ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 88 (2002) 59–64

Tissue Mimicking Materials for Thin Film Phantom

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Summary
A systematic approach is proposed for developing tissue mimicking materials. Speed of sound and the attenuation coefficient slope are combined in a so-called c-α chart. The procedure described was used to produce the tissue mimicking materials with a speed of sound of 1540±6 m/s and the attenuation slopes of 0.3 dB/cm.MHz and 0.45 dB/cm.MHz with very low scatter as required for Thin Film Phantom. The tissue mimicking materials were applied to a TFP (Thin Film Phantom) system to get images of a character set made of digital scatterers deposited on a plastic substrate.

PACS no. 43.80.Jz, 43.80.Ev, 43.35.Bf

1. Introduction

Tissue mimicking (TM) materials are widely used in assessing the performance of ultrasound diagnostic systems. Although the ultrasonic properties of different tissues show significant variations, it is possible to select appropriate standard TM properties, depending on the applications [1]. Sound speed, attenuation and backscattering coefficients are the three key properties of a TM material, although other parameters, such as nonlinerity parameter B/A [2], may be specified. It is not a simple matter, however, to find a single substance with the appropriate ultrasonic properties. Some excellent commercial-grade TM materials being used today contain several components combined through multiple-step processes [3, 4, 5]. It was our goal to determine a simple and systematic way of finding very low backscatter TM materias, suitable for use with Thin Film Phantom (TFP) [6, 7, 8], made of inexpensive and readily available substances.

The basic idea starts with the 'c-α chart', a two dimensional graph of speed and attenuation coefficient slope, to visualize the trends both in the speed of sound and the attenuation slope. We can start with a given substance and add diluting fluid, preferably water, to produce TM materials which fall into the appropriate range of speed and attenuation slope with some error margin. The simplest case would be a perfect mixture where the simple mixture laws are valid [2, 9, 10]. The speed of sound and the attenuation coefficient slope of the resulting material can be expressed as a combination of those properties of the ingredients. The c-α chart facilitates the understanding of the trends and the possibility of whether or not the procedure would lead to a TM material with the desired properties.

This approach was applied to produce TM materials for use in Thin Film Phantom (TFP) system [6]. The phantom is composed of a thin planar substrate acoustically matched to surrounding media, and a character set formed from precisely located scatterers on the substrate. Several observers tested the phantom and found it to be easy to use. Also high recognition rate of character set verified the usefulness of the phantom.

Received 8 January 2001,
accepted 16 December 2001.

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2. Basic Theory

2.1. Mixture laws of a perfect mixture

When two or more substances are mixed together, we can describe mathematically the acoustic properties of the resulting material if the substances are such that they follow the perfect mixture model [2, 9, 10]. Also, for the sake of simplicity, let us assume initially that the attenuation coefficient slope of each component does not vary with frequency. Let the x_i, α_i, ρ_i and c_i denote the volume fraction, attenuation coefficient slope, density and sound speed of the i-th components respectively. Since the perfect mixture model assumes the components form a homogeneous mixture and the total volume is the sum of the volumes of the components, x_i will be such that

$$\sum_i x_i = 1. \tag{1}$$

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the water-sample interface perpendicular to the ultrasonic beam, the holder was mounted on an optical jig and care was taken to ensure that the Saran Wrap interface was perpendicular to the beam. All the measurements were done at the temperature of 21±2 °C. The errors in measuring the speed of sound and the attenuation slope, mainly from the error in thickness and density of the sample, were estimated from reproducibility measurement to be ±2 m/s and ±0.15 dB/cm respectively.

Among many candidate materials tried, Bovine Serum Albumin (BSA) and transparent glycerin soap were chosen for making tissue mimicking materials. Both materials were found to be lying inside or close to the 'target zone'. Also they were very low backscattering as desired in TFP application where precisely controlled digital scatterers are scanned.

3.2. Results and discussion

Experimental data on the 30% BSA solution (Sigma-Aldrich A1662) and on the transparent glycerin soap (Soapberry Lane, Syracuse, NY) are summarized in Figure 4. As described above, data are displayed in the c-α chart as a bar from $(c, \alpha_{\min})$ to $(c, \alpha_{\max})$.

BSA 30% solution (b1) showed c=1612 m/s and the attenuation coefficient slope ranges from 0.52 to 0.61 dB/cm.MHz in the frequency range of 3-8MHz. By diluting the BSA 30% solution with water to 55% BSA(30%) +45% water by weight (b2), the sound speed dropped to 1545 m/s and an attenuation slope range of 0.27-0.32 dB/cm.MHz was obtained for 3–8 MHz. The solution was transparent with a light yellow color and was stable in an airtight container kept at constant room temperature for more than 3 months. The solution was devoid of scatterers and showed backscattering lower than the measurable limit with the equipment used.

To make another formulation, both the glycerin soap and degassed water were put in a beaker and heated in a microwave oven to 50 °C until the soap was melted. It was then gently stirred to get a clear mixture with no air bubbles captured inside. The solution was put in an airtight container and cooled to 4 °C. As Figure 4 shows, the speed of sound was 1621 m/s and the attenuation slope range was 1.23–1.68 dB/cm.MHz at 50% of dilution (s1), 1577 m/s and 1.20–1.38 dB/cm.MHz at 70% (s2), 1546 m/s and 0.56–0.69 dB/cm.MHz at 80% of dilution (s3) with water respectively. To produce TM material with lower attenuation, gelatin (Gelatin Powder 2124-01, J.T. Baker Inc. Phillipsburg, NJ) was used for speed adjustment. A mixture of 82.2% water +16.8% soap +1.0% gelatin (s4) showed c=1542 m/s and attenuation slope range of 0.40–0.51 dB/cm.MHz. Another mixture of 82.35% water +15.69% soap +1.96% gelatin (s5) showed c=1538 m/s and attenuation slope range of 0.26–0.34 dB/cm.MHz. Backscatter levels of batches s4 and s5 were at least 12dB lower than the reference liver phantom used in our lab. All glycerin soap used was from the same manufacturer's lot and showed consistent reproducibility.

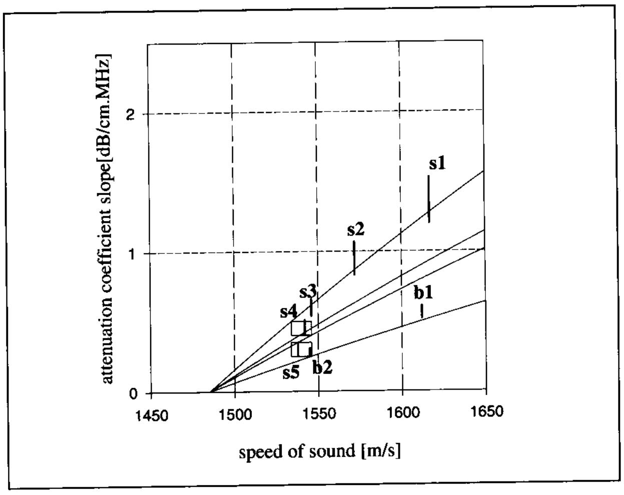

Figure 4. A c-α chart that shows the procedure of producing TM materials and their properties. Each bar denotes speed of sound and the range of attenuation slope in the 3-8MHz frequency range, where each data means s1:glycerin soap 50% + water 50%, s2:glycerin soap 30% + water 70%, s3:glycerin soap 20% + water 80%, s4:glycerin soap 16.8% + water 82.2% +gelatin 1%, s5:glycerin soap 15.69% + water 82.35% +gelatin 1.96%, b1:BSA 30% solution, and b2: (BSA 30% solution) 55% +water 45%, respectively. (all compositions are by weight).

Enough soap was held in stock for all experiments. When the soap from another lot was tried it was found that the acoustic characteristics of the resultant TM materials vary only a few percent, and TM material with desired range of speed of sound and attenuation slope could be made with slight modifications of component ratio. Also each of the TM batches produced were kept at constant temperature of 21±2° C for measurements over a prolonged time and all the materials showed properties varying within 5% after three months of time. It can be seen in Figure 4 that these mixtures fall along a curve predicted by equation (11). Figure 5 shows experimental results of attenuation of TM batch of b2 and s4. TM batch of b2 (α ≈0.3 dB/cm.MHz) and s4 (α ≈0.45 dB/cm.MHz) were selected for TFP applications.

We evaluated the TM materials in a novel Thin Film Phantom. The TFP used was composed of a container, a substrate film, background tissue mimicking material, film holder, and a cover. The thin film was made by depositing scatterers of copper onto a plastic substrate in a white noise half toning scheme. The substrate was chosen to be closely matched acoustically to the background material. A set of characters was incorporated on the substrate similar to a doctor's eye chart. The substrate was attached to the holder with enough tension to ensure it was flat. The bottom of the container was covered with antireflective rubber to prevent echoes from the bottom. The phantom was assessed by several observers, who scanned the phantom with their own imaging system settings and obtained as clear images as possible to read the character set. Figure 6 shows two of the sample images obtained with BSA phantom (α ≈0.3 dB/cm.MHz) and soap+water+gelatin

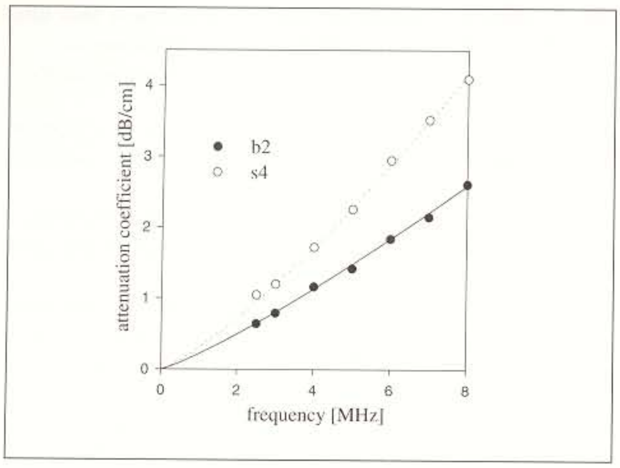

Figure 5. Attenuation coefficients vs frequency for batches s4 (α $\approx$ 0.45 dB/cm.MHz, glycerin soap 16.8% + water 82.2% +gelatin 1%) and b2 ($\alpha \approx 0.3$ dB/cm.MHz, (BSA 30% solution) 55% +water 45%).

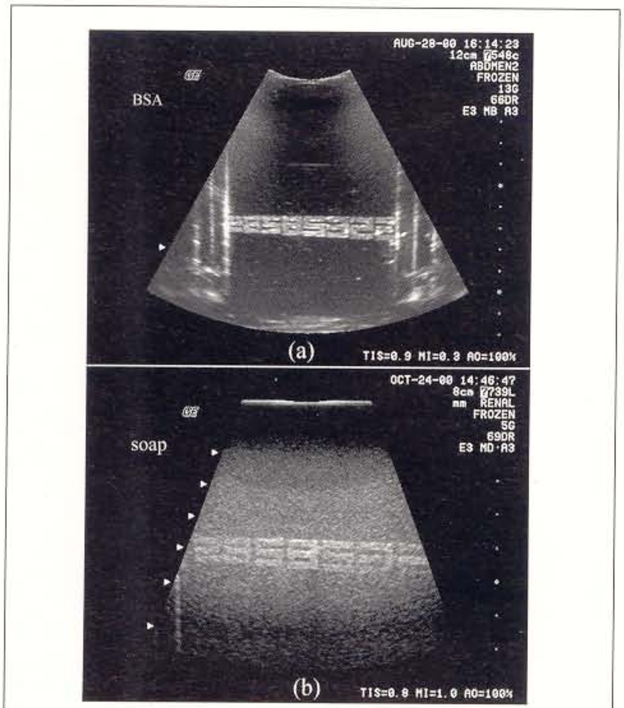

Figure 6. Sample TFP (Thin Film Phantom) images with digital scatterers and TM background materials. Character set used was the sequence of '2 8 5 8 5 3 2' from the left and background materials had the properties of c=1540±6 m/s and attenuation coefficient slopes of (a) $\alpha \approx 0.3$ dB/cm.MHz and (b) $\alpha \approx$ 0.45 dB/cm.MHz, respectively.

phantom (α $\approx$0.45 dB/cm.MHz) respectively using GE Logiq 700MR system. Both images were obtained with convex probes with 7 MHz of center frequency, while size of the transducer and imaging system settings are different depending on the scanning window size, backscattering, attenucation, target depth, etc. Since maximum penetration depth of the phantom is dependent upon the echogenecity of scatterers and attenuation of surrounding material, a target depth of 7.5 cm from the window to the middle was chosen for BSA phantom, while for soap phantom it was 4.5 cm. For both images the character sequence was '2 8 5 8 5 3 2' from the left. All observers found the phantom easy to use and recognition of characters was correct only except for confusion of character '2' and '8'. Further details on the TFP test will be presented in another paper.

4. Discussion and Conclusion

We have described two phantom preparations that are made with readily available substances, easy to prepare, and pourable. These preparations provide attenuation slope of 0.3 - 0.5 dB/cm.MHz and speed of sound of 1540± 6 m/s in the recommendable range of AIUM guidelines, but at the same time are hypoechoic. In experimental situations such as the Thin Film Phantom, it is highly desired to have minimally scattering tissue mimicking background materials. Both the BSA diluted mixture and the soap+water+gelatin mixture have sufficiently low backscatter to satisfy this need. Also we have introduced the c-α chart, as an aid to production and assessment of experimental TM materials. The chart shows the diluting curves pass through the desired range of sound speed and the attenuation slope. A good choice of the solute can be made for the given solvent and the desired TM materials can be obtained by diluting the solute. The frequency dependence of the attenuation is also indicated on the chart. It is possible in some cases to predict dilution behavior based on the mixture laws, which describe a simple curve in the c-α chart. The TM materials were applied to TFP with digital scatterers to get the images of a character set. The phantom was easily recognizable and the usefulness of the TM materials produced for TFP purpose was verified.

It remains, however, to be solved how to handle the frequency dependence of the material. The current model can not predict this parameter and it solely depends on the choice of the material. Another subject for future work would be on those materials that do not follow the perfect mixture laws, and it should be assisted by more detailed models including chemical and ultrasound mechanisms.

Acknowledgement

Authors are grateful to the support from NIH-1R43-HL62041 and to Robert Naum and Applied Imaging, Inc.

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