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Local heat source detection inside of the human body by means of microwave radiothermography

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Abstract. The possibility of non-invasive simultaneous detection of the depth and the temperature of a cancerous tumor inside the human body by means of multifrequency microwave 3D-radiothermography is regarding. The models for the description of the reception processes of the own human radio-thermal field are resulted. The possibility of calculating the required parameters by measuring antenna temperatures simultaneously in two different frequency ranges is analyzed. The conditions for solutions finding by both analytical and numerical methods are revealed. The possible maximum depth for tumors detection depending on the parameters of radiothermograph and thermal contrast in the source is determined. The necessity of multi frequency receiving is approving. Analytical solutions for tumor depth and temperature for the current model are presented.

Keywords: microwave radiothermography, non-invasive temperature measurement, malignant tumor, 3D-visualization, antenna-applicator

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CONTENTS

1. INTRODUCTION (306)

2. METHODOLOGICAL BASIS OF 3D RADIOTHERMOGRAPHY (307)

3. MODELING OF HEAT FIELDS AND HEAT TRANSFER PROCESSES IN THE HUMAN BODY (308)

4. CONCLUSION (310)

REFERENCES (311)

1. INTRODUCTION

Pathological processes inside the human body are usually accompanied by distortion of the natural heat field inside the body and on its surface. Knowledge of the heat field distribution in the human body and the reaction of the heat field to various physiological tests allows reliably to diagnose various diseases. The external temperature of the human body is measured by conventional medical thermometers or infrared pyrometers and thermal imagers. It is impossible to measure the temperature inside the body by such methods, and the introduction of a thermal sensor under the skin leads to a violation of the natural heat field.

Therefore, it is urgent to improve non-invasive methods of measuring internal temperatures in the human body for the purpose of early diagnosis and monitoring of malignant neoplasms and other pathologies by radiothermography, which is actively developed by specialists and scientists all over the world [1].

Some scientists have hypothesized that a long inflammatory process can eventually lead to a malignant neoplasm. Traditional diagnostic methods (magnetic resonance imaging (MRI), computed tomography (CT), etc.) give the doctor information about structural changes in tissues: the size of the tumor, its localization, the presence of microcalcifications, density, and allow to identify, mainly, already formed tumors at "clinically late" stages of development. Temperature is the first marker of pathological changes in the human body. For example, the temperature of a malignant tumor due to increased metabolism is 2-3 degrees higher than the temperature of intact tissues. Moreover, thermal changes occur not only when there is a high probability of malignancy. You can get information about the temperature of internal tissues using MRI, but

this approach requires access to sophisticated medical equipment. MRI equipment has a high cost and is not suitable for measurements that need to be repeated frequently over a long period of time. It opens up huge opportunities for applying the radiometry method in practical medicine [7-9].

However, the development of this method is hindered by the presence of a number of scientific and technical barriers that need to be overcome. Combining in one radiometric complex the principles of multichannel, multi-frequency and microminiature will lead to a significant reduction in the size of the radiometric receiver and the need to develop fundamentally new design and technological solutions, namely, its implementation in the form of a single module, which implies the use of a monolithic integrated design. The results of work in this direction are shown in the works [10-16].

Another main problem that the research has described in this article is that the construction of 3D images of radio-brightness temperatures based on electromagnetic radiation registered by a digital module for processing radiometric signals built on new principles requires the development of a fundamentally new set of algorithms and programs that are adequate to the biological object under study.

The radiothermography method is based on receiving and measuring the characteristics of the human body's own radiothermal radiation using a specialized high – sensitivity receiver in the range of centimeter or decimeter waves—a microwave radiometer with special antenna applicators [2] installed on the surface of the human body. At the same, for ensuring an acceptable accuracy of temperature measurements (the order of 0.1 degrees), it is necessary to take into account the degree of coordination of the antenna applicators with the human body at the installation places, which is achieved due to a special reception mode—scatterometric reception.

It is especially effective to use radiothermography for malignancies (cancers)

detection in the early stages of the development of pathology, even when they are not yet detected by X-ray method. The radiothermography method is also applicable for glucose testing, when the patient is given to drink 30 grams of an aqueous glucose solution on an empty stomach. Glucose, as a high-calorie substance, is absorbed and carried by the bloodstream throughout the body, feeding cells [3]. At the same time, the body temperature increases uniformly for a short time by one to two tenths of a degree. If there is a malignancy somewhere, then the temperature increases significantly more at the place of its localization, by one or two degrees. Detecting of a local temperature anomaly shows where the cancer is located.

Multichannel radiothermography enable to receive, process and visualize data from multiple antennas-applicators at the same time. This displays a two-dimensional image of the temperature distribution, which changes over time during the analysis [4]. However, this method does not allow to determine the depth of the tumor location under the skin.

The purpose of this article is to show the possibility of determining not only the location of the cancer, but also the depth of cancer location using volumetric radiothermography.

2. METHODOLOGICAL BASIS OF 3D RADIOTHERMOGRAPHY

The method of volumetric radiothermography is based on the use of natural electromagnetic radiation from various objects (including tissues of living creatures), whose temperature is different from absolute zero [16-17]. Any element of the human body is a source of thermal electromagnetic radiation in a wide range of frequencies. Radiation that occurs in the depth of the human body, spreading to the surface, is partially damped by absorption in human tissues. The amount of wave attenuation depends on the type of tissue (muscle, fat, bone, cranial, brain) and the wavelength. Numerically, attenuation is characterized by the size of the skin layer or the

depth at which the power of the electromagnetic wave decreases by a factor of e (2.7282). The size of the skin layer depends on the wavelength of radiation. So, for a 43 cm wave, the value of the skin layer for breast tissue is about 7 cm, and for a 21 cm wave-about 3.5 cm. Thus, by measuring the power of the body's own thermal radiation at one point, but in different frequency ranges, it is possible to differentiate the location of the source of increased thermal radiation by depth. This is the methodological basis of three dimensional radiothermography.

For refining the algorithms of processing signals received by a multi-channel multi-frequency radiothermograph and calculating the temperature distribution within the human body by depth, it is necessary mathematical modeling of heat transfer processes and thermal fields to calculate the values of radio-brightness temperatures received by the radiothermograph in each frequency range [5]. In practice, it is necessary to solve the inverse problem, namely, to calculate the distribution of thermodynamic temperature by depth for each applicator antenna from the measured values of radio-brightness temperatures at different frequency ranges and from the measured values of surface temperatures. The obtained values must be interpreted over the entire surface of the body and over the depth to restore the 3D structure of the thermal field. Analysis of the 3D dynamic picture of the structure of the heat field allows us to determine three coordinates of the local source of abnormal heating, if it is present, which will allow us to more accurately localize the position of the malignant tumor.

Using of several antennas and multi-channel radiometric receivers operating in the microwave range allows to make dynamic studies of deep human body temperatures with computer processing and presentation of results in the form of temperature maps and dynamic graphs. Providing the required resolution and sensitivity in real time is an extremely difficult task. It will be possible to use an affordable and inexpensive

device for early diagnosis of a large number of pathologies for personal medicine. It should be particularly noted that in addition to early diagnosis of various pathologies, it can be used for non-invasive monitoring of the disease treatment process [19-20].

A conventional radiothermograph [6] measures the average temperature from the radiation pattern of the applicator antenna inside the human body. The novelty of this approach consists in an attempt to more accurately locate a point heat source in the main beam area of the antenna-applicator directional diagram and calculate its temperature.

3. MODELING OF HEAT FIELDS AND HEAT TRANSFER PROCESSES IN THE HUMAN BODY

A complete model of the human body that takes into account all processes (heat release, heat transfer, radiation of the thermal electromagnetic field, its propagation and reception) is extremely cumbersome and complex. We consider several models built on the principle of "from simple to complex" to solve this problem.

A section of the human body is considered as a homogeneous medium of electromagnetic waves propagation with a constant absorption coefficient and without thermal conductivity. The applicator antenna, that is perfectly aligned with the body at the installation place, has a pencil form of directivity inside the human body, and does not have side lobes or back scattering. The cancer is a point source of heat with an increased temperature compared to the body temperature. We can consider the area with the tumor an absolutely black body, then its radio-brightness temperature is equal to the thermodynamic one without limiting generality. In practice, the tumor is a "grey" body, since it has not yet been detected differences in the dielectric properties of normal tissues and tissues affected by the tumor. Considering the tumor as a "grey" body does not limit the generality of the model, but only leads to a decrease in brightness contrast.

The location of the model elements is shown in **Fig. 1**. The model is considered in a coordinate system with the beginning at the point of installation of the antenna-applicator, the X and Y axes in the plane of the skin surface, the Z axis is directed from the surface to the depth of the human body. All further calculations will be considered in one-dimensional space along the Z -axis.

General, the brightness temperature is defined as follows (1):

$$T_b = \int_0^{\infty} w(z)T(z)dz, \quad (1)$$

where $T(x)$ - thermodynamic temperature, $w(x)$ - the weight function determined by absorption, and

$$\int_0^{\infty} w(z)dz = 1.$$

As the absorption changes by the exponential law:

$$w(z) = ke^{-kz},$$

where k - absorption coefficient for a given wavelength. Value, reverse k is a value for the skin layer z_s , the thickness of the layer at which the radiation decreases in e times.

$$z_s = \frac{1}{k}.$$

Let the tumor have a temperature T_c located at a depth of z_s , and T_0 - body temperature. Given

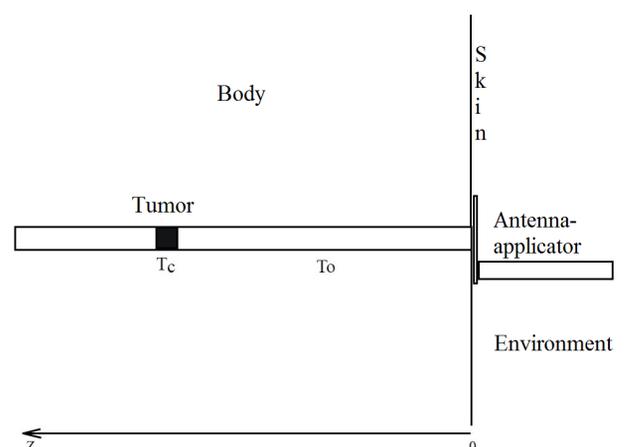


Fig. 1. Model for localization of a heat source in the human body.

that the tumor is assumed to be a completely black body, the temperature distribution in the body can be written as a function:

$$T(z) = \begin{cases} T_0, & \text{if } z < z_c, \\ T_c, & \text{if } z \geq z_c. \end{cases} \quad (2)$$

Then, substituting this expression in equation (1), we get the brightness temperature measured by a microwave radiometer connected to the antenna-applicator:

$$T_b = T_0\rho + T_c(1 - \rho), \quad (3)$$

where

$$\rho = 1 - e^{-kz_c} = 1 - e^{-\frac{z_c}{z_s}}. \quad (4)$$

Substituting formula (4) in formula (3) we get:

$$T_b(z_c) = (T_c - T_0)e^{-\frac{z_c}{z_s}} + T_0. \quad (5)$$

Formula (5) is valid for all frequency channels in the decimeter range, but the value of the z_s skin layer depends on the frequency range. The graph of the antenna temperature dependence calculated by the formula (5) is shown in **Fig. 2** by solid line.

Formula (5) allows us to estimate the maximum depth at which a source with temperature T_c can be detected by a radiometer with sensitivity δT :

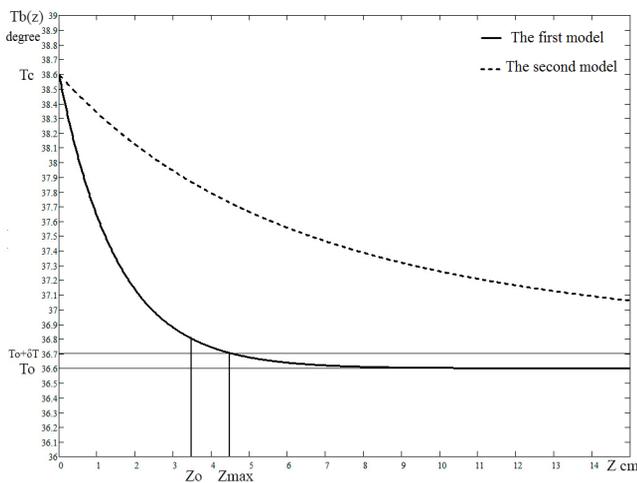


Fig. 2. Brightness temperature values for two models calculated using formulas (3) and (11). The depth of the tumor is deposited in cm on the x-axis for the skin layer - 3.5 cm.

$$z_{\max} = z_s \cdot \ln\left(\frac{T_c - T_0}{\delta T}\right). \quad (6)$$

Analysis of formula (6) shows that the maximum detection depth of a heat source directly depends on the value of the skin layer (attenuation in the medium, than attenuation is less that the detection depth is greater), depends on the value of the thermal contrast (the difference between the source temperature and body temperature) and the sensitivity of the radiometer (than the sensitivity is higher, that the detection depth is greater).

In formula (5), the known values are $T_b(z_c)$ (measured by a radiometer), the body temperature T_0 (measured by a thermal sensor on the surface of the body), the value of the skin layer for a given frequency range z_s , can be determined by special calibration. Unknown are the temperature of the source T_c and the depth of its occurrence z_c . One equation with two unknowns does not have an unambiguous solution, therefore, a single-frequency (single-band) radiothermograph is not able to simultaneously measure the temperature and depth of the tumor.

Measurements must be made simultaneously in at least two different frequency ranges with frequencies λ_1 and λ_2 to uniquely determine the temperature of the tumor and the depth of its occurrence. Then applying the formula (5) to each frequency range, we get a system of two equations with two unknowns:

$$\begin{cases} T_{b\lambda_1}(z_c) = (T_c - T_0)e^{-\frac{z_c}{z_{s\lambda_1}}} + T_0 \\ T_{b\lambda_2}(z_c) = (T_c - T_0)e^{-\frac{z_c}{z_{s\lambda_2}}} + T_0 \end{cases}. \quad (7)$$

It should be noted that the solution of the system of equations (7) makes sense to determine only under the condition that the source T_c will find both frequency channels, more accurately, you find the shortwave channel, as if the source is found a shortwave channel, it will be found by a longwave channel. If this condition is, the system of equations (7) has an unambiguous analytical solution:

$$z_c = \frac{z_{s\lambda_1} z_{s\lambda_2}}{z_{s\lambda_1} - z_{s\lambda_2}} \ln \left(\frac{T_{b\lambda_1} - T_0}{T_{b\lambda_2} - T_0} \right) \tag{8}$$

$$T_c = T_0 + \frac{T_{b\lambda_2} - T_{b\lambda_1}}{\alpha^{z_{s\lambda_1}} - \alpha^{z_{s\lambda_2}}},$$

where

$$\alpha = \left(\frac{T_{b\lambda_1} - T_0}{T_{b\lambda_2} - T_0} \right)^{\frac{1}{z_{s\lambda_1} - z_{s\lambda_2}}}.$$

Analysis of formulas (8) shows that expressions make sense if $z_{s\lambda_1} \neq z_{s\lambda_2}$, which always holds under the condition that $\lambda_1 \neq \lambda_2$. And the conditions $T_{b\lambda_1} \neq T_0$ and $T_{b\lambda_2} \neq T_0$, must also be, which means that the T_c source can be detected in both frequency channels, as noted above.

A more accurate model should take into account the distribution of heat and, consequently, the temperature inside the body. The classical method consists in solving the heat equation, but given the complexity and heterogeneity of the object, the presence of heat transfer by blood, etc. this can only be done by numerical methods.

Therefore, a one-dimensional stationary equation of thermal conductivity in a homogeneous medium is considered as the next step. In this case, the solution is represented by a linear equation in the area from 0 to z_c (from the surface to the tumor). Taking into account the previous assumptions, the temperature function can be represented as:

$$T(z) = \begin{cases} az + b, & z < z_c, \\ T_c, & z \geq z_c. \end{cases} \tag{9}$$

The values of parameters a and b are determined by the boundary conditions for the section $(0, z_c)$, namely

$$\begin{cases} T_0 = a \cdot 0 + b = b \\ T_c = a z_c + b \end{cases} \Rightarrow \begin{cases} a = \frac{T_c - T_0}{z_c} \\ b = T_0 \end{cases}. \tag{10}$$

In general case, the boundary condition for $z = 0$ is set by conditions of the 3rd kind, i.e. by the heat flow between the surface and the

external environment, but taking into account the fact that the temperature on the surface is set, i.e. always measurable, a simpler option is chosen.

Substituting the temperature function in the expression for the brightness temperature and taking into account the boundary conditions, we get:

$$T_b = T_0 \rho' + T_c (1 - \rho'), \tag{11}$$

where

$$\rho' = 1 - \frac{z_s}{z_c} (1 - e^{-\frac{z_c}{z_s}}).$$

It can be seen that equation (11) is identical to equation (3) for a simpler model. The difference is that the system of equations for two frequencies does not have an analytical solution in this case.

Calculations of the brightness temperature T_b for two models are given in Fig. 2. So the body temperature T_0 is 36.6 degrees, and the tumor temperature T_c -38.6 degrees. It can be seen that in the case of model 2, the effect of the tumor on the measured value of the brightness temperature is expected to be greater than in model 1, since it takes into account the distribution of heat in the body.

4. CONCLUSION

New results were obtained as a result of the research and modeling within the framework of the built models:

- it was shown that using a single-frequency radiothermograph it is impossible to simultaneously determine the temperature of a local thermal anomaly and the depth of its occurrence. There was a justification for the need to make measurements in at least two different frequency ranges and use data from surface thermal sensors to determine the temperature of a local thermal anomaly and the depth of its occurrence;
- there were proposed 2 models of brightness temperature formation on the body surface;
- the maximum depth of thermal anomaly detection in the human body was determined

depending on the value of the skin layer for a given wavelength, thermal contrast, and the sensitivity of the radiometer;

- it was obtained a system of equations describing the dependences of the measured and desired physical quantities;
- it was shown that the solution of the system of equations is possible only if the thermal anomaly occurs at a depth not exceeding the maximum detection depth of the thermal anomaly for a shorter frequency channel of the radiothermograph;
- analytical solutions for the temperature of a thermal anomaly and its depth were obtained for one of the models.

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