Journal of Physics: Conference Series **2140** (2021) 012027 doi:10.1088/1742-6596/2140/1/012027

Application of the migration method for radiotomography of breast cancer

A I Eremeev[1], V V Vasin[1], R N Satarov[1], I S Tseplyaev[1] and S S Shipilova[2]

[1] Tomsk State University, Tomsk, Russia
[2] Tomsk Polytechnic University, Tomsk, Russia

E-mail: aleksandr_eremeev_93@mail.ru

Abstract. A new method to visualize microwave image is presented to early non-invasive detection of breast cancer tumors. A new processing method to compute microwave images of heterogeneity in a biological environment is described here, as well as a new algorithm for accelerating the calculation of three-dimensional radio images. Sounding of synthetic phantoms with dielectric properties of breast tissue was carried out in the range of 2–8 GHz using a special radar system developed by the authors. Results show that it is possible to use this microwave imaging method to form 3D accurate images using hemispherical scan Images of tumor phantoms were obtained during probing in the 2–8 GHz range with a resolution of about 5–7 mm.
According to the results of the reconstruction of three-dimensional radio images, it was revealed that the calculation time can be reduced by at least 2 times with an insignificant loss of quality.

1. Introduction

This article proposes the approach to the development of a microwave visualization method for solving the problem of early non-invasive diagnosis of breast neoplasms. This direction is actively developing in the world, since breast cancer is the second most common cancer in the world after lung cancer and, along with cardiovascular and respiratory diseases, is a socially significant disease. Survival for cancer primarily depends on the stage at which treatment began, so they need to be diagnosed as early as possible (the probability of complete recovery reaches 93% in the case of early diagnosis of breast cancer (stages I-II)) [1, 2]. Non-invasive and comfortable for the patient (as opposed to painful X-ray mammography), but at the same time fast diagnosis is a long-standing medical request, despite the existing methods of X-ray and ultrasound diagnostics. At the same time, each of the methods is not absolute and sufficient and has its own limitations associated with the following factors: inaccurate location and size of tumors, long scanning time, the requirement for a homogeneous background environment, ambiguity of the images obtained, the presence of ionizing radiation, high cost of installations, low probability of detecting small forms of benign and malignant neoplasms. Most of these limitations are associated with the characteristics of oncological tumors. On the one hand, the density practically does not change in tumors at an early stage, but these changes are recorded during X-ray and ultrasound examinations. On the other hand, the dielectric constant changes in the area of tumor formation due to the proliferation of blood vessels that provide blood flow to new tumor cells in this area of space. Such change in the electrophysical characteristics can be recorded by radio wave sounding. Thus, the tumor detection can be based on the fact that the dielectric properties of a healthy tissue and a malignant tissue are different. This is confirmed by large-scale studies that have shown that the values of the dielectric constant of the tumor and healthy tissue are different [3, 4].

It follows from here that methods of detecting neoplasms are needed at present, that will improve the diagnosis of breast cancer and allow starting treatment as early as possible, thereby significantly increasing the chances of recovery. Use of microwave electromagnetic radiation is the most promising non-invasive method for searching for neoplasms in a biological environment. Microwave radio waves penetrate deep enough into biological tissues that can be used for mammography purposes. The advantages of radio wave methods are that they are harmless to humans and do not require the special conditions for working with the equipment, unlike X-ray installations.

Scientists around the world have shown promising results in the development of a microwave tomograph for the diagnosis of breast cancer. However, long scan time and low resolution are still the main unsolved problems.

2. Method for calculating microwave images

The radiolocation approach to obtaining the information about inhomogeneities in the biological environment is used in this investigation. It is known that the use of focusing radiation significantly reduces the influence of multiple interactions and diffraction effects so that an adequate description of the dominant wave interactions can be described in the single interaction approximation.

The main idea of this operation is to sum all received signals with calculated delay for a given focus point $\mathbf{r}_F$. Scanning the dedicated sounding area by focus point allows getting the spatial distribution of inhomogeneities. If sounding is carried out from a large number of angles, then the superposition (sum) of a plurality of interference patterns of the received signals decreases the level of side lobes and increases the value of the main maximum at the focal point. In the case of a monostatic locating scheme, the result of signal focusing is written as

$$U(\mathbf{r}_F) = \sum_n S(\mathbf{r}_n, \tau_n), \ \tau_n = \frac{2\sqrt{\varepsilon}}{c}\left|\mathbf{r}_F - \mathbf{r}_n\right| \tag{1}$$

where S is the received and transmitted signal at the point $\mathbf{r}_n$, ε is the average background medium dielectric constant, τ_n is the signal delay when reflected from heterogeneity.

For studies of volumetric objects, it is convenient to scan along a hemispherical surface with the radius B and angular coordinates of the azimuth and zenith (φ_n, θ_m), surrounding the object under study. In this case, the expression (1) takes the form:

$$U(\mathbf{r}_F) = \sum_n \sum_m S(\varphi_n, \theta_m, B, \tau_{n,m}), \tag{2}$$

where the delay for focus point with the coordinates $\mathbf{r}_F = (x_F, y_F, z_F)$ is calculated by the formulas

$$\tau_{n,m} = \frac{2\sqrt{\varepsilon}}{c}\sqrt{\left(x_F - B\sin(\theta_m)\cos(\varphi_n)\right)^2 + \left(y_F - B\sin(\theta_m)\sin(\varphi_n)\right)^2 + \left(z_F - B\cos(\theta_m)\right)^2}. \tag{3}$$

The problem of eliminating the additive interference that occurs during reflection from the scanner design, internal re-reflections in the channels of microwave paths and receiving-transmitting antennas, arises when processing the received signals. There are a number of methods for eliminating this interference. In some cases, the differential calibration is used [5], in which the previously obtained signals from the healthy breast of the same patient, previously measured at periodic examinations, are subtracted. The disadvantage of this approach is the need for long-term observation of the patient and regular sounding procedure. Another approach uses the technology of rotating the antenna array [6]. When the grating is rotated, two signals are recorded, and then they are subtracted. This assumes that the chest has cylindrical symmetry, however, this approximation is too rough. The standard filtering method is to subtract the DC component of the received signal P for each time point t_i . Mathematically, this operation is described by the following expression.

$$U(\mathbf{r}_F) = \sum_n \left(S(\mathbf{r}_n, \tau_n) - P_{f(\mathrm{n})} \right),\ \ P_i = \frac{1}{N} \sum_n S(\mathbf{r}_n, t_i),\ \ f(\mathrm{n}) = \left[\frac{\tau_n}{\Delta t} \right]. \quad (4)$$

Here the operator $f(\mathrm{n})$ calculates the integer part of the number, and Δt is time sampling step. This operation assumes that at each sounding point the noise has the same temporal shape. In the case of sounding on a hemispherical surface, the interference associated with multiple reflections in the microwave channels and antennas is the same, and the interference associated with reflections from the scanner design is different.

To eliminate the interference in this work, it is proposed to use the special filtering of the constant components of the signal Q at each of the angular latitudes of sounding θ_m using the expression

$$U(\mathbf{r}_F) = \sum_n \sum_m \left(S(\varphi_n, \theta_m, B, \tau_{n,m}) - Q_{m,f(\mathrm{n})} \right),\ \ Q_{m,i} = \frac{1}{N} \sum_n S(\varphi_n, \theta_m, B, t_i)\,. \quad (5)$$

The proposed original solution will be applied further to obtain three-dimensional radio images of the phantom breast.

3. Accelerated algorithm for calculating 3D microwave image

To develop an algorithm for increasing the speed of calculating the radio image, we consider the situation (Figure 1). The area is divided into nodal and small grids. The grid step is determined by the formula (6):

$$N = \frac{D}{d}, \quad (6)$$

where D is the scale of the nodal grid, d is scale of the small grid. The nodes that correspond to the elements of the small grid are highlighted in red. The elements of the small grid are highlighted in blue. Receiving and transmitting antennas are highlighted in yellow.

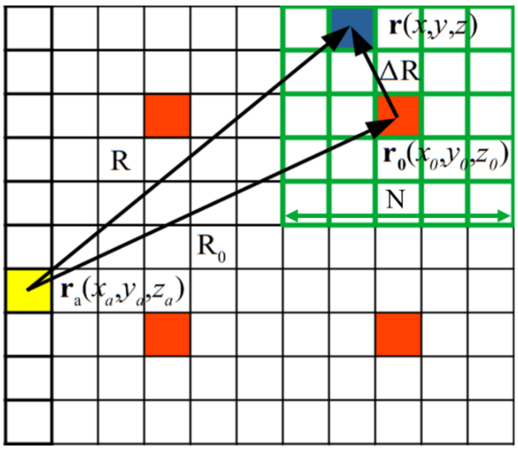

Figure 1. Dividing the space into nodal and small grids.

The algorithm calculates the distance for small elements of the space relative to the nodal grid. The distance for nodes is calculated without any approximations. Vector $\mathbf{r}$ is the vector between the node and the element of small grid, vector $\mathbf{r}_0$ is the vector between antenna and the node, $\mathbf{r}_a$ is the vector between antenna and the element of small grid. R is the distance between antenna and the element of small grid, ΔR is the distance between the node and the element of small grid, R_0 is the distance between antenna and the node. The distance between the nodes, expressed in the number of elements of the small grid, is called the step of the nodal grid. To calculate the distance using the formula (7) and expanding it to Taylor series we obtain the formula (8), which allows to calculate the distance approximately necessary for calculating the radio image.

$$R_0 = \sqrt{\sum_{i=1}^{3} (\mathbf{r}_i - \mathbf{r0}_i)^2}, \tag{7}$$

$$R \approx R_0 - \frac{1}{R_0} \sum_{i=1}^{3} (\Delta \mathbf{r}_i (\mathbf{r}_i - \mathbf{r0}_i)) \tag{8}$$

A program in the C++ language has been created. The program allows to compute the distance with approximation and without it. The calculation of the radio image was carried out on the configuration I7-3635QM 2.4 GHz, 8 GB DDR3. Two material points were modeled in the space and the inverse problem of building a radio image is solved. 3D Radio Image Resolution is 200×200×200. Figure 2 shows the dependences in red of the time of solving the inverse problem with increasing the step of the nodal grid and the difference between the images with increasing the step of the nodal grid (in blue). The Figure 2 shows that use the nodal grid with the smallest possible step reduced the computation time of the radio image by two times, and the quality of the radio image changed by several percent.

With an increase in the step of the nodal grid, the time for calculating the radio image decreases to a certain value, while the quality of the calculated radio image decreases. The optimal step of the nodal grid is chosen to be 20.

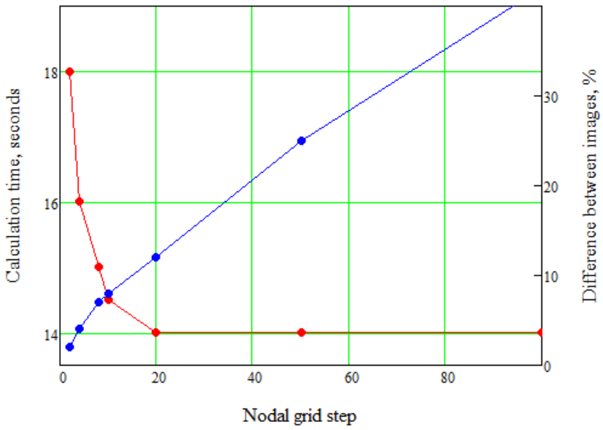

Figure 2. Calculated radio image at different step of the nodal grid.

4. Hardware for sounding the model environments

To test the microwave tomography method, a laboratory model in the form of a scanner was developed (Figure 3).

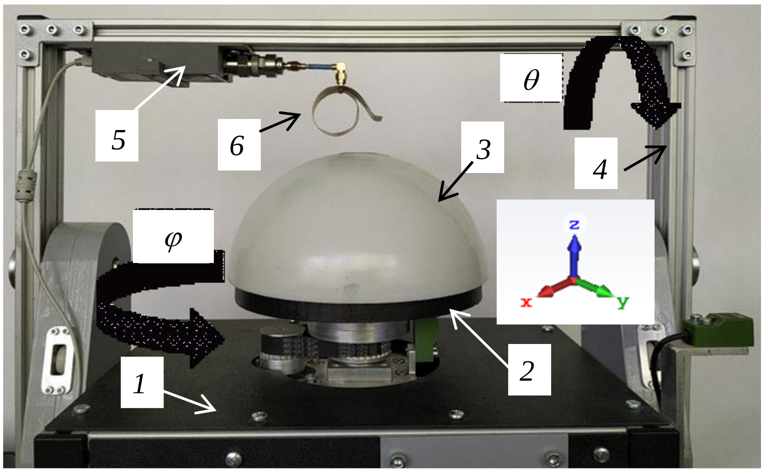

Figure 3. Hemispherical scanner. 1 – body; 2 – rotating platform; 3- object of investigation; 4 – rotation frame; 5 – VNA; 6 – antenna.

Scanner allows to scan in the spherical system by rotating the table on the angle φ in the diapason of 0–360 degrees and rotating frame on the angle θ in the diapason of 0–90 degrees. VNA CABAN R140 by "Planar" firm with the working frequency range of 0.3–14 GHz uses as RF generator. The vector reflectometer was attached to the moving frame of the scanner. An ultra-wideband antenna was connected to the reflectometer. A wide antenna frequency band and a stable directional pattern allow providing an operating sounding frequency band in the 2–8 GHz range.

5. Results

The results of detecting inhomogeneities in a homogeneous medium were obtained earlier for the case of scanning along the plane [7]. In this study, a breast phantom similar in electrophysical properties to a real breast was developed in order to fully test the system for detecting the heterogeneities. During the development of the breast phantom, polyurethane mixtures with the various graphite contents were used [8]. With the help of calculations and experiments, the proportions of polyurethane and graphite were selected to simulate human fat, skin and glands. Figure 4 shows the photo of the phantom and its cross section.

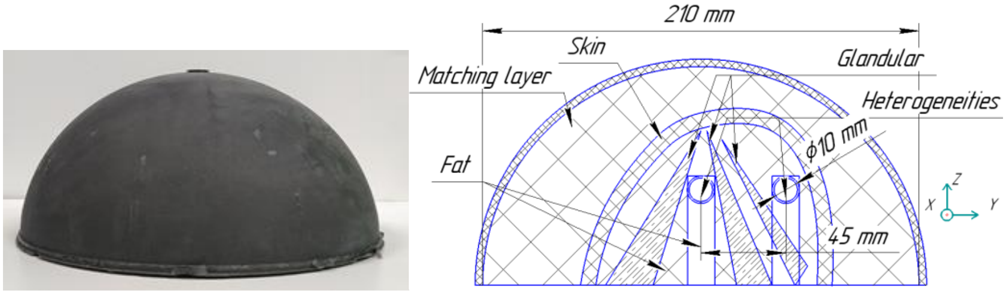

Figure 4. Breast phantom and its cross section.

The developed mammary gland phantom was used to test the algorithms for calculating the radio image. Multi-angle sounding was provided using a spherical scanner. Figure 5 shows the results of experiments with the phantom. Radio image resolution is 100×100×20. The computation time without optimization was 47 seconds, and the use a nodal grid with the smallest possible step reduced the computation time to 37 seconds. The use of a nodal grid with the maximum possible step has reduced the time for calculating the radio image to 27 seconds. In this case, it is possible to determine the location and size of the tumors. Without optimization, the calculated radio image quality improved slightly.

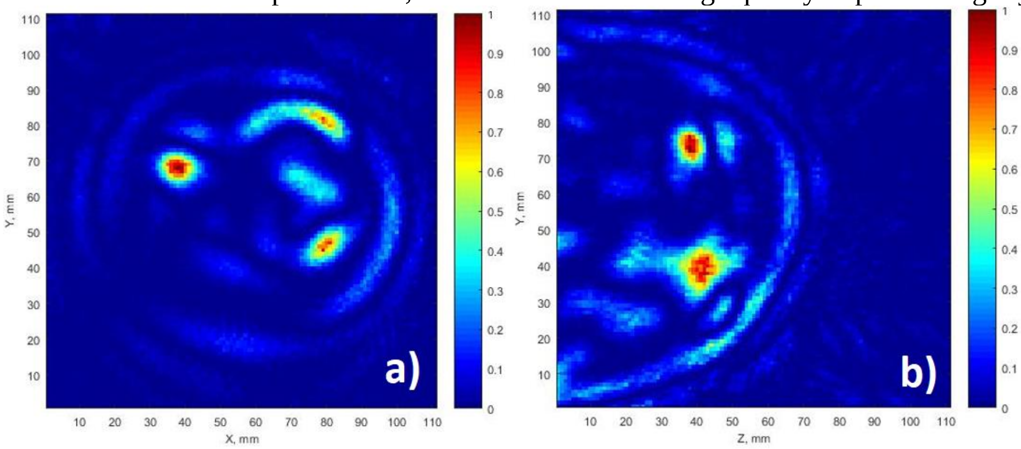

Figure 5. Radio images of heterogeneities in the coronal plane (a) and in the sagittal plane (b).

Also, analyzing the obtained results, it is possible to estimate the resolution of the proposed approach, which does not exceed the dimensions of the heterogeneities themselves and is about 5–7 mm.

The obtained result allows us to conclude about the advantages of the proposed approach for calculating the radio image in comparison with the standard methods.

6. Conclusion

This paper proposes the approach to the development of a microwave imaging method for solving the problem of early non-invasive diagnosis of breast tumors. The method of data processing for obtaining radio images of heterogeneities in a biological environment is described, as well as the algorithm for accelerating the calculation of a three-dimensional radio image is described. The results obtained by scanning on the hemisphere of the breast phantom using the proposed method show that this microwave visualization method is able to form 3D accurate images.

Acknowledgments

This research was supported by Ministry of Science and Higher Education of the Russian Federation, project № FSWM-2020-0038.

References

[1] Onitilo A A *et al.* 2009 *Clinical medicine and research* **7**(1–2) 4–13 doi: 10.3121/cmr.2008.825
[2] Cancer: Facts and Figures 2019–2020 2020 *American Cancer Society*. Available at: https://www.cancer.org/research/cancer-facts-statistics/all-cancer-facts-figures/cancer-facts-figures-2020.html
[3] Lazebnik M *et al.* 2007 *Phys. Med. Biol.* **52** 6093–6115 doi: 10.1088/0031-9155/52/20/002
[4] Lazebnik M *et al.* 2007 *Phys. Med. Biol.* **52** 2637–2656 doi: 10.1088/0031-9155/52/10/001
[5] Porter E *et al.* 2013 *IEEE Antennas and Wireless Propagation Letters* **12** 229–232 doi: 10.1109/LAWP.2013.2247374
[6] Klemm M *et al.* 2010 *IEEE Transactions on Antennas and Propagation* **58** (7) 2337–2344 doi: 10.1109/TAP.2010.2048860
[7] Shipilov S *et al.* 2018 *MATEC Web of Conferences* **155** 01025 doi: 10.1051/matecconf/201815501025
[8] Shipilov S *et al.* 2020 *Medical Physics* **47** (10) 5147–5157 doi: 10.1002/mp.14408