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The improved algorithm for human body internal temperature calculating by multi-frequency radiothermography method

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Abstract: **An improved algorithm for calculating the temperature and depth of a cancerous tumor in the depth of the human body by the method of multi-frequency multi-channel radiothermography is considered. An improved model is presented to describe the processes of receiving the human body's own radiothermal field by a multi-channel multi-frequency radiothermograph. The possibility of simultaneous calculation of temperature, the depth of the location under the skin and the size of the tumor is analyzed. The conditions for determining these values depending on the parameters of the tumor and the radiothermograph are investigated. The maximum possible depth of tumor detection is determined depending on the parameters of the radiothermograph and the thermal contrast in the source. The necessity of increasing the number of frequency ranges of the radiothermograph is justified. The results of calculating brightness temperatures at different depths of occurrence and tumor temperature are presented in the framework of an improved model.**

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

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Contents

1. INTRODUCTION

Body temperature is the most important indicator of human health. Usually, the body surface temperature is measured using contact thermometers or non-contact infrared radiation for general diagnostic purposes. If measure the subsurface internal body temperature, it is passible significantly increase the list of various detectable diseases. Measuring the internal temperature of the body using ordinary invasive sensors gives a significant error, since the introduction of the sensor under the skin causes a violation of the internal thermal field. It is possible to measure the internal temperature of the body noninvasively by measuring the power of radiothermal radiation emitted by the internal tissues of the body and reaching its surface in the microwave range of electromagnetic waves.

The possibility of non-invasive measurement of the parameters of a malignant tumor-the depth of location and temperature was considered in [1]. It was proposed the model to describe the receiving processes of the own radiothermal field of the human body. The analysis of the possibility of calculating the desired parameters based on the results of measuring antenna temperatures simultaneously in two different frequency ranges was carried out. The conditions for finding solutions by both analytical and numerical methods were revealed. The maximum possible depth of tumor detection was determined depending on the parameters of the radiothermograph and the thermal contrast in the source. The results of these studies were used to improve the methods of measuring and 3D visualization of the internal thermal field of a human body [2].A number of experiments were made on the equivalent of the human body and directly on the real human body in order to obtain data for further 3D interpolation and visualization of the structure of the internal thermal field inside the human body on the computer monitor screen using the developed five-channel dual-frequency radiothermograph.

The results obtained can be used to further improve the methods of using multi-channel multi-frequency radiothermographs in medical practice for more accurate localization of pathological neoplasms inside the human body. The results of studies of the internal thermal field of a human body are using in practical application of the diagnosis and treatment of a number of diseases such as breast cancer [3,4], various brain pathologies [5-9], coronary heart disease [10], arthritis and blood flow disorders [11,12], urological diseases [13] and some others [14-16].

Further improvement of the multichannel multi-frequency radiometry method requires the search for new algorithms for signal and information processing based on an improved model of radiation and propagation of radio waves and heat inside the human body in order to determine more parameters of internal thermal pathology. Particularly, it is necessary to determine not only the depth of the cancer, but also its thickness.

To solve this problem, it is necessary to design new improved model for describing the processes of receiving the human body's own radiothermal field, based on the model described in [1]. It is necessary to determine the minimum required number of channels and frequency ranges to solve the task.

The purpose of this article is to show the possibility of detection not only the temperature, the depth and location, but also the size of a cancerous tumor by means of multi-channel multi-frequency radiothermography.

2. IMPROVED MODEL OF THE HUMAN BODY'S OWN RADIOTHERMAL FIELD RECEIVING PROCESSES

As the simplest model represented in [1], a part of the human body is considered as a homogeneous medium for the propagation of electromagnetic waves with a constant absorption coefficient and without thermal conductivity. The antenna-applicator is perfectly contact with the body at the installation site, has a pencil radiation pattern inside the human body and does not have side lobes and back scattering. A cancerous tumor is a point source of heat with an increased temperature compared to the body temperature. The area of the body with a tumor is considered an absolutely black body, while its radio brightness temperature is equal to the thermodynamic one.

All assumptions made can be accepted for a refined model of the human body radiation, which permits to calculate the thickness of the tumor, with the exception of one – a cancerous tumor can not be considered an absolutely black body, since an absolutely black body is opaque and, therefore, it is impossible to determine any parameters of tissues located at a greater distance from the surface of the body than the beginning of the tumor. In addition, in practice, the tumor should be considered a "gray" body, since no differences in the dielectric properties of ordinary tissues and tissues affected by the tumor have yet been revealed.

The improved model for determining the depth and thickness of the tumor is shown in **Fig. 1**. In Fig. 1, the body is located vertically. The applicator antenna is installed on the skin surface on the left. The tumor is located under the skin at a depth of Z_1. The tumor layer ends at a depth of Z_2. The thickness of the tumor $\Delta = Z_2 - Z_1$. Body thickness is Z_3. Body temperature is T_0. Tumor temperature is T_1.

The own body's radiothermal radiation that has reached the antenna applicator can be divided into three components. The first is the radiation emitted under the antenna in a layer with a temperature of T_0 from the skin to the beginning of the tumor with coordinates from 0 to Z_1. The second is the radiation emitted in the layer of the tumor itself with a thickness of Δ with a temperature of T_1 and coordinates from Z_1 to Z_2. And the third is the radiation emitted by the body layer below the tumor with a temperature of T_0

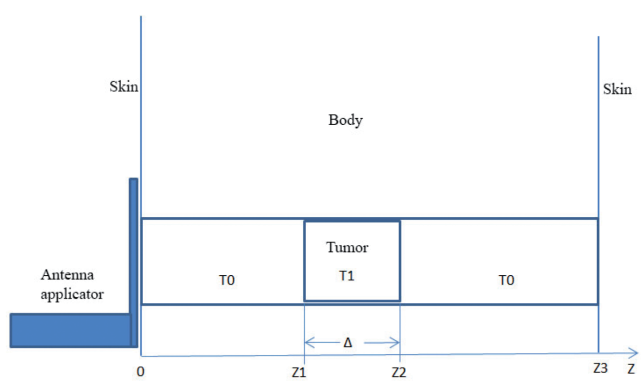

Fig. 1. *Improved model for determining the depth and thickness of the tumor.*

and coordinates from Z_2 to Z_3. The radiation generated outside the body can be ignored, provided that the measurements are carried out in a shielded camera that does not allow external interference. The radiation of the camera itself can be neglected with a sufficient thickness of the body and the magnitude of the attenuation of the electromagnetic wave inside the body.

The brightness temperature is determined by formula (1), as shown in [1]:

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

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

$$\int_0^{\infty} w(z)dz = 1. \tag{2}$$

Since the absorption is subject to an exponential law, then:

$$w(z) = ke^{-kz}, \tag{3}$$

where k is the absorption coefficient for a given wavelength. In this case, k is constant, over the entire depth $0 - Z_3$. The inverse value of k is the value of the skin layer, i.e. the layer thickness at which the radiation decreases by e times.

$$z_s = 1/k.$$

It is possible to calculate all three components of radiation and the antenna temperature, using formulas 1-3:

$$T_b = T_0\left(1 - e^{-\frac{Z_3}{Z_s}}\right) + (T_1 - T_0)\left(1 - e^{-\frac{\Delta}{Z_s}}\right)e^{-\frac{Z_1}{Z_s}}. \tag{4}$$

If consider the body thickness and body temperature as known values, then the measured brightness temperature is a function of three variables – the tumor temperature, the thickness of the tumor layer Δ and the depth of the tumor Z_1.

If suppose that the value of the skin layer is much less than the thickness of the body $Z_S << Z_3$, then approximately:

$$T_b(T_1, \Delta, Z_1) = T_0 + (T_1 - T_0)\left(1 - e^{-\frac{\Delta}{Z_s}}\right)e^{-\frac{Z_1}{Z_s}}. \tag{5}$$

It follows from formula (5) that if the thickness of the tumor tends to zero, then the measured temperature tends to the body temperature. And if the depth of the tumor tends to zero, then the measured temperature is determined by the thickness of the tumor and the thermal contrast, that is, the temperature difference between the tumor and the body, as well as the body temperature.

The graphs of the $T_b - T_0$ dependence calculated by the formula (5) with a thermal contrast of the tumor of 2 degrees and the size of the skin layer of 7 cm are shown in **Fig. 2.**

Formula (5) permits to estimate the maximum depth at which a tumor with a temperature contrast ΔT can be detected by a radiometer with a sensitivity of δT:

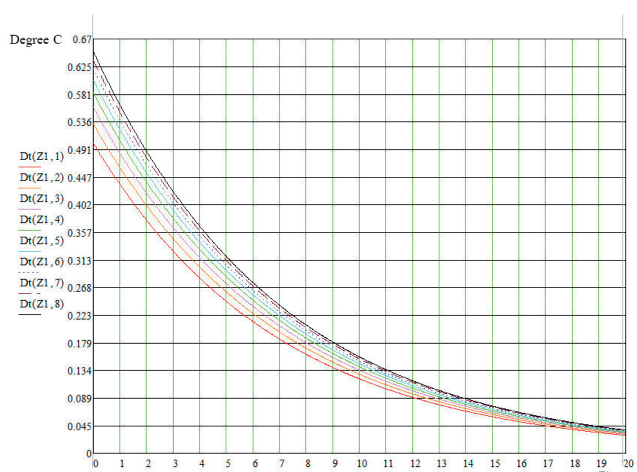

Fig. 2. *The charts of the dependence of the measured thermal contrast on the depth of the tumor at different tumor thicknesses.*

$$Z_{MAX} = Z_S ln\left(\frac{\Delta T}{\delta T}\left(1-e^{-\frac{\Delta}{Z_S}}\right)\right). \quad (6)$$

In the represented model, the maximum depth of tumor detection depends not only on the sensitivity of the radiometer, the thermal contrast of the tumor and the size of the skin layer, but also on the thickness of the tumor itself, which is quite expected.

The formula (5) analysis permits to determine the minimum required number of frequency channels of the radiothermograph for simultaneous detection of the tumor temperature, its depth and thickness. Indeed, formula (5) represents one equation with three unknowns. To solve it, it is necessary to have additionally two independent equations, which can be obtained if add two frequency channels to the existing range. The system of three equations with three unknowns will be obtained.

$$\begin{aligned} T_{b\lambda 1}(T_1,\Delta,Z_1) &= T_0 + (T_1 - T_0)\left(1-e^{-\frac{\Delta}{Z_{s\lambda 1}}}\right)e^{-\frac{Z_1}{Z_{s\lambda 1}}}, \\ T_{b\lambda 2}(T_1,\Delta,Z_1) &= T_0 + (T_1 - T_0)\left(1-e^{-\frac{\Delta}{Z_{s\lambda 2}}}\right)e^{-\frac{Z_1}{Z_{s\lambda 2}}}, \quad (7) \\ T_{b\lambda 3}(T_1,\Delta,Z_1) &= T_0 + (T_1 - T_0)\left(1-e^{-\frac{\Delta}{Z_{s\lambda 3}}}\right)e^{-\frac{Z_1}{Z_{s\lambda 3}}}. \end{aligned}$$

Unlike the simplified model described in [1], the system of equations (7) has no analytical solution and can be solved by numerical methods only. The solvability conditions for the system of equations are similar: it is necessary that the entire tumor has located in the detection zone for each frequency channel, the thermal contrast of the tumor is sufficient for detection by a radiometer with the sufficient sensitivity and the frequencies would be different.

3. DISCUSSION

The necessity radiothermograph receiving channels and the frequency ranges number increasing for the diagnosis reliability based on the tests results is proved. Both number of receiving channels determines the area and the resolution ability of the sensing the body area and the number of frequency ranges used define the resolution ability on the depth. Usually multichannel is achieved by using big number of antenna applicators connected to a common receiver via microwave switches. This design permits to reduce the size and cost of the radiothermograph, but the disadvantage of such a scheme is a decrease the sensitivity, since the receiver can simultaneously process the signal from one antenna only, and the rest are idle at this time. As more antennas are connected to one receiver, as greater the sensitivity loss. The same method is used when receiving a signal in different frequency ranges. For example, it is known the radiothermograph [17], which simultaneously uses five frequency ranges from 1.2 to 3.6 GHz. At the same time, two different antennas are used – one for the 1.2 and 1.65 GHz bands and the second for the 2.3, 3 and 3.6 GHz bands. Each frequency channel has its own band pass filter; the filters are switched by coaxial microwave switches. The signals from the outputs of the microwave switches are amplified by broadband low-noise amplifiers, one for two low-frequency bands and three high-frequency ones. Such receiving channel scheme is too complex and cumbersome for a multi-channel multi-frequency radiothermograph. When switching both receiving channels and frequency ranges to one broadband amplifier, it is too short time spent for a signal processing, what reduces the sensitivity of the receiver. An increase in the total time of signal accumulation is also unacceptable, since it is impossible to follow the rapid dynamic processes of temperature changes inside the body as a reaction to various physiological influences. It is necessary to have a broadband antenna-applicator with frequency division of the receiving bands and a set of portable low-noise amplifiers, one for each frequency range to optimize the parameters of a multi-channel multi-frequency radiothermograph. There should be several such antennas with receivers, according to the number of receiving channels. The design of broadband antenna applicators with portable receivers is a complex technical task, which will be solved by further research. Future development of the model should take into account the uneven distribution of heat along the measurement axis, determined by the thermal conductivity equation, as well as the lobe radiation of the antenna pattern. This will give opportunity under certain assumptions and multi-channel sensing, to estimate other tumor parameters besides the thickness.

4. CONCLUSION

As a result of the research and modeling within the framework of the considered model, the following new results were obtained:

- the model of the brightness temperature forming on the surface of the body is constructed, regarding both the depth of location and the thickness of the tumor were created;
- the impassibility of simultaneous detection the local thermal anomaly temperature, depth and thickness using a single-frequency radiothermograph was shown. The necessity measurements on at least three different frequency ranges for local thermal anomaly temperature, depth and location detection was proved;
- the maximum detection depth of a tumor in the human body depending on the thickness of the tumor, the size of the skin layer for a given wavelength, thermal contrast and sensitivity of the radiometer was determined;
- the system of three equations with three unknowns describing the dependences of the measured and desired physical values was obtained;
- the system of equations solution possibility only when the thermal anomaly located at the depth not exceeding the maximum detection depth of the thermal anomaly for each frequency channel of the radiothermograph was shown;

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