasonic properties, is treated.

Experience with upwards of thirty batches, produced using either the spoon stirring technique or the blender technique, has shown that the speed of sound can be reproduced quite easily. The variation in speed of sound from that predicted depends primarily on the accuracy with which the volumes (or masses) of the component materials are measured. If the amount of each component material (e.g. olive oil) is measured to within about 3%, then the speed of sound for the batch will be within ± 3 m/s of the expected value.

For TM materials produced using both the spoon stirring and blender techniques in which no extra scatterers have been added, the backscatter levels are always at least 15 dB below those levels in TM materials used in our lab to simulate soft tissues (including backscatter simulation). Thus, the backscatter levels in oil-in-gelatin dispersions without extra scatterers are considered negligible.

Reproducibility of the attenuation coefficient using the spoon stirring technique is shown in Fig. 7. In this figure data are shown from attenuation coefficient measurements made at 22°C using pairs of test cylinders poured from three different batches of TM fat, each batch having been also used in the manufacture of a breast phantom. The time between production of successive batches was approx. 6 months. For each of the three batches, measurements of ultrasonic properties were made within 2 weeks after production. Using the same set of test cylinders produced from one of the original three batches, measurements of the speed of sound and of the attenuation coefficient at 2.5 MHz were repeated at 22°C 2 months after the first set of measurements; the latter measurements were to demonstrate temporal stability. The four sets of attenuation coefficients described are displayed in Fig. 7. A high degree of reproducibility is demonstrated. In addition, the repeated measurement of the attenuation coefficient at 2.5 MHz demonstrates temporal stability particularly since the difference between the earlier and later measurements is less than twice the estimated error (± 0.1 dB/cm).

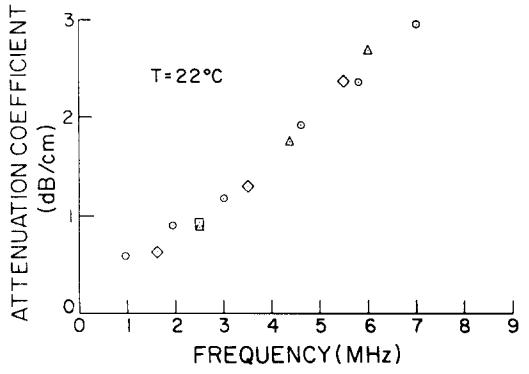

Fig. 7. Four sets of data points corresponding to three pairs of test cylinders, each pair taken from a different batch of TM fat made using the spoon stirring technique of emulsification. The time between production of successive batches was about 6 months, and for each batch a set of measurements was made within 2 weeks of the production of the batch. The set of data points (⊙) corresponds to one batch, and the set (◇) corresponds to a second batch. The remaining two sets of data points (△ and ⊡) resulted from measurements using the same pair of test cylinders corresponding to a third batch; those of the form △ resulted from measurements made within 2 weeks of the production of the batch, and the single data point (⊡) resulted from measurements made about 2 months later. The uncertainty for each point is about ± 0.1 dB/cm.

Regarding reproducibility of speeds of sound in the three batches of TM fat just described, were found to be 1458.5, 1462.5 and 1457.7 m/s at 22°C. The measurement of speed of sound after two months yielded 1458.3 m/s compared to the original value of 1457.7 m/s.

To insure reproducibility of ultrasonic properties in the case of the emulsion technique employing the blender, it is important that the blender speed be reproduced and that the temperature of the emulsion at the onset of emulsification be reproduced within approx. 2°C. Typically, an initial temperature of 40°C might be used. A careful study of reproducibility was done regarding the production of an oil-in-gelatin dispersion to be used as a low scatter phantom material otherwise simulating liver. The speed of sound desired was 1540 m/s ± 5 m/s at 22°C and the desired slope of the attenuation coefficient was 0.45 dB/cm/MHz ± 0.05 dB/cm/MHz at 22°C. This particular TM material has been developed for commercial use in quality assurance phantoms; it is considered better than the TM material of Batch *B* because it has a slightly lower attenuation coefficient slope (See Discussion section) and because it has fewer component materials, containing no castor oil. This emulsion contains 27% olive oil and 0.54% Ivory Liquid by volume. Two batches were made on different

days. In one batch the blending time was two minutes, and one pair of cylinders was made in the usual way by pouring the emulsion into the short and long test cylinders. In the other batch *two* pairs of test cylinders were made: starting with a portion of the batch, one pair was made after two minutes of blending, the remaining blended emulsion being discarded; starting with a second portion, the other pair was made after four minutes of blending. The speeds of sound in the order described were found to be 1539.3, 1540.0 and 1540.1 m/s at 22°C. Measurements of the attenuation coefficients at 22°C are shown in Fig. 8. Slightly larger attenuation coefficients resulted for the case in which the emulsion was subjected to four minutes of blending compared to the others.

Temporal stability of the TM material in the pair of cylinders was demonstrated in a remeasurement of the speed of sound and attenuation coefficients at 22°C. These measurements were done seven months after those described above. The speed of sound was found to be 1538.9 m/s compared to 1539.3 m/s obtained seven months before, and the attenuation coefficients were 0.90, 1.50 and 2.18 dB/cm at 2.0, 3.5 and 5.0 MHz, respectively. The attenuation coefficients for this pair of samples, plotted in Fig. 8 and measured seven months earlier were 0.84. 1.52 and 2.21 dB/cm at 1.6, 3.5 and 5.0 MHz, respectively. Considering uncertainties in the measurements, the attenuation coefficients and speed of sound have remained unchanged. An attempt was made to measure the mean backscatter level in the three samples of low scatter TM liver just described. The backscatter level was too low to be detected with our technique. This means that the backscatter was more than 75 dB below a perfect flat reflector.

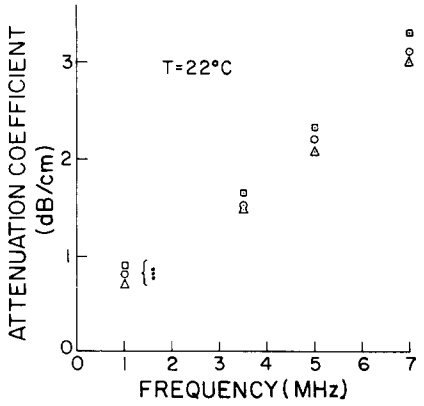

Fig. 8. Three sets of data points corresponding to low scatter TM liver made using the blender technique of emulsification. The set (⊙) was made from a batch produced on one day and the sets (△) and (⊡) were made from a batch produced on a different day; in particular, the set (△) was made from a portion of the batch subjected to 2 min of blending and the set (⊡) was made from another portion of the same batch subjected to 4 min of blending. The uncertainty in the measurements is about ±0.1 dB/cm.

DISCUSSION

We have developed methods for producing oil-in-gelatin dispersions considerably extending downward the ranges of speed of sound and density available in our materials. Following are some of the trends seen in the data:

(1) The greater the concentration of oil in the TM material, the larger the attenuation coefficient is and the lower the speed of sound is.

(2) The attenuation coefficients are nearly proportional to the frequency.

(3) The larger the concentration of *n*-propanol, the higher the speed of sound is.

(4) The backscatter level of the oil-in-gelatin dispersions is very low if extra scatterers are not added.

One important result is that fat can be mimicked ultrasonically. Wells has made a study of published values for the speed of sound in, and density of, mammalian fat (Wells, 1977). He finds the speed of sound to lie in the range 1460–1470 m/s and density to be about 0.92 g/cm^3. Goss *et al.* have tabulated published experimental results of measurements of ultrasonic properties of mammalian tissues (Goss *et al.*, 1978). Our analysis of these data (Dussik *et al.*, 1956; Colombati and Petralia, 1950; Chivers and Hill, 1975; Baboux *et al.*, 1975) shows the attenuation coefficient for fat to be approximately proportional to the frequency; this seems to be the case for most soft tissues. A representative value for the slope of the attenuation coefficient for fat is 0.4 dB/cm/MHz. The TM fat reported here, which is the material being used in our anthropomorphic phantoms, comes close to reproducing these ultrasonic properties as can be seen by referring to Table 1. The concentration of *n*-propanol is 4.5% in the gel matrix of the TM fat, the same as that in most of our TM materials; thus, diffusion of *n*-propanol across boundaries between TM fat and TM materials corresponding to other parenchymal tissues does not occur in anth-

ropomorphic phantoms. As a result, changes in speed of sound due to changes in *n*-propanol concentration do not occur.

Batch *B* was the result of one of our first attempts to produce an oil-in-gelatin dispersion displaying a speed of sound of 1540 m/s at 22°C and an attenuation coefficient slope in the range of that for liver. The resulting slope was 0.55 dB/cm/MHz in the range 2–5 MHz. Recent *in vivo* data (Kuc and Taylor, 1980) indicate that a slightly lower value of 0.45 dB/cm/MHz might be more appropriate for normal liver. A value in this range was attained as described in the section entitled *Reproducibility*. Such a material, without the addition of extra scatterers, would make excellent TM liver for use in quality assurance phantoms for estimating axial and lateral resolutions under conditions corresponding to the near absence of background scatter; thus, the upper limits on resolution of an ultrasonic imaging system could be determined. With addition of an appropriate concentration of scatterers, the material might mimic liver in backscatter level as well.

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