Temperature Reconstruction in Depth of Biological Object by Acoustical Radiometer

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Abstract— Acoustothermometrical measurements were carried out for the model biological objects. As model objects we used the plasticine bodies placed in the water. In the experiment the model objects were being heated up and cooled down. The temporal dependences of their acoustobrightness temperatures were obtained and the reconstruction of the 2-D temperature distribution was made. The position, size and temperature of the thermal source were detected. The reconstruction error was about 1–2 mm for the position and size and about 1 K for the temperature. These results were obtained when the measurement time was about 50 s. As well we carried out the acoustothermometrical control during the laser hyperthemia of the mammary gland. The medicine procedure was continued 10 min and the maximum gland acoustobrightness temperature was increased at about 7 degrees.

1. INTRODUCTION

It is well known that the temperature in depth of a human body can be measured using the thermal electromagnetic radiation of the body. Bowen [1] suggested to use for this purpose the thermal acoustic radiation in megahertz frequency range. This radiation emitted from an object results from the thermal movement of atoms and molecules in it. The intensity of the thermal acoustic radiation is determined by the absolute temperature and absorption coefficient in the object. Both method have the advantages and imperfections. The advantage of the acoustothermography over the radiothermography is the better spatial resolution for the temperature reconstruction because of the small wave lenght (about 1 mm). The advantage of the radiothermography is the smaller measurement error because of the bigger frequency bandpass. We suggest to use the acoustothermography for the temperature distribution reconstruction in depth of a human body.

The physical basis of acoustothermography was considered theoretically and checked experimentally by Passechnick [2]. The theoretical estimations [3] show that the acoustotermography method permits to detect the internal temperature at the depth of up to 5–10 cm with accuracy approximately up to 0.5–1 K in the volume of about 1 cm^3. The objective of our work is to carry out the acoustothermometrical measurements during modeling hyperthermia, to reconstruct the temperature distribution for model object and to conduct the acoustothermometrical control during laser hyperthemia of human tissues.

2. APPARATUS AND METHOD

The scheme of the model hyperthermia experiments is shown in Fig. 1. These experiments were carried out in a thermostat tank ($43 \times 43 \times 15\,cm^3$) filled with water. The plasticine cylinder (base diameter 22 mm) was placed vertically in a cavity (base square $13 \times 18\,cm^2$) with glycerin water solution. The side walls of the cavity were made from acoustically transparent film (from thin polyethylene). A metallic rod (4 mm diameter) of a soldering iron (25 W power) was used as thermal sourse in the plasticine. Mercury and electronic thermometers controlled the temperature of the tank and the model objects with precision of 0.2 K. The thermal acoustic radiation measurements were carried out with acoustothermometers constructed by Mansfeld's group from the Institute of Applied Physics of RAS, Nizhny Novgorod, Russia [4]. The frequency region of the receivers was 1.8 ± 0.4 MHz and the diameter was 10 mm. The acoustothermometers registered the pressure of acoustic waves, transformed it to voltage and amplified it. Then electrical signal passed through square detector and was received by a computer where was averaged over several seconds. The acoustothermometers were placed in a horizontal plane on different sides of the plasticine cylinder.

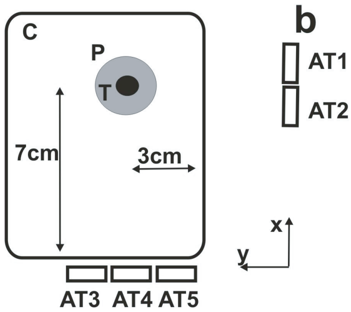

Figure 1: The scheme of the experiment: T is the source of heat, AT1-5 are the acoustothermometers, C is the cavity, P is the plasticine cylinder.

The thermal acoustic radiation pressure has the nature of a noise signal with zero mean value. The mean value of the pressure square was used to obtain meaningful information. This value is proportional to the acoustobrightness temperature T_A of the object [2]. It is convenient to operate with the increment of the acoustobrightness temperature $\Delta T_A = T_A - T_0$, where T_0 is the tank temperature. The acoustobrightness temperature increment is given by

$$\Delta T_A = \int\limits_{\Omega(y)}\int dxdz \int\limits_0^{+\infty} \alpha(x,y,z)A(x,y,z)\Delta T(x,y,z)\exp\left(-\int\limits_0^y \alpha(x,y,z)dy\right)dy, \tag{1}$$

where $\Delta T(x,\ y,\ z) = T(x,y,z) - T_0$ is the increment of the internal temperature distribution $T(x,\ y,\ z)$, axis y is directed along the acoustothermometer acoustical axis and the integration along y axis is calculated in the region where $\Delta T > 0$, $A(x,\ y,\ z)$ is the directive pattern of the acoustothermometer and $\Omega(y)$ is the transversal region of the directive pattern, $\alpha(x,\ y,\ z)$ is the absorption coefficient distribution. In the experiment conditions the absorption coefficients were measured and equal to 0.11 cm^{-1} for the glycerin water solution and 5.0 cm^{-1} for the plasticine. For the thermal acoustic radiation measurements the wideband receiver was used. The relation of the frequency region to the mean frequency was equal to 44%. Therefore the acoustothermometer directive pattern was approximated by Gaussian function

$$A(x,y,z) = \frac{1}{2\pi\, d_A(y)^2}\exp\left(-\frac{x^2+z^2}{2d_A(y)^2}\right), \tag{2}$$

where $d_A(y)$ is the transversal size of the directive pattern at the distance y from the receiver. In the experiment conditions the measured value $d_A(y)$ can be considered as a constant value equal about 3 mm.

The reconstructed 2-D temperature distribution was given by Gaussian function

$$\Delta T = \Delta T_0 \exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2d^2}\right) \tag{3}$$

with four parameters: coordinates x_0 and y_0 of the heated region center, its maximum temperature ΔT_0 and its size d. The actual size of the thermal source (the plasticine cylinder) was equal to 22 mm (see above) and was greater than the transversal size of the receiver directive pattern. Therefore the directive patterns of the acoustothermometers can be considered as the rays. In these conditions the acoustobrightness temperatures of five acoustothermometers can be calculated as follows:

$$\begin{aligned} \Delta T_{Ai} &= \Delta T_0 \exp\left(-\alpha\, y_0 - \frac{(x_{ATi}-x_0)^2}{2d^2}\right), \text{ if } i=1,2; \\ \Delta T_{Ai} &= \Delta T_0 \exp\left(-\alpha\, x_0 - \frac{(y_{ATi}-y_0)^2}{2d^2}\right), \text{ if } i=3,4,5 \end{aligned} \tag{4}$$

where i are the acoustothermometer numbers, x_{ATi} and y_{ATi} are the coordinates of the acoustothermometers centers, ΔT_{Ai} are the acoustobrightness temperature increments, $\alpha = 0.11\,\mathrm{cm}^{-1}$.

The coordinates of the heated region center were calculated as follows:

$$x_0 = \frac{x_{i+1} + x_i}{2} + \frac{(\Delta T_{Ai+1} - \Delta T_{Ai})(x_{i+1} - x_i)}{2\Delta T_{Ai+1}},$$
$$y_0 = \frac{y_{i+1} + y_i}{2} + \frac{(\Delta T_{Ai+1} - \Delta T_{Ai})(y_{i+1} - y_i)}{2\Delta T_{Ai+1}}, \tag{5}$$

where x_{i+1} (y_{i+1}) and x_i (y_i) are the coordinates of the neighbouring acoustothermometer centers. The minimization of function $F(\Delta T_0,\, d)$ allowed to detect the temperature ΔT_0 and size d of the source:

$$F(\Delta T_0, d) = \sum_{i=1}^{5} (\Delta T_{AiEXP} - \Delta T_{Ai}(\Delta T_0, d))^2 \to \min, \tag{6}$$

where ΔT_{AiEXP} are the experimental acoustobrightness temperatures, ΔT_{Ai} are the acoustobrightness temperatures determined by Eq. (4).

3. RESULTS AND DISCUSSION

Temporal variations of the acoustobrightness temperature increment of the plasticine cylinder were connected with the experiment script too. The signals have increased when the heating was switched on (after some time delay), and the signals have decreased when the heating was switched off (again after some time delay). These delays were connected with the heat transfer inside the plasticine cylinder. For the reconstruction the experimental data were averaged over 50 s. The position, size and temperature of the thermal source were detected. Both the reconstructed position and the size of the heat source were close to the actual values and changed insignificantly (in limits of about 1 mm). The temporal dependences of the reconstructed effective temperatures were connected with the experimental script very close. All these results shown that the reconstruction of the temperature distribution inside the model object was quite good. These results allowed us to pass to the next experiment where the acoustothermometrical control of the laser hyperthemia of human tissies was carried out.

The acoustothermometrical measurements during the laser hyperthermia of the mammary gland were carried out in Central Hospital of RAS. The infrared laser radiation (wave length 1060 nm) was introduced through the optical fiber in the mammary gland. The power of the laser was 3 W. The time of the procedure was about 10 minutes. The laser impulse and pause time were equal to half of second. The laser radiation was absorpted in the soft tissues, and they were heated up. Acoustothermometrical measurements were conducted with two acoustothermometers. The acoustical axis of the first acoustothermometer was directed into the center of the heated region

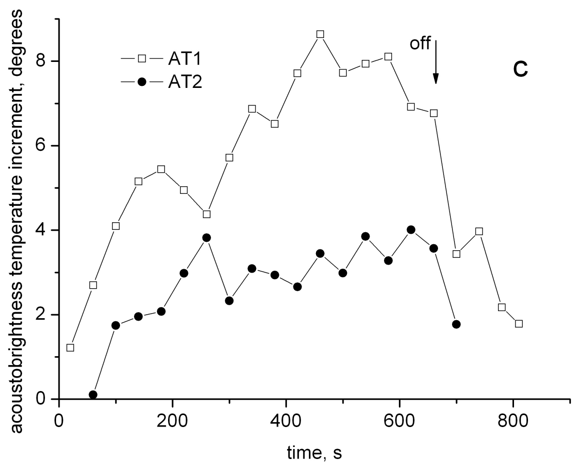

Figure 2: The temporal dependences of the acoustobrightness temperature increments during the laser hyperthermia of the mammary gland. Zero corresponds to the temperature of the body before the heating. The moment of the heat switching off is shown with arrow.

and the acoustical axis of the second acoustothermometer was directed about 1 cm sideways. The experimental data averaged over 40 s were presented in Fig. 2. We can see that the acoustobrightness temperarure increments rised after switching on the laser and reduced after switching off the laser. According to the experimental scheme the data obtained with the first acoustothermometer were greater than ones obtained with the second acoustothermometer. Before switching the heating off the acoustobrightness temperature measured by first acoustothermometer was equal to about 7.5 degrees and measured by the second acoustothermometer was equal to about 3 degrees. In these conditons a question remains unanswered: what temperature was in the depth of the human tissues?

The measurements of infrared thermal electromagnetic radiation were used to answer this question. These measuments give information about the surface temperature of an object. The portable computer thermograph IRTIS-2000 developed by "IRTIS" Ltd. was used to control the model hyperthermia of the tumour which was cut out from the mammary gland [5]. For the laser hyperthermia simulation the optical fiber was entered into the tumour at the depth about 2 mm from the investigated surface. The hyperthermia duration was 10 min. The experimental data allowed us to estimate the temperature maximum $\Delta T_0 \approx 14\,\mathrm{K}$ and the transversal size of the heated region $d \approx 1\,\mathrm{cm}$. We suggested that these results can be used for the estimate the temperature distribution in the actual laser hyperthermia. The temperature distribution was given by 3-D Gaussian function. We suggested also that the heated region center was at the depth 1 cm and the absorption coefficient was equal to $0.4\,\mathrm{cm}^{-1}$. The calculations with help of Eq. (1) gave the values 6.2 degrees for the first acoustothermometer and 3.3 degrees for the second acoustothermometer. These results were close to the experimental data.

Thus, the results of both the model experiments and the acoustothermometrical mesurements of the actual laser hyperthermia show that the acoustothermography can be used during the laser hyperthermia for the temperature control.

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