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● *Original Contribution*

LIQUID OR SOLID ULTRASONICALLY TISSUE-MIMICKING MATERIALS WITH VERY LOW SCATTER

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Abstract—A new tissue-mimicking material for ultrasound, using evaporated milk as the primary absorption component, is described. It has very low backscatter but still exhibits the 1540 m s^{-1} propagation speed and proportionality of attenuation coefficient and frequency over the diagnostic frequency range. The material can be produced in solid or liquid form with attenuation coefficient slopes spanning the range 0.1–0.7 dB cm^{-1} MHz^{-1}. The liquid form is useful in phantoms where detailed beam patterns are to be determined, either involving translation of measurement devices in the liquid or phantoms with fibers present for causing the only detectable echoes. In the latter case, the liquid quality allows removal of liquid with one attenuation coefficient slope and replacement with another. The solid form may be more useful than the liquid for two reasons. First, many simulated lesions (including ones that produce essentially no internal echoes) can lie in the scan slice with positions extending over the entire image area without enhancement or shadowing effects being of concern. Second, the lack of significant backscatter from the material in the absence of added scatterers allows the backscatter coefficient to be varied over a considerable range. A critical result is that intrinsic material contrast between targets and surroundings can be accurately predicted in terms of the concentrations of added scatterers and, assuming all scatterers are of the same type, the contrast will be completely independent of frequency. Use of the fungicide thimerosal eliminates deterioration, and ultrasonic properties have been shown to be stable over 2.5 years. © 1998 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Low scatter, Low echo, Tissue-mimicking, Ultrasound imaging, Phantoms.**

INTRODUCTION

Materials that mimic tissues with respect to diagnostic ultrasound should possess attenuation and speed of propagation characteristic of soft tissues. Soft tissues generally attenuate ultrasonic beams in such a way that the attenuation coefficient is nearly proportional to the frequency and the ultrasonic speed of propagation on average is about 1540 m s^{-1}. The recommended attenuation coefficient slopes for use in phantom materials range from 0.3–0.7 dB cm^{-1} MHz^{-1} (AIUM Technical Standards Committee 1990; American Institute of Ultrasound in Medicine 1992). The speed of propagation for performance and quality assurance testing of ultrasound imagers should be that assumed in the data analysis in essentially all ultrasound scanners, *viz,* 1540 m s^{-1} (AIUM Technical Standards Committee 1990). Liquid forms of tissue-mimicking (TM) material would be desirable for use in tanks for measuring beam properties allowing translation of immersed hydrophone receivers. (Such investigations are diagnostic safety studies avoiding unrealistically high nonlinear propagation effects occurring in water). Liquid forms also would be useful in phantoms allowing easy replacement of TM material with one having different ultrasonic properties, such as attenuation coefficient slope.

Whether liquid or solid, a very low backscatter level would be desirable to allow assessment of artifacts due to beam side-lobe effects. In the case of solid TM materials, very low scatter level of the base material would be desirable so that complete control of backscatter coefficient is facilitated through addition of appropriate scatterers.

Solid TM materials possessing the desired attenuation and propagation speed characteristics, except that the backscatter level is not insignificant, have been used in phantoms for many years. These materials consist of water-based rigid gels with uniformly suspended microscopic graphite particles, the latter providing absorption but, unfortunately, significant unavoidable scattering

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Table 1. Backscatter coefficients.

Tissue-mimicking (TM) material	Backscatter $A \times 10^5$ (sr^{-1} cm^{-1} MHz^{-m})	Backscatter m	Relative backscatter coefficient at 4 MHz (dB)
Low scatter graphite-containing TM material	0.0121 ± 0.0018	4.16 ± 0.10	-17.4 ± 0.4
Background TM material	1.68 ± 0.17	3.49 ± 0.07	0

Backscatter coefficients $\eta(f) = A f^m$, where f is the frequency of graphite-containing materials used in spherical lesion phantoms reported earlier (Rownd et al. 1997).

(Burlew et al. 1980; Madsen et al. 1978, 1991). The mechanism for absorption and scattering by such microscopic particles in ultrasound phantoms has been reported (Wu et al. 1992).

The necessarily solid spherical lesion type phantom described earlier (Rownd et al. 1997) ideally should provide a means for determining how well a scanner can show that a focal region is echo-free anywhere in the scan slice. Such a phantom contains a regular array of equivalent coplanar simulated spherical lesions so that the scan slice can be superimposed on them. Two conditions must be met for a spherical lesion phantom, automated system (Rownd et al. 1997) to be effective as a rapid method of performance and quality assurance (QA) testing. First, the intrinsic backscatter level of the spherical lesions must be very low, but ultrasonic pulses and echoes must be negligibly affected during passage through spherical lesions, *i.e.*, significant alteration with depth in background echo level due to cumulative shadowing or enhancement is not tolerable. Second, specular reflections at sphere surfaces must be negligible. These two conditions mean that, other than backscatter coefficient, the ultrasonic properties of spherical targets and background should be the same. Thus, some form of absorbing material must be present in the spherical lesions even though detectable echogenicity may be undesirable.

Therefore, a rigid material that mimics soft tissue in terms of attenuation, propagation speed and mass density, but which has a much lower backscatter coefficient than is the case of the material containing finely powdered graphite for absorption, is needed for use in spherical lesion phantoms. A corresponding very low scatter liquid material would be useful in phantoms with resolution structures, such as fibers that do not require support from the low scatter medium. An advantage of the liquid form is that it can be removed and replaced with another liquid having different absorption properties, *e.g.*, 0.7 dB cm^{-1} MHz^{-1} instead of 0.5 dB cm^{-1} MHz^{-1}.

Particulate material commonly used in phantoms for absorption is powdered graphite with particle diameters < 22 μm (product no. 9039, Superior Graphite Company, Chicago, IL, USA). This form of powdered graphite exhibits the lowest backscatter coefficient for a given concentration of any particulate material we have been able to find, excluding the materials reported in the present work; however, the backscatter level of this material is not low enough to be considered negligible. The backscatter coefficient over the frequency range 3–5 MHz is given in Table 1 for TM material in the lowest scatter spherical simulated lesions contained in spherical lesion detectability phantoms for ultrasound (Rownd et al. 1997). The attenuation coefficient slope in these phantoms is nearly 0.5 dB cm^{-1} MHz^{-1} throughout, the (background) material surrounding the spheres having a backscatter coefficient about 3 dB higher than that recommended for performance testing in the AIUM Performance Standard. At 4 MHz, the lowest scatter lesions exhibit a backscatter coefficient of -17.4 dB relative to the background (Table 1). Thus, the backscatter level of the lowest scatter TM material is about 14 dB below that recommended for background scatter in ultrasound performance testing phantoms. Notice that the frequency dependencies for the low scatter material and the background material *via* the power m are considerably different and that the backscatter of the low scatter material relative to the background material at 4 MHz is limited to -17.4 dB.

A new TM material that has extremely low backscatter is reported here, and the desirable TM values for propagation speed, density and attenuation coefficient can still be represented. The material can be produced in a liquid or solid form (US patent no. 5,625,137 applies to these materials). The liquid form is useful when it is important to move measurement instruments within the medium, such as in obtaining beam profiles in TM material and/or when removal and replacement of TM material in a container is desirable. The solid form allows essentially total control of echogenicity through choice of scatterer concentration. The solid material also allows inclusion of simulated lesions with no significant backscatter, other ultrasonic properties being the same as in the surroundings. Another illustration of the advantage of the solid material would be use in a phantom containing simulated lesions exhibiting, *e.g.*, -9 dB contrast. Glass

Table 2. Attenuation coefficients propagation speeds and densities of whole milk, evaporated milk and samples of liquid and solid TM materials at 22°c.

Material	Density (g)	Speed (m s^{-1})	Attenuation coefficient (dB cm^{-1})			
			2.50 MHz	4.50 MHz	6.20 MHz	8.00 MHz
Whole milk	1.03	1518	0.90	1.58	2.16	2.79
Evaporated milk	1.055	1547	2.30	3.70	4.89	6.29
Liquid TM material at	(1.03)	(1536)	(1.33)	(2.39)	(3.22)	(4.02)
$\sim$ 0.5 dB cm^{-1} MHz^{-1}	(1.03)	1536	1.31	2.49	3.18	4.11
Change over 30 months		0 m s^{-1}	−1.5%	+4.1%	−1.2%	+2.2%
Solid TM material at	[1.03]	[1542]	[1.19]	[2.20]	[3.13]	[3.87]
$\sim$ .5 dB cm^{-1} MHz^{-1} and 0 g ℓ$^{-1}$ beads	[1.03]	1545	1.16	2.28	3.10	4.01
Change over 31 months		+3 m s^{-1}	−2.5%	+3.6%	−1.0%	+3.6%
Solid TM material at	[1.03]	[1543]	[1.23]	[2.29]	[3.25]	[4.00]
$\sim$ .5 dB cm^{-1} MHz^{-1} and 1 g ℓ$^{-1}$ beads	[1.03]	1545	1.18	2.32	3.18	4.11
Change over 31 months		+2 m s^{-1}	−4.1%	+1.3%	−2.2%	+2.7%
Solid TM material at	[1.03]	[1542]	[1.29]	[2.40]	[3.38]	[4.11]
$\sim$ .5 dB cm^{-1} MHz^{-1} and 2 g ℓ$^{-1}$ beads	[1.03]	1544	1.26	2.49	3.36	4.21
Change over 31 months		+2 m s^{-1}	−2.4%	+3.7%	−0.6%	+2.4%
Solid TM material at	[1.03]	[1543]	[1.31]	[2.47]	[3.59]	[4.46]
$\sim$ .5 dB cm^{-1} MHz^{-1} and 8 g ℓ$^{-1}$ beads	[1.03]	1544	1.29	2.59	3.54	4.76
Change over 31 months		+1 m s^{-1}	−1.5%	+4.7%	−1.4%	+6.5%

Long-term stability of the TM materials is demonstrated, *i.e.,* values in parentheses were measured in August 1994, those in brackets were measured in July 1994, and all other values were measured in February 1997. The uncertainties are as follows. Density = ±0.005 g mL; propagation speed = ± 1 m s^{-1}; attenuation coefficients (any frequency) = ± 0.1 dB cm^{-1}. (Note that uncertainties include instrumental errors that may be unidirectional, *i.e.,* the true value of all attenuation coefficients may be higher by 0.1 dB cm^{-1} than the measured values. Thus, differences may be more accurate than implied by equally likely positive and negative errors.)

bead scatterers can be present in the surroundings at a concentration yielding the recommended backscatter coefficient (AIUM Technical Standards Committee 1990) and in the lesions at a concentration of one eighth of that. Because there is no scattering component other than the glass beads, the backscatter coefficients would differ by 9.0 dB at all frequencies.

MATERIALS

It has been reported that bovine milk exhibits a proportionality between attenuation coefficient and frequency over a broad range of frequencies from 1–40 MHz. The slope, however, was 0.4 dB cm^{-1} MHz^{-1} (Schwan 1969), which is not quite large enough for general use in phantoms. We also measured the ultrasonic properties of homogenized whole milk and, at 22°C, found a propagation speed of 1518 m s^{-1} and an attenuation coefficient slope of 0.35 dB cm^{-1} MHz^{-1}. Measurements of the latter at discrete frequencies are included in Table 2. Thus, whole milk might be useful but only as a liquid for mimicking low attenuation soft tissue.

We investigated evaporated milk, as available in grocery stores, and found an attenuation coefficient slope of about 0.8 dB cm^{-1} MHz^{-1}, a propagation speed of 1547 m s^{-1} and a density of 1.055 g cm^{-3} (Table 2). Thus, the attenuation coefficient slope exceeds the range recommended for performance and QA phantoms.

Dilution of evaporated milk with water allows selection of any lower attenuation coefficient slope in the 0.3–0.7 dB cm^{-1} MHz^{-1} range and also lowers the propagation speed. Thus, we have concentrated our study on evaporated milk as the fundamental component material.

For materials with attenuation coefficient slopes in the 0.3–0.7 dB cm^{-1} MHz^{-1} range, the speed of propagation is 1540 m s^{-1} or lower; adjustment upward to reach 1540 m s^{-1} can be done by adding small concentrations of n-propanol.

A major concern is prevention of bacterial invasion. A highly soluble and effective agent to assure long-term stability is thimerosal (product no. T8784, Sigma Chemical Company, St. Louis, MO, USA) at a concentration of 1.0 g ℓ$^{-1}$. We have found stability extending for years for both liquid and solid forms of TM material.

The liquid very low scatter material reported is a mixture of evaporated milk, distilled water, n-propanol and thimerosal. The solid form is made with the same materials except that there is an agarose component added to produce rigidity. The solid form has the advantage that objects can be fixed in position within it, *e.g.*, glass bead scatterers or simulated tumors.

Thimerosal hazard

Thimerosal is a skin irritant and care should be taken to avoid contact of liquid TM material with the skin during or after manufacture. If accidental skin exposure occurs, wash thoroughly immediately. Note, however, that the concentration of thimerosal used in the TM materials is the same as that used in a cutaneous antiseptic solution available for decades under the name Merthiolate®.

METHOD OF PRODUCTION OF THE LIQUID FORM

It was found that evaporated milk contains a low concentration of solid particles, many of which are visible to the naked eye when they are separated from the liquid. These particles give rise to unwanted isolated scatter sites in TM materials; thus, the evaporated milk is filtered through no. 540 Whatman filter paper (Whatman International Ltd., Maidstone, UK) using a simple water flow lab Bernoulli vacuum filter. Insoluble particulate impurities also can exist in the thimerosal used; therefore, the appropriate amount of thimerosal is added to the evaporated milk before filtering.

Because the evaporated milk is too viscous for sufficiently rapid transmission through the filter, it is heated to 68°C to reduce viscosity before filtration. Care must be taken not to exceed 72°C, however, because a solid casein-containing ''skin'' material will be irreversibly produced. About 20 min is required to filter 1 L of evaporated milk plus thimerosal using our laboratory method.[1,2]

Once the filtered evaporated milk plus thimerosal is available, the production of the liquid TM material involves adding distilled water and n-propanol in appropriate amounts. So far, interest of ultrasound equipment manufacturers in very low scatter liquid TM material has been limited to that with an attenuation coefficient slope of 0.5 dB cm^{-1} MHz^{-1} and propagation speed of 1540 m s^{-1} at 22°C (room temperature). Thus, a step-by-step recipe for production of 1 L of such material is given as follows.

(1) Dissolve 1.33 g of thimerosal into 800 mL of evaporated milk in a 1-L beaker.
(2) Raise the temperature of the mixture to 68°C in a double boiler, stirring sufficiently to prevent the temperature of any part of the mixture from reaching 72°C.
(3) Filter the mixture through the vacuum filter apparatus after wetting the filter paper with distilled water to ensure that the paper is in place and none of the mixture escapes filtration. The filter paper may need changing; our experience is that the paper must be changed for every 100 mL of mixture filtered.
(4) Mix together 370 mL distilled water and 30 mL of n-propanol in a 1-L beaker.
(5) Add 600 mL of filtrate and mix.
(6) Degas by warming in a double boiler to 40°C and cooling to about 30°C before sealing into a phantom container (or using in an open tank).

METHOD OF PRODUCTION OF THE SOLID FORM

The main difference in production method from that used for the liquid form is that a high purity agarose is used to produce a gelled ''solid.'' Because the backscatter level of the resulting material is very low, impurities in agar ordinarily used (Difco-Bacto agar, Difco Laboratories, Detroit, MI, USA) in graphite-containing ultrasound TM materials were found to give rise to relatively high (although spatially isolated) echoes.

The following is the step-by-step procedure for producing 1 L of the solid, very low scatter TM material with an attenuation coefficient slope of 0.5 dB cm^{-1} MHz^{-1} and propagation speed of 1540 m s^{-1}.

(1) Mix together 644 mL distilled water and 56 mL of n-propanol at room temperature in a 1-L beaker.
(2) Rapidly mix in 28 g of dry high-purity agarose.[3]
(3) Cover the beaker with a polymer food wrap such as Saran Wrap® and warm in a double boiler to 90°C until the mixture is transparent. (A puncture in the polymer food wrap will ensure no undesirable pressure difference while still suppressing evaporation of the beaker contents.)
(4) Produce 500 mL of filtered evaporated milk containing 1 g of thimerosal following steps 1, 2 and 3 in the previous section on producing the liquid TM material.
(5) Warm the 500 mL of filtered evaporated milk and thimerosal to 55°C in a double boiler.
(6) Cool the molten agarose solution to 55°C by immersing the lower part of the beaker in a large

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[1] It should be noted that such demanding filtration is only necessary when large volumes of TM material must be made where there are no impurities. An example of a situation where less demanding filtration would be warranted is the production of spherical lesion phantoms (Rownd et al. 1997); glass bead scatterers will generally mask the effect of impurities, high level filtration being needed only for production of small volumes of very low scatter lesions.

[2] See the last paragraph of the Discussion section for description of a more rapid (and apparently equivalent) method of filtration developed recently.

[3] In our material, Type 1-A, low EEO, 0.09–0.13 agarose is used. See product number A0169, Sigma Chemical Company, St. Louis, MO, USA.

container of cold water, stirring the agarose to ensure that no part of it is cooled below the (37°C) congealing point.

(7) Combine the 500 mL of 55°C evaporated milk plus thimerosal with 500 mL of 55°C molten agarose and mix well.

(8) If soft tissue-like scatter is desired, scatterers such as 4 g ℓ^{-1} of 45 to 53-μm diameter glass beads warmed to 60°C should now be stirred in.

(9) After cooling to about 45°C, the liquid can be poured into any container and allowed to cool. Gelling occurs at 36° ± 1°C.

The melting point of the resulting solid gel is above 80°C.

ULTRASONIC PROPERTIES

All measurements were made at 22°C. Measurement of ultrasonic speeds of propagation and attenuation coefficients were done using through-transmission techniques described previously (Madsen et al. 1982). Each type of material is prepared in a cylindrical vessel that is 7.6 cm in diameter and either 2.5 or 5 cm thick; the parallel transmission windows consist of 25-μm thick Saran Wrap 18 (a copolymer of vinylidene chloride and vinyl chloride produced by Dow Chemical Co., Midland, MI, USA). Measurement of amplitudes and time shifts of tone bursts, with displacement of water by the sample, allows computation of attenuation coefficient and propagation speed of the material relative to water. Backscatter coefficients also were measured using a broadband method described previously (Chen et al. 1993). For each material, software-gated temporal backscatter signals from 5-cm thick samples were digitized along with the echo from a planar reference reflector; data reduction allows elimination of instrumental effects yielding the backscatter coefficient intrinsic to the material. Measurement of the density of the liquid TM material was done by hydrometer and of the solid TM material by displacement of water; details have been described previously (Yang et al. 1991).

Results of these measurements for various versions of the materials are given in Table 2. Except for the pure whole milk and pure evaporated milk, all materials are intended to exhibit a propagation speed of 1540 m s^{-1} and attenuation coefficient slope of 0.5 dB cm^{-1} MHz^{-1}. The four solid TM materials differ only in the concentration of 45- to 53-μm diameter glass beads (Potters Industries, Parsippany, NJ, USA). Note the description of uncertainties in the legend to Table 2. Glass bead concentrations in the four solid TM materials are given in Table 3.

Table 3. Identification number of each of the four types of solid tissue-mimicking material produced and the concentration of glass bead scatterers in each.

Identity no. of tissue-mimicking material	1	2	3	4
g ℓ^{-1} of 45- to 53-μm diameter beads	0	1.0	2.0	8.0

The results in Table 2 include a long-term stability study of the liquid and solid TM materials for propagation speed and attenuation. The earlier measurements (values in parentheses and brackets) were made about 2.5 y before the second set (no parentheses or brackets). Between measurements, all samples were kept in a sealed container with a 3% n-propanol aqueous solution at the bottom to prevent desiccation.

Backscatter coefficients for the liquid and solid TM materials are shown in Table 4, where curve-fitting constants *A* and *n* are given. Relative backscatter values at 4 MHz are given in the column on the right.

Some ultrasonic properties of a few related materials at 22°C, in which evaporated milk or powdered graphite was replaced with distilled water, may be of interest. The following sample test cylinders were made: one (sample A) with the same relative proportions of water, n-propanol, and dry weight Difco-Bacto agar as used in the phantoms in which powdered graphite provides the absorption (Rownd et al. 1991) and the other (sample B) with same agarose, n-propanol and thimerosal concentrations as in the solid very low scatter materials reported in the present work. The speed of propagation for sample A was 1542 ± 1 m s^{-1} and was 1514 ± 1 m s^{-1} for sample B. Backscatter coefficients in these samples are comparable, based on side-by-side comparison images using an Acuson scanner, the difference being that isolated reflectors were present in sample A and nearly absent in sample B. The very low contribution to backscatter by the agarose is evident from the nearly equal values of backscatter coefficients for the liquid vs. solid material in Table 4. Attenuation coefficient values for the two samples are shown in Table 5. They are very low and about the same for both samples.

It has been found that the slope of the attenuation coefficients for evaporated milk directly out of the can differ from one batch of cans to another. All of the approximately 10 samples we tested had attenuation coefficients within 1% of those given in Table 2. Two cans, obtained a few months later, had attenuation coefficients 8% lower than the sample characterized in Table 2. The latter material was used to produce samples C and E for which attenuation coefficients are shown in Table 6. Samples D and F in Table 6 were produced with the higher attenuation evaporated milk. Samples B, C and D are solids and samples E and F are liquids (see the legend of Table 6 for composition details).

It is reasonable to assume that the total attenuation

Table 4. Fitted backscatter coefficients using the broadband method of Chen et al. (1993) for the liquid and solid TM materials addressed in Tables 1 and 2.

	Backscatter coefficient parameters			
Material	A ($\text{sr}^{-1}\ \text{cm}^{-1}\ \text{MHz}^{-n}$)	n	Backscatter coefficient at 4.0 MHz ($\text{sr}^{-1}\ \text{cm}^{-1}$)	Backscatter coefficient relative to solid TM material 4 (dB)
Liquid TM material at 0.5 dB cm^{-1} MHz^{-1}	$(1.26 \pm 0.13) \times 10^{-8}$	2.37 ± .06	$(3.37 \pm 0.34) \times 10^{-7}$	−38.4 ± 0.5
Solid TM material 1	$(1.74 \pm 0.18) \times 10^{-8}$	2.36 ± .07	$(4.59 \pm 0.50) \times 10^{-7}$	−37.1 ± 0.5
Solid TM material 2	$(1.27 \pm 0.07) \times 10^{-6}$	3.90 ± .03	$(2.83 \pm 0.14) \times 10^{-4}$	−9.2 ± 0.3*
Solid TM material 3	$(2.80 \pm 0.14) \times 10^{-6}$	3.82 ± 0.4	$(5.60 \pm 0.28) \times 10^{-4}$	−6.2 ± 0.3[†]
Solid TM material 4	$(1.13 \pm 0.06) \times 10^{-5}$	3.85 ± .03	$(2.34 \pm 0.12) \times 10^{-3}$	0

Measurements were made in February 1997. The fitting constants A and n are shown corresponding to the assumed relation $\eta(f) = A\ f^n$, where $\eta(f)$ is the backscatter coefficient at frequency f. The frequency range over which the fitting is applicable is 3.0–5.0 MHz. Also shown are backscatter coefficients at 4.0 MHz and relative backscatter coefficients at 4.0 MHz. Materials were at 22°C.

* Expected value based on relative scatterer concentration of −9.0 dB; [†]expected value based on relative scatterer concentration of −6.0 dB.

coefficient at any frequency is the sum of that due to the agarose and that due to the evaporated milk and that the latter is proportional to the concentration of evaporated milk in a sample. Evidence supporting this assumption is given in Table 6 where, *e.g.*, sample B has an attenuation coefficient of 0.3 (dB cm^{-1}) at 4.50 MHz, sample C, 1.0 dB cm^{-1} and sample D, 2.2 dB cm^{-1}. The volume % of evaporated milk in sample C is 20%, and that in sample D is 50%; thus, the ratio of concentrations is $50/20 = 2.5$. Applying the above conjecture, $(2.20 - 0.3)/(1.0 - 0.3) \cong 2.7$, and the evaporated milk concentration ratio, adjusted for the differing attenuations for pure evaporated milk, is $2.5/0.92 \cong 2.7$. The two 2.7 values support the additive conjecture.

The same test can be applied for the liquid samples E and F. In that case, there is no agarose contribution. In this case, the concentration ratio is $60\%/(20\% \times 0.92) \cong 3.3$, and at 4.50 MHz, the ratio of attenuation coefficients is $(2.4/0.7) \cong 3.4$, again supporting the additive conjecture.

Variation of the frequency dependence of the attenuation coefficient with evaporated milk concentration can be assessed in a limited fashion after curve fitting of the values for each sample in Table 6, assuming the usual power law, *viz*, attenuation coefficient $\propto (\text{frequency})^n$. For samples B, C, D, E and F, respectively, n has the values 1.5 ± 0.1, 1.03 ± 0.03, 1.03 ± 0.01, 0.95 ± 0.04, and 0.95 ± 0.01. Thus, the value of n does not appear to be significantly dependent on evaporated milk concentration for either the liquid- or solid-type material. The 1.5 power for the agarose alone (sample B) does not affect the power for solid-type samples containing evaporated milk for concentrations of evaporated milk of 20% and above (samples C and D), presumably because of the small attenuation values for sample B.

DISCUSSION

All of the TM materials addressed in Table 2 exhibit an attenuation coefficient slope of nearly 0.5 dB cm^{-1} MHz^{-1} through at least 8.0 MHz. This is demonstrated in Fig. 1, where attenuation coefficients from Table 2 for the liquid and solid material 1 are plotted as a function of frequency. Notice also that the ultrasonic propagation speeds for the TM materials are all nearly equal to 1540 m s^{-1}.

Long-term stability of the liquid TM material and four versions of solid TM material is shown in Table 2, where changes of speed and attenuation coefficients over the 2.5-y period are displayed for each TM material. Propagation speeds increased by 3 m s^{-1} or less, the average being +1.6 m s^{-1}. Percent changes in attenuation coefficients also are shown for the four frequencies at which measurements were made. Changes shown are only a few percent, with all shifts being negative at 2.5 and 6.2 MHz and positive at 4.5 and 8.0 MHz. Thus, changes in attenuation coefficients over the 2.5-y period appear to be due predominantly to instrumental error. The root mean square percent change for the 20 values corresponding to the four frequencies and five samples is 3.0%.

Table 5. Attenuation coefficients at 22°C for sample A, containing Difco-Bacto agar, and sample B, containing the high-purity agarose used in the solid form of the material reported in this study.

	Attenuation coefficient (dB cm^{-1})	
Frequency (MHz)	Sample A	Sample B
2.50	0.1 ± 0.1	0.1 ± 0.1
4.50	0.3 ± 0.1	0.3 ± 0.1
6.20	0.5 ± 0.1	0.4 ± 0.1
8.00	0.7 ± 0.1	0.6 ± 0.1

Table 6. Attenuation coefficients at 22°C for solid and liquid samples differing in volume fraction of evaporated milk.

	Attenuation coefficient (dB cm^{-1})				
Frequency (MHz)	Sample B	Sample C	Sample D	Sample E	Sample F
2.50	0.1 ± 0.1	0.53 ± 0.1	1.19 ± 0.1	0.39 ± 0.1	1.33 ± 0.1
4.50	0.3 ± 0.1	0.96 ± 0.1	2.20 ± 0.1	0.73 ± 0.1	2.39 ± 0.1
6.20	0.4 ± 0.1	1.33 ± 0.1	3.13 ± 0.1	0.95 ± 0.1	3.22 ± 0.1
8.00	0.6 ± 0.1	1.77 ± 0.1	3.87 ± 0.1	1.18 ± 0.1	4.02 ± 0.1

Sample B is the same sample B as in Table 5, *viz,* the solid material with evaporated milk replaced with distilled water. Sample C is the same as sample B except that it contains 20% evaporated milk instead of 0%. Sample D is the same as sample A except that it contains 50% evaporated milk instead of 0%. Sample E is a liquid TM material with 20% evaporated milk. Sample F is the liquid TM material with 60% evaporated milk. Note that the pure evaporated milk used to make samples C and E had attenuation coefficient(s) that were 92% of those for the evaporated milk used to make samples D and F.

The very low scatter levels of the TM liquid material and TM solid material containing no glass bead scatterers (1) is shown in Table 4. Solid material 4 has a backscatter level that is at the upper end of the range recommended for performance and QA phantoms in the AIUM Performance Standard. At 4 MHz, the backscatter coefficient of the liquid TM material is 38.4 dB below that of 4, and the solid very low scatter TM material is 37.1 dB below that of 4. The backscatter level in these two samples is so low that spurious noise in our measurement apparatus may be a significant contributor, which might explain the somewhat low values of *n* in their curve fits. Because the backscatter level in the absence of glass bead scatterers is so low, the frequency dependencies (values of *n* in Table 4) of backscatter coefficients of samples 2, 3 and 4 in Table 4 are essentially the same, and the relative backscatter levels (right column) are those predicted using relative glass bead concentrations.

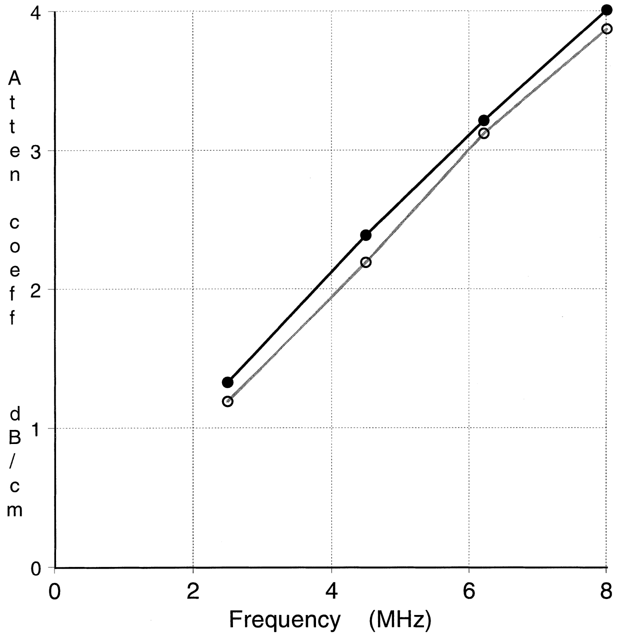

Fig. 1. Graph of attenuation coefficients vs. frequency for the sample of liquid very low scatter material (solid circles) and the sample of solid material 1 (open circles) showing approximate proportionality of attenuation coefficients to frequency. Plotted values are shown in Table 2. The uncertainty of each value is ±0.1 dB cm^{-1}.

Predictability and frequency independence of relative backscatter levels are demonstrated by comparing values in Table 4 for solid samples 2, 3 and 4. Recall from Table 3 that the glass bead concentrations in these samples are 1.0, 2.0 and 8.0 g ℓ^{-1}, respectively. These concentrations yield predicted backscatter coefficients of samples 2 and 3, relative to that of 4, of −9.0 and −6.0 dB, respectively, assuming backscatter coefficient is proportional to bead concentration. The measured values are −9.2 ± 0.3 and −6.2 ± 0.3 dB, corroborating the predictions. Note also that the frequency dependencies of backscatter in terms of the *n* values are nearly the same for the three samples. In fact, differences in *n* values are likely measurement error because the glass beads for all three samples came from the same well-mixed supply.

It is important to note that we have recently begun filtering the evaporated milk in a more rapid fashion than that given in steps 2 and 3 in the section on Method of Production of the Liquid Form, with apparently equivalent results for the final liquid or solid forms of the TM material. The evaporated milk with the thimerosal dissolved in it is filtered in two steps using the vacuum system and plastic mesh fabric-type filters instead of the Whatman paper filters. These cloth-like filters are stretched across and glued to an acrylic ring (about 7 cm in diameter) prior to their use. The sieve opening in the coarser filter is 17 μm and 7 μm in the fine version (the coarse version is Pecap® polyester HD 7-17/12 and the finer version is Pecap® polyester 7-10/2, Tetko, Inc., Kansas City, MO, USA). The milk is filtered at room temperature, first through the coarse filter and then through the finer one. A half liter of evaporated milk can be passed through the coarse filter in about 1 min and through the finer filter in about 5 min. A second filtration through the 7 μm filter is done about 16 to 24 hours later, immediately before production of TM material.

SUMMARY AND CONCLUSIONS

The liquid and solid TM materials reported are very low scatter compared to other TM materials, being about $37 - 17 = 20$ dB lower than ‘‘low scatter’’ TM materials previously used in our laboratory. The solid materials will allow adequate representation of echo-free lesions in phantoms while maintaining uniform ultrasonic properties other than backscatter. The solid materials also provide for frequency-independent predictable relative backscatter levels as a result of their intrinsic very low scatter level.

The liquid TM material allows beam studies in TM media with immersed detectors. Because of its very low backscatter level, the liquid material also can be used in phantoms with nylon or stainless steel fibers providing the only detectable echoes; this allows study of low level side-lobe effects. Also, in a given phantom, the liquid material can be easily changed to a different liquid TM material having a different attenuation coefficient slope.

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