Modeling of brightness temperature in biological tissue

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Abstract. Microwave radiothermometry is a passive and non-invasive technique which is used to measure the depth temperature of biological tissue. The method of microwave radio thermometry is based on measuring the intensity of the own electromagnetic radiation of the internal tissues of the patient in the ultra-high frequency range. The temperature measured by the instrument is called brightness. Modeling the brightness temperature is carried out to research the effectiveness of the method of medical diagnostics based on microwave radiothermometry data. A mathematical model of the distribution of the electromagnetic and temperature fields in the mammary gland was built. A numerical simulation of the electromagnetic and temperature fields for models differing in internal structure was carried out. The structure of the mammary gland is a multicomponent, heterogeneous environment and consists of the following types of biological tissues: skin, adipose tissue, muscle tissue, milk lobules, blood flow. The contribution of the electromagnetic field to the formation of the brightness temperature was determined. The dependence of the brightness temperature on the radius of the tumor is presented.

1. Introduction
Radiothermometry is gaining high popularity as a method for diagnosing cancer. This method is based on the experimental measurement of the temperature inside biological tissue and on the surface at various points. These points are determined by the method and scheme of measurement. An important problem is the dependence of the measured temperature field on the individual physicochemical parameters of biological tissue in different people. Temperature measurements are carried out using the RTM-RES-01 radiothermometer. It uses an antenna created on the basis of a circular waveguide, having a thermal stabilization system that maintains the antenna temperature constant to provide an approximate thermal equilibrium between the measuring system and the biological object. The depth of detection of temperature anomalies is up to 5-7 cm, depending on the moisture content of the tissues. The device gives the accuracy of determining the temperature of internal tissues 0.2 °C. Measurement time at one point is 8 s. The diameter of the surface of the antenna applicator is 39 mm. The role of modern computer technology is very large for the detection of cancer. Phantoms are built, which are designed to test microwave visualization systems, to evaluate performance in realistic configurations before possible clinical use for visualization of breast cancer or monitoring brain stroke [1]. The paper [2] presents numerical estimates of the thermal behavior of two types of mammary gland cancer: ductal carcinoma in situ and invasive ductal carcinoma. The analysis is performed using a two-dimensional model that characterizes the anatomy of the breast. The results obtained in
this research can significantly help in the development of new diagnostic methods using thermal images obtained using infrared thermography. New methods are being developed to help detect breast tumors using thermographic images. They allow you to assess the location and intensity of tumors present in the breast [3]. The extent to which these methods are applicable to real biological structures with a complex structure is difficult to estimate. Methods are used to classify tumors into malignant and benign tumors by analyzing the deformation of biotissue. Tumor tissue and normal tissue differ in these parameters [4]. A GPU parallel algorithm is used to estimate the size and locate the tumor. The introduction of parallel computing greatly accelerates the solution of the inverse problem of identifying the thermophysical and geometric properties of tumors [5]. A three-dimensional ultrasound can also be used for the secondary analysis of obscure damages of the breast [6]. Three-dimensional ultrasound offers high sensitivity and specificity, which indicates a high diagnostic value for detecting benign and malignant tumors of the breast. In tasks of this kind it is important to take into account the temperature response on the outer surface of the fabric. They may be caused by changes in the characteristics of the tumor tissue. For more than two decades, confocal microwave imaging has been developed for the early detection of breast cancer and is already in the early phase of clinical evaluation. Various algorithms are being developed for the reconstruction of three-dimensional images obtained by this survey method. All algorithms are in good agreement with the clinical data of patients. The Delay-Multiply-and Sum algorithm creates images of better quality than all other algorithms [7]. In this paper [8] shown that with microwave imaging, beam formation in a particular patient has a tangible effect on the expected sensitivity in experimental cases, and that achieving a sufficiently high specificity value in a dense mammary gland can be quite a challenge. In this work, a model is used to construct the brightness temperature maps, which is based on the numerical integration of Maxwell’s equations. This choice is due to the technology used to conduct the survey. The heterogeneous spatial structure of biological tissue on a small scale requires the use of unstructured numerical grids for calculating both electric and temperature fields. The brightness temperature is calculated and a comparative analysis of the results is carried out taking into account the distribution of the electromagnetic field.

2. Formulation of the problem

Early diagnosis of breast cancer is currently one of the urgent problems [9–16]. This disease in a number of countries comes to the first place among the causes of death of the female population. The change in temperature (temperature anomaly) can be, in particular, caused by increased metabolism of cancer cells, which is the basis for early diagnosis of cancer [17–19].

| Table 1. Physical properties of human biological tissues [20]. |
|---------------------------------------------------------------|
| Thermal conductivity $\lambda$, W/(m $^\circ$C) | Skin | Adipose tissue | Milk lobulus | Bloodstream | Muscle |
|-----------------------------------------------|------|---------------|--------------|-------------|-------|
| Heat capacity $c_p$, J/(kg $^\circ$C)          | 2930–3445 | 2250–2300 | 3000–3200 | 3600–3900 | 3300–3400 |
| Density $\rho$, kg/m$^3$                       | 0.4–0.5 | 0.15–0.25 | 0.35–0.45 | 0.5–0.6 | 0.45–0.55 |
| Electrical conductivity $\sigma$, S/m          | 2.2–2.4 | 0.35–0.4 | 2.4–2.6 | 3.1–3.4 | 2.65–2.8 |
| Dielectric constant $\varepsilon$              | 35.45–35.55 | 12.2–12.3 | 9.8–10 | 84.5–86.5 | 50–52 |

Improving the quality of diagnostics, in particular, is related to the determination of the dependence of the brightness temperature on the processes occurring inside the biological tissue. As the object of modeling is considered the mammary gland. The computational model has a
complex nature and takes into account the shape, size, parameters of the mammary gland in the aggregate, taking into account the internal small-scale structure of biological tissues, including the complexity and their complex spatial structure.

The main physico-chemical parameters of the biological tissue (Table 1) substantially depend on the coordinate, while they are individual and vary within the given boundaries [21, 22]. It is necessary to calculate the brightness temperature for models with different internal structure. The calculation of the brightness temperature is carried out according to the scheme (see Fig.1).

An important task is to determine the dependence of the internal temperature on the size of the tumor, which can be done by computer simulation by varying the tumor radius.

3. Used models

3.1. Heat dynamics model

The energy equation for modeling the dynamics of heat in the mammary gland is limited only by the mechanism of heat conduction

$$\frac{dU}{dt} = - \text{div}(\vec{q}),$$

(1)

where $U$ is energy, $\vec{q}$ is heat flux vector. In order to qualitatively describe all inhomogeneities, it is convenient to use the computational method Smoothed Particle Hydrodynamics (SPH). The authors in [23] proposed an approximation of the heat equation, which was obtained on the basis of an approach that uses solutions of the decay of discontinuities. The temperature distribution in this case is defined as

$$\frac{dU_i}{dt} = - \sum_j \frac{m_j W_{ij}'}{\rho_i \rho_j} \left[ 2\lambda_i \lambda_j \frac{1 + \sqrt{a_i/a_j}}{\lambda_i + \lambda_j \sqrt{a_i/a_j}} (T_j - T_i) \frac{1}{|r_j - r_i|^2} \right],$$

(2)

where $a$ is thermal diffusivity, $W_{ij}'$ is weight (smoothing) function or the core, $m_j$ is particle mass $j$.

It should be noted that this equation determines the temperature profile at the contact of particles from different materials [24]. Comparison of results with known accurate data leads
Figure 2. Comparison of the results of a numerical experiment (black points) with an analytical solution (solid line) (a). Dependence of the computational error on the number of computational cells $N$ (b).

Figure 3. The initial distribution of particles in the mammary gland (a). The thermodynamic temperature distribution (b).
3.2. Radiation field model
An important problem of the method of microwave thermometry is the determination of the brightness temperature, which is different from thermodynamic. This temperature is measured using microwave antennas. An antenna with a frequency of several GHz allows you to measure thermal radiation from biological tissues in a certain frequency range.

Brightness temperature equals

\[ T_B(\vec{r}) = \frac{1}{\Delta f} \int |S_{11}(f)|^2 T_{REC} + \left[ 1 - |S_{11}(f)|^2 \right] \times \]

\[ \times \left( \int_{V_0} T(\vec{r}) \frac{P_d(\vec{r}, f)}{\int_{V_0} P_d(\vec{r}, f) dV} dV + T_{EMI} \right) df, \]  

where \( P_d = \frac{1}{2} \sigma(\vec{r}, f) \cdot |\vec{E}(\vec{r}, f)|^2 \) is electromagnetic field power density, \( \vec{E} \) is electric field vector. Values \( T_{EMI} \) and \( T_{REC} \) characterize electromagnetic interference when measured with a radiometer [25, 26]. Coefficient \( S_{11} \) determines the interaction between the antenna and the biological tissue. Integration is carried out over the entire volume of biotissue \((V_0)\).

To construct a stationary electric field distribution, it is convenient to solve the time-dependent Maxwell equations and as the result to obtain the stationary-state:

\[ \nabla \times \vec{E} = 0, \quad \nabla \times \vec{B} = 0, \quad \vec{B} = \mu \vec{H}, \quad \vec{D} = \varepsilon \vec{E}, \]

where \( \vec{B} \) is magnetic induction, \( \vec{E} \) is electric field strength, \( \vec{D} \) is electric induction, \( \vec{H} \) is magnetic field strength, \( \varepsilon(\vec{r}) \) is the dielectric constant, \( \mu(\vec{r}) \) is magnetic permeability.

Procedure of numerical solution for determination of internal temperature distribution \( T_B(x, y, z) \) inside the tissue volume in the model (2)–(3) described in [27, 28].

4. Numerical experiments to study the characteristics of the brightness temperature
To calculate the brightness temperature, the distribution of the thermodynamic temperature (see Fig.3(b)) and the distribution of the electric field intensity were initially calculated.

Further, according to the algorithm, the brightness temperature was simulated at 9 points of the mammary gland taking into account the measurement scheme, which is determined by the diagnostic method. The data obtained using a numerical experiment were compared with data from real patients to verify the result. Two data samples gave a good agreement among themselves, based on which it can be concluded that the used models are applicable to this problem. It should be noted that the brightness temperature is not the temperature in the usual sense. It characterizes radiation, and, depending on the radiation mechanism, it can differ significantly from the physical temperature of the radiating body.

To determine the effect of tumor size on the distribution of the internal temperature, 4 models were built with the same internal structure, but different tumor radii. It follows that the radius of the tumor significantly affects the brightness temperature from the above graphs. The task of early diagnosis is to detect and localize a tumor of a small size, which in real conditions is difficult to do. Since it is clear that the tumor of the smallest radius makes the weakest contribution to the general thermal field of the mammary gland.

5. Conclusion
Instead of traditionally used models with homogeneous parameters in a multilayer approximation (usually limited to four types of tissues – skin, muscles, mammary glands, tumors), in this
6. References
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