Characterization and FEA Simulation for a HIFU Phantom Material

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Abstract - Results are presented for a new formulation of HIFU phantom material made with polyacrylamide gel and Bovine Serum Albumin. This formulation closely matches the acoustic attenuation as well as the velocity and impedance of tissue, while providing a uniform and optically transparent medium. The phantom material turns permanently opaque whenever the material achieves a temperature greater than 70°C. Computer simulations of the formation and growth of opaque lesion-mimicking regions in the phantom material were performed, and good agreement with experiment was obtained. This material holds some promise both as (i) a controllable, quantitative tool for development of HIFU systems, and (ii) as a quality assurance tool for such systems.

I. BACKGROUND

The desirability of good tissue mimics for HIFU studies has previously sparked investigation into combining Polyacrylamide gel with Bovine Serum Albumin (BSA) to produce such a material [1-2]. It is believed that the BSA serves as a temperature-sensitive marker, denaturing under thermal excitation, which turns the phantom material opaque.

It is hoped that such a material can provide a good test bed for conducting research on HIFU as well as for developing therapeutic protocols. Additionally, such a material may provide a quality assurance check for HIFU systems in clinical use, assuring users that HIFU beams are of adequate strength and can be properly aligned.

For this purpose, a tissue mimic needs to be as close as possible to tissue in its acoustic and thermal properties, which should be well characterized. Also, the conditions under which the material turns opaque and under which HIFU creates lesion-mimics in the material should be well understood.

Furthermore, experiments on such a phantom can be used to test and improve the validity of software simulations. Also, software models allow simulation of the effects of differences between tissue and phantom material properties, thereby fostering a better understanding of the accuracy of the phantom material for predicting tissue response to HIFU. For this reason, we feel it is valuable for development of software simulations of HIFU to go hand-in-hand with the development of phantoms.

The subject of this paper is the development and characterization of such a phantom material, as well as comparison to a Finite Element model under moderately high power, so that highly non-linear effects such as cavitation or boiling can be excluded.

II. FORMULATION AND CHARACTERIZATION OF THE GEL

The phantom material is based on a proprietary formula using Polyacrylamide gel mixed with liquid Bovine Serum Albumin. Both the BSA and water components are degassed. The final product is an optically transparent gelatin-like material, with a density of 1060 kg/m^3.

Acoustic characterization is accomplished as shown in figure 1. Broadband pulses are propagated through samples of 4mm and 8mm thickness, which are alternately interrogated by the ultrasound beam as the temperature in the tank is increased. The spectra of the pulses through each sample are then compared to obtain the acoustic phase velocity and attenuation. Results are shown in figure 2.

Optical characterization is accomplished as outlined in figure 3. A sample of gel material approximately 1mm in thickness is cured between two glass coverslips glued at their borders to a slide frame to provide structural rigidity. This sample fixture is then immersed in a water tank that can be heated with an immersion heater. A laser light source and photodetector monitor the optical transmission through the sample as the temperature rise is recorded by a thermocouple. A typical transmission curve is shown in figure 4. The sample begins to turn opaque at around 66ºC, and has completed its optical transition by 75ºC.

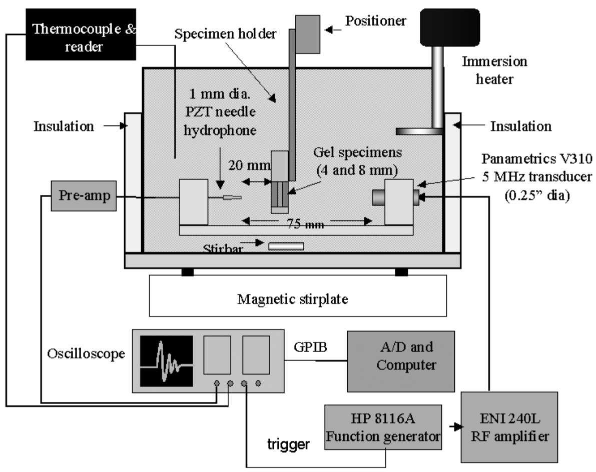

FIGURE 1: Acoustic Test set-up. The positioner moves in and out of the page to align either the 4 mm or 8 mm sample with the acoustic beam.

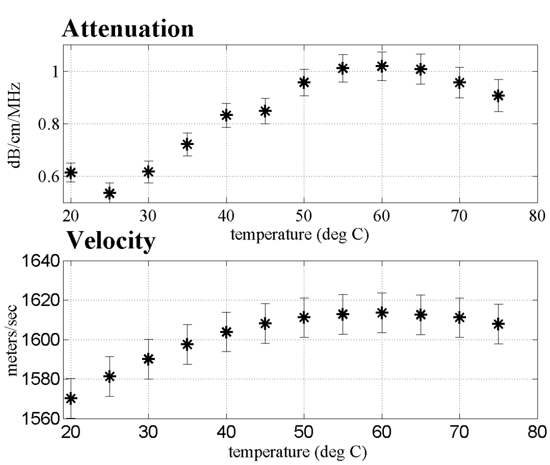

FIGURE 2: Attenuation and velocity of gel samples averaged over two sets of samples of 4mm and 8mm.

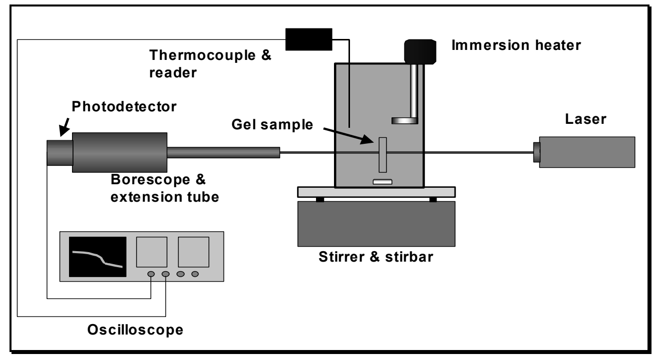

Figure 3: Set-up for measuring the optical transition in the gel samples.

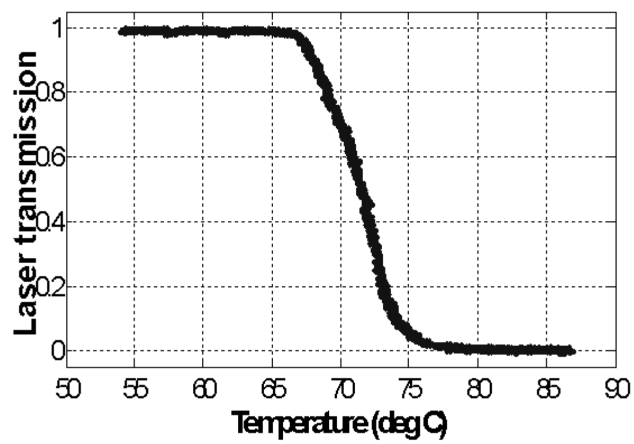

Figure 4: Typical optical transmission curve, normalized to the initial transparency of the sample.

Preliminary estimates of the material's thermal conductivity and specific heat have been made based on calorimeter measurements and previously published data on similar materials [3]. Calorimetry indicates that our materials' specific heat is within 600 J/kg/ºK of the specific heat of water-- i.e., 4180 +/- 600 J/kg/ºK. Additionally, Hirata, et. al [3] present strong experimental and theoretical arguments that Polyacrylamide gels should obey a simple mixture theory for their thermal properties, which suggests that specific heat should be somewhat lower than that of water, and the thermal conductivity should be no higher. Because the content of BSA is small in our gels, we believe they, too, should follow this mixture theory. Based on our mixture ratios, we have therefore tentatively ascribed a specific heat of 3850

+/- 250 J/kg/ºK and a thermal conductivity of 0.5 +/- 0.05 W/m/ºK to our material.

III. COMPARISON TO FINITE ELEMENT MODEL

The use of finite element and pseudospectral models to simulate the application of HIFU in tissue has been discussed in References [4-5], which describe an approach where the acoustic field is first modeled to compute losses due to attenuation. These losses then become the source term to solve the heat equation in a separate calculation. Some acoustic nonlinearities can be modeled by appropriately setting the B/A ratio for the medium. More important, perhaps, is that some nonlinearities due to acoustic properties' temperature dependence can be modeled by taking an "incrementally linear approach" [4] where the acoustic model is updated after incremental runs of the thermal model. However, the approach we will discuss here follows the strictly linear case, for reasons of simplicity. The FEA package used was PZFLEX (Weidlinger Associates, Los Altos, CA).

To model the gel acoustically, we used the room-temperature values of figure 2 and assumed that the absorption was equal to the attenuation, because no scatterers are present in the medium. Thus, we used a velocity of 1570 m/s, and an absorption of 0.6 dB/cm/MHz. An axisymmetric model with a grid discretization of 7 micrometers was employed to model an area of 26.6 mm (axial) by 13.3 mm (radial) and a time step of 4 nanoseconds was used. For the thermal model, a 0.3 mm mesh was used along with a time step of 0.05 sec. A specific heat of 3600 J/kg/ºK and conductivity of 0.5 W/m/ºK provided the best correlation with experimental observations, and are within the ranges discussed in the previous section. After the temperature map of the entire field was calculated, lesion growth was simulated by approximating the opacity function of figure 4 as a step function with the transition at 70ºC—thus any element was designated as completely and permanently opaque once it exceeded a temperature of 70ºC.

In order to compare the simulation to the phantom's performance, a sample of gel was insonified with a 20mm diameter 4 MHz transducer with an F-number of 1.0. Figure 5 shows a Schlieren image of the beam measured in water. Figure 5 also shows, superimposed on the beam, a digital image of a lesion photographed in the gel after 72 seconds exposure with a total beam power of 10W (the beam power was measured beforehand with a radiation force balance: the UPM-DT-1 from Ohmic Instruments of Easton, MD, USA). At powers higher than 10W, bubbles form in the gel, probably due to temperature-induced vaporization, and distort the shape of the lesion. As this phenomenon is highly uncontrollable, we performed our comparison to the model only at lower power. Figure 6 shows snapshots of the growth of the lesion obtained with a digital movie camera. Superimposed on each snapshot is the outer envelope of the lesion at the corresponding time produced by the simulation. The envelope was obtained by passing the simulated lesion shape at each time through an edge detection algorithm.

IV. CONCLUSIONS

The good agreement obtained between simulations and experiments suggests the characterization of the gel is, at least, approximately valid. However, we would like to put these results on a more rigorous footing by performing a thorough experimental characterization of the thermal properties, and by considering the contribution of nonlinear effects such as the temperature dependence of the attenuation as well as nonlinear propagation (i.e., through the B/A ratio).

This material is clearly promising as a quality assurance tool for HIFU systems. Unfortunately, it appears clear that the gel forms visible lesions at a temperature (70 degrees Celsius) that is significantly high for mimicking true lesions in tissue. We are therefore exploring new formulations that would lower this transition temperature.

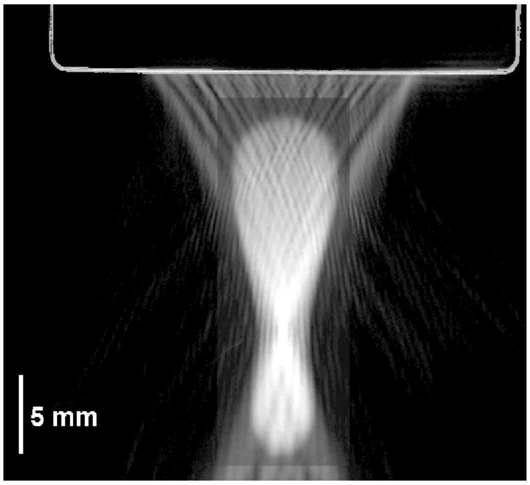

FIGURE 5. Schlieren image of the beam from the 4 MHz transducer used to evaluate the gel phantom. Superimposed is an image of a lesion obtained after 72 seconds of exposure at 10W of total beam power.

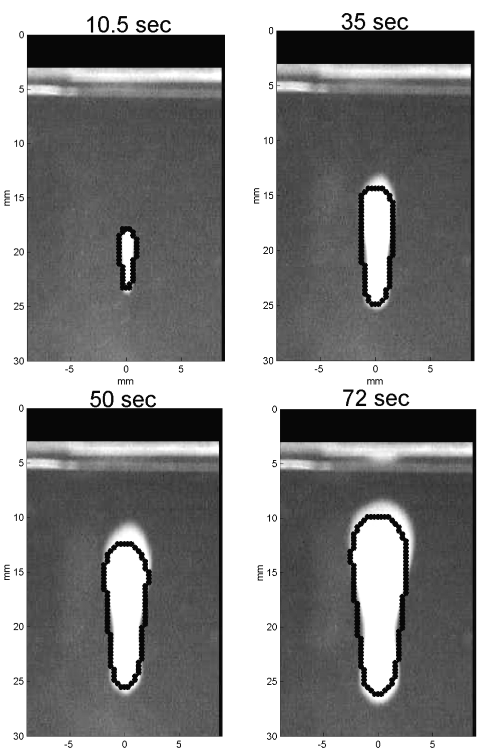

Figure 6: Movie frames of lesion growth in the phantom, with FEA predictions of the extent of the lesion superimposed as a solid line. The bright line at the top of the image is an optical reflection off of the top surface of the gel, which occurred because the camera was placed at a slight angle.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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