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# THERMOGRAPHIC INVESTIGATION OF ULTRASONICALLY INDUCED TEMPERATURE DISTRIBUTION IN TISSUES AND TISSUE-EQUIVALENT PHANTOMS

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The purpose of the paper was to develop a computerised thermographic method for the investigation of the temperature fields in tissue phantoms irradiated by ultrasound and to study heating patterns in sonicated heterogeneous and homogeneous phantoms. The developed thermographic system provided the possibility of obtaining threedimensional images of the temperature distributions in the irradiated samples. It is shown that the temperature pattern in the heterogeneous tissue phantoms irradiated by ultrasound can be dependent not only on the differences in bulk acoustical properties of the adjacent tissues but also on the differences in their shear properties.

## 1. Introduction

One of the most important problems involved in the effective therapeutic application of ultrasonic hyperthermy is that of obtaining required temperature distributions in the sonicated tissue. There are two methods for the investigation of ultrasonically induced temperature fields in tissues described in literature. One, the most widely used, method is the thermocouples method described in the works of LELE, HYNYNEN, WATHMOUGH, G. TER HAAR and others [4, 5, 7]. Another is the thermographic method which was first used by L. FILIPCZYŃSKI [1] and was recently described in the work of G. TER HAAR and CARNOCHAN [6]. In spite of the fact that the thermocouples method has given better quantitative results, it has a number of disadvantages, namely: a long and complicated procedure of preparation of the object, limited spatial resolution and the possibility of artifacts caused by destructions in the tissue as a result of introduction of thermocouples.

The purpose of the present study was to develop a computerized thermographic method and to investigate temperature fields in homogeneous and heterogeneous tissue phantoms irradiated by ultrasonic pulses.

## 2. Materials and methods

Tissue phantoms mimicking the properties of biological tissues with regard to velocity and attenuation of longitudinal ultrasonic waves, velocity of shear waves, density and heat capacity, were made of aqueous agar gels with addition of sodium chloride and chalk powder. Table 1 shows the composition of

**Table 1.** Tissue-equivalent phantom

| Composition | | Physical properties |
|---|---|---|
| water | −100% | $U_l = 1570$ m/s |
| agar | − 3% | $a_l = 0.24$ neper/cm |
| NaCl | − 7% | $U_s = 6$ m/s |
| chalk powder | − 3% | $C_p = 1.17$ cal/g.deg °C |
| | | $\varrho = 1.06$ g/cm$^3$ |

the physical properties of one of the tissue phantoms used in most of the experiments described below. The values of the parameters given in Table 1 are similar to those of liver [2, 3]. Usually, the value of shear velocity in tissue is not considered as an important parameter in making tissue equivalent phantoms. We have tried to investigate the role of this factor in the production of heat by ultrasound, on the basis of the hypothesis according to which shear properties can be responsible for some thermal effects of ultrasound, in the case of heterogeneous soft tissues at the boundaries between adjacent tissues having similar bulk properties but different shear properties [9].

We measured this velocity and attenuation of longitudinal waves by a resonator device described previously [8]. The velocity of shear waves was calculated from measurements of the time-of-flight of a shear pulse between two piezoelectric transducers. Density was measured by a pycnometer and heat capacity was measured by the calorimetric method. Heterogeneous tissue phantoms were made by composing some pieces of gels with required parameters, pieces of fat, muscle, etc., into a bigger piece of gel having parameters shown in the table.

A schematic diagram of the experiments is presented in Fig. 1. Ultrasonic irradiation was performed by plane or focusing piezoceramic transducers at frequencies of 0.88 MHz and 0.5 MHz respectively and intensities 0-0.1 kW/m$^2$ (spatial average and time peak) for plane waves and 0.3-15 kW/m$^2$ (average over the section of the focal region) in the case of focusing transducers. The length of focal region was $l = 0.03$ m and the diameter $r = 0.003$ m. The intensity of ultrasound was measured by radiation pressure techniques and by a differential thermocouple which was precalibrated by a known ultrasonic source.

Temperature distributions were measured on the surface of a sample irradiated either by a plane transducer, in the near field, or by a focusing transducer using distilled degassed water as the coupling medium. Measurements of the temperature fields inside the sample were made by cutting the sample along a chosen axis such that after heating it could be split in less than one second and exposed to an infrared probe.

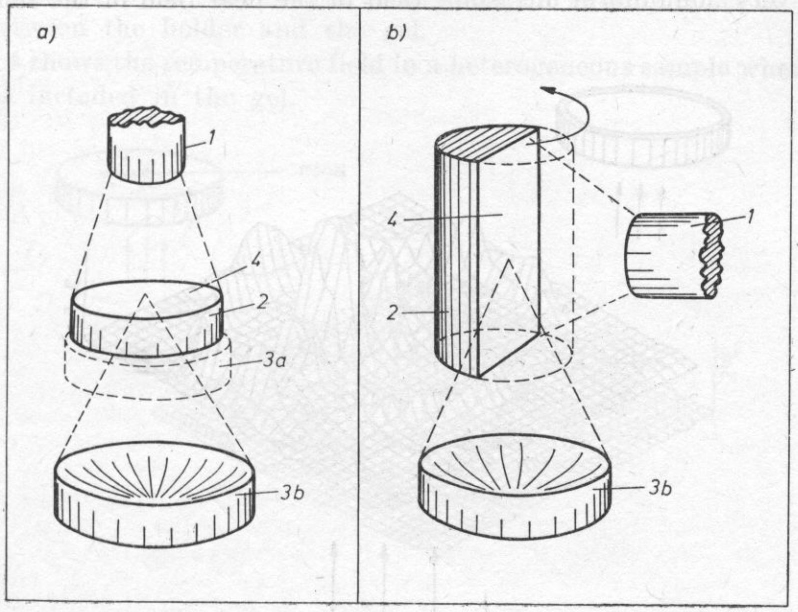


Fig. 1. A schematic diagram of the experiments. $a$ – measurements of the heating patterns on the surface of the cylindrical sample 0.005 m thick and 0.035 m in diameter; 1 – infrared-probe, 2 – sample, 3a – plane transducer, 3b – focusing transducer, 4 – surface exposed to the probe. $b$ – measurements of the heating patterns on the surface of the sample section. The diameter of the sample 0.024 m and the height –0.1 m

The exposed plane was imaged by a scanning thermographic system, AGA-Thermovision-780, having the spatial resolution of about $10^{-3}$ m and accuracy of measurements of temperature changes 0.2°C. The obtained image was than recorded digitally on magnetic tape and was displayed as a threedimensional picture after computer analysis. The computer analysis provided the possibility of obtaining differential images of the temperature fields before and after ultrasonic heating of the sample. Just before the measurements the distribution of the temperature fields was not uniform, because of the differences in the rate of evaporation, so that by making this differential picture we could analyse much more precisely the heating pattern produced by ultrasound. The system also provided the possibility of measurements of the kinetics of heating and cooling of the sample surface.

### 3. Results and discussion

Fig. 2 shows the temperature field on the surface of a sample surrounded by a circular plastic holder in the near field of a plane ultrasonic transducer. A complicated temperature distribution in the middle of the heating area is due to a very nonuniform ultrasonic field in the near field of the source. The

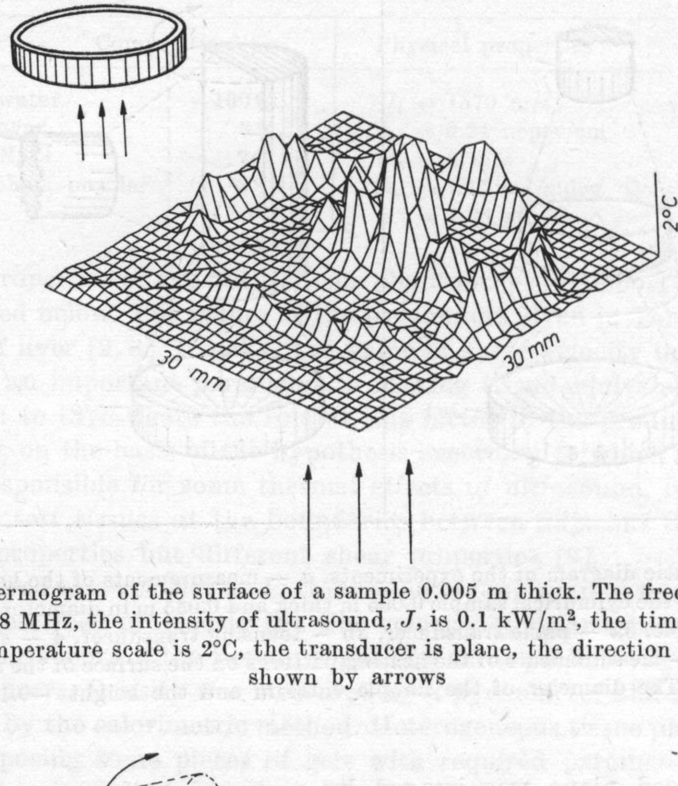


Fig. 2. The thermogram of the surface of a sample 0.005 m thick. The frequency of ultrasound, $f$, is 0.88 MHz, the intensity of ultrasound, $J$, is 0.1 kW/m$^2$, the time of irradiation, $\tau$, is 2s, the temperature scale is 2°C, the transducer is plane, the direction of irradiation is shown by arrows

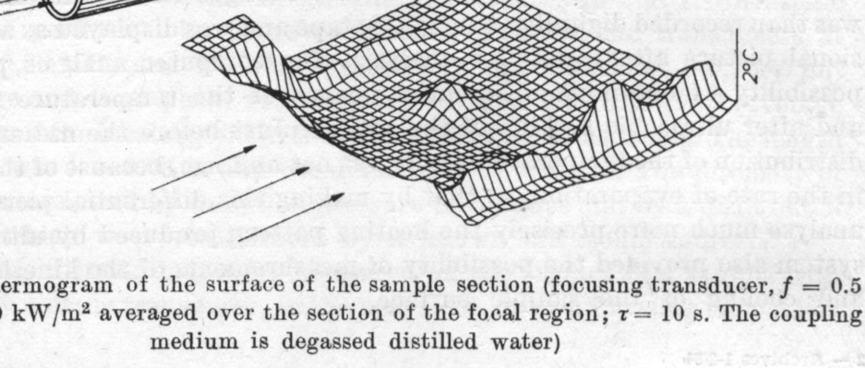


Fig. 3. The thermogram of the surface of the sample section (focusing transducer, $f = 0.5$ MHz, $J = 14.0$ kW/m$^2$ averaged over the section of the focal region; $\tau = 10$ s. The coupling medium is degassed distilled water)

heating on the boundary between the sample and the holder is due to the well known fact of the heat production at the interfaces between tissue and any solid (e.g. bone) and it is usually explained by the formation of highly attenuated shear waves in the solid.

Fig. 3 shows the heating inside a sample irradiated by focused ultrasound. One can clearly see the shape of the focus and some heating effect at the boundaries between the holder and the gel.

Fig. 4 shows the temperature field in a heterogeneous sample where a small bone was included in the gel.

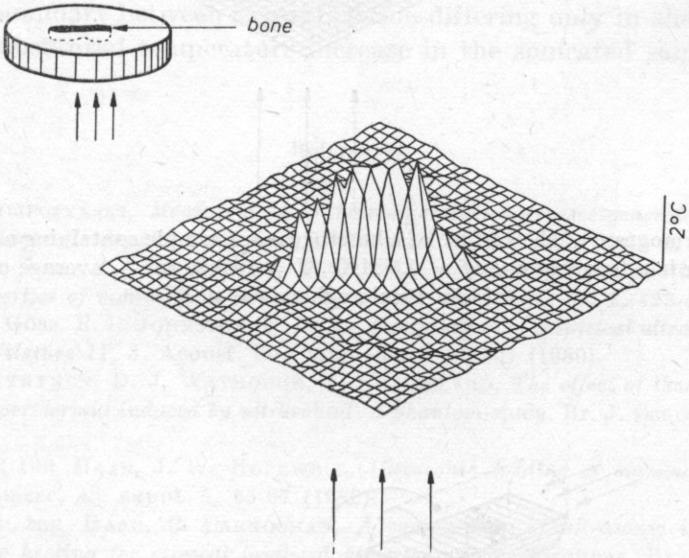


Fig. 4. The thermogram of the surface of a heterogeneous sample with a bone inclusion. The transducer is plane ($f = 0.88$ MHz, $J = 0.1$ kW/m², $\tau = 0.5$ s)

It is interesting to note that even at such a short exposure (half a second at the intensity close to that used in theraphy: 0.1 kW/m²) we have a substantial increase in temperature up to 3 degrees.

Fig. 5 shows the temperature field on the surface of the same sample but irradiated by focused ultrasound. The temperature increase on the bone is about 75°C and the rate of heating is about 20°C/c.

Fig. 6 shows a thermogram of a heterogeneous tissue phantom containing an inclusion of a piece of gel having the same value of ultrasound velocity and attenuation as the bulk gel but different values of the velocity of shear waves. The difference in shear properties is about 20 per cent. For longitudinal waves there is no physical boundary between the inclusion and the bulk gel. One can see here that at the first interface between the inclusion and the bulk gel the increase in temperature reaches about 2°C. This is just one example out of many such images which we obtained for inclusions different from the bulk sample in terms of shear properties.

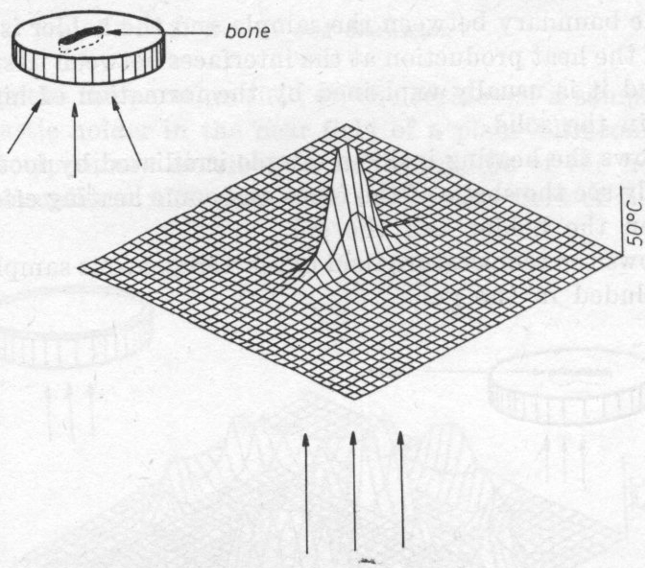


Fig. 5. The thermogram of the surface of a heterogeneous sample containing a bone inclusion. The transducer is a focusing one ($f = 0.5$ MHz, $J = 14$ kW/m$^2$ – average over the section of the focal region, $\tau = 4$ s)

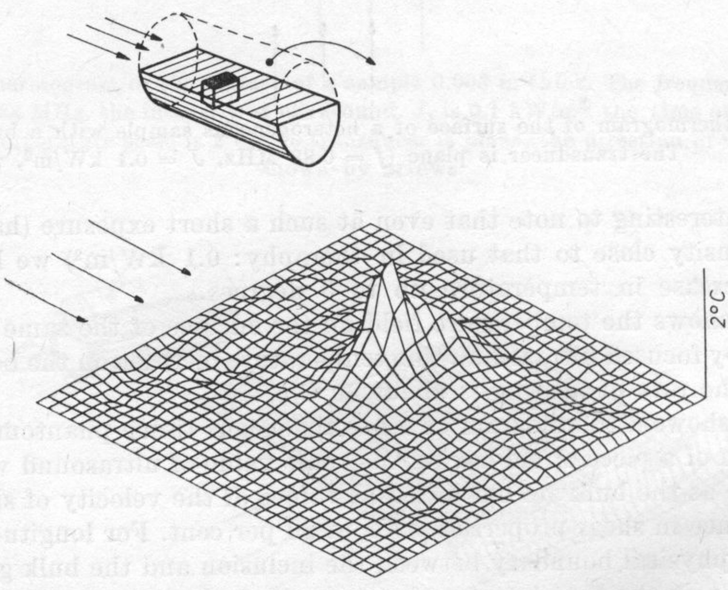


Fig. 6. The thermogram of the surface of a heterogeneous sample containing as an inclusion a piece of gel differing from the bulk gel only in terms of shear properties. The transducer is a plane one ($f = 0.88$ MHz, $J = 0.1$ kW/m$^2$, $\tau = 3$ s)

**4. Conclusions**

1. A computerized differential thermographic method is developed for visualisation of temperature distributions in sonicated homogeneous and heterogeneous tissue phantoms.

2. The temperature pattern in irradiated heterogeneous tissue phantoms depends on the differences among the acoustical characteristics of the inclusions.

The rate of temperature increase at the interface bone-soft tissue may reach 4-5°C per second at intensity of plane ultrasonic wave of about 0.1 KW/m².

3. The boundary between two soft tissue differing only in shear properties can give a substantial temperature increase in the sonicated sample.

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