Paper

Estimation of internal distribution of temperature inside biological tissues by means of multifrequency microwave thermograph

Bronisław Stec and Andrzej Dobrowolski

Abstract — The paper presents problems connected with thermal radiation of human bodies in microwave range in aspect of diagnosis breast carcinoma. A mathematical model of transmission thermal radiation through tissues is introduced and methods of measurement of temperature, depth and size of heat source, by means of multifrequency microwave thermograph [1 – 7], are described. Theoretical considerations are supplemented with presentation of result experiments.

Keywords — microwave thermograph, radiometer, thermal radiation, breast carcinoma.

1. Introduction

A monofrequency passive microwave radiometry enables measurements of average temperature of an object on certain depth. From a practical point of view, the problem of estimation of the temperature spatial distribution inside investigated object is extremely interesting. The presented solution uses power thermography on different frequencies. The method is based on the decreasing power penetration distance into biological tissues and simultaneous increasing intensity of thermal radiation versus frequency.

Because of a build of tissue and specificity of breast carcinoma one can conclude, that focus has spherical shape and a distribution of temperature resulted from it exponentially disappears to zero in layer of gland. Thus, the Gauss curve describing deep-seated distribution of temperature, has been assumed.

As presented in [7] in a three-layer model of tissue [4, 6] the real increase of temperature T of the internal heat source leads to increasing brightness of the effective temperature T_f on the surface of tissue, measured by a radiometer working on frequencies f. This relationship can be written as follows:

$$T_f = T \exp\left(-\frac{d_g}{\delta_g}\right) t_{gf} \exp\left(-\frac{d_f}{\delta_f}\right) t_{fs} \exp\left(-\frac{d_s}{\delta_s}\right) \left(1-|\Gamma_f|^2\right), \tag{1}$$

where: d_g, d_f, d_s – lengths of ways in layers of gland, fat and skin, δ_g, δ_f, δ_s – power penetration distance in each layer, t_{gf}, t_{fs} – coefficients of power transmission on the interfaces contact, Γ_f – reflection coefficient on antenna and skin interface.

2. Three – band microwave radiometer system

Since the temperature distribution is given by:

$$T(z) = T_S \exp\left[-\left(\frac{z-d_g}{\sigma}\right)^2\right], \tag{2}$$

the temperature brightness (1) in surface model of tissue, shown in Fig. 1, can be written as

$$T_f = T_g t_{gf} \exp\left(-\frac{d_f}{\delta_f}\right) t_{fs} \exp\left(-\frac{d_s}{\delta_s}\right) \left(1-|\Gamma_f|^2\right), \tag{3}$$

where temperature T_g on the gland and fat interface is defined with an integral of temperature distribution $T(z)$ in range $< 0, \infty >$, with regard of transfer coefficient

$$\xi(z) = \exp\left(-\frac{z}{\delta_g}\right). \tag{4}$$

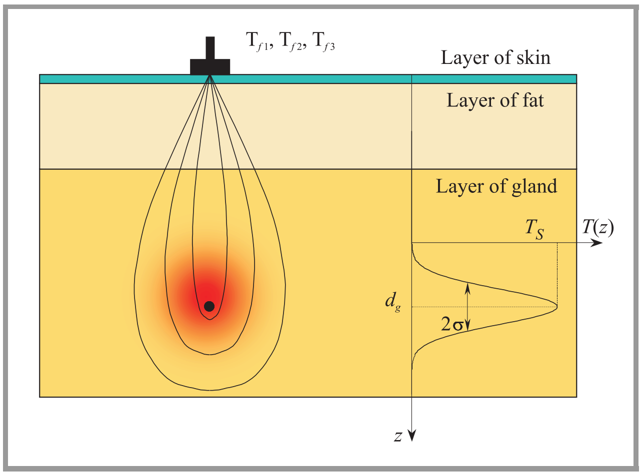


Fig. 1. Distribution of temperature inside biological tissue.

From Eqs. (2) and (4), $T(\xi)$ can be found to be:

$$T(\xi) = T_S\, e^{-\left(\frac{d_g}{\sigma}\right)^2} \xi^{-\frac{\delta_g}{\sigma^2}(\delta_g \ln \xi + 2d_g)}. \tag{5}$$

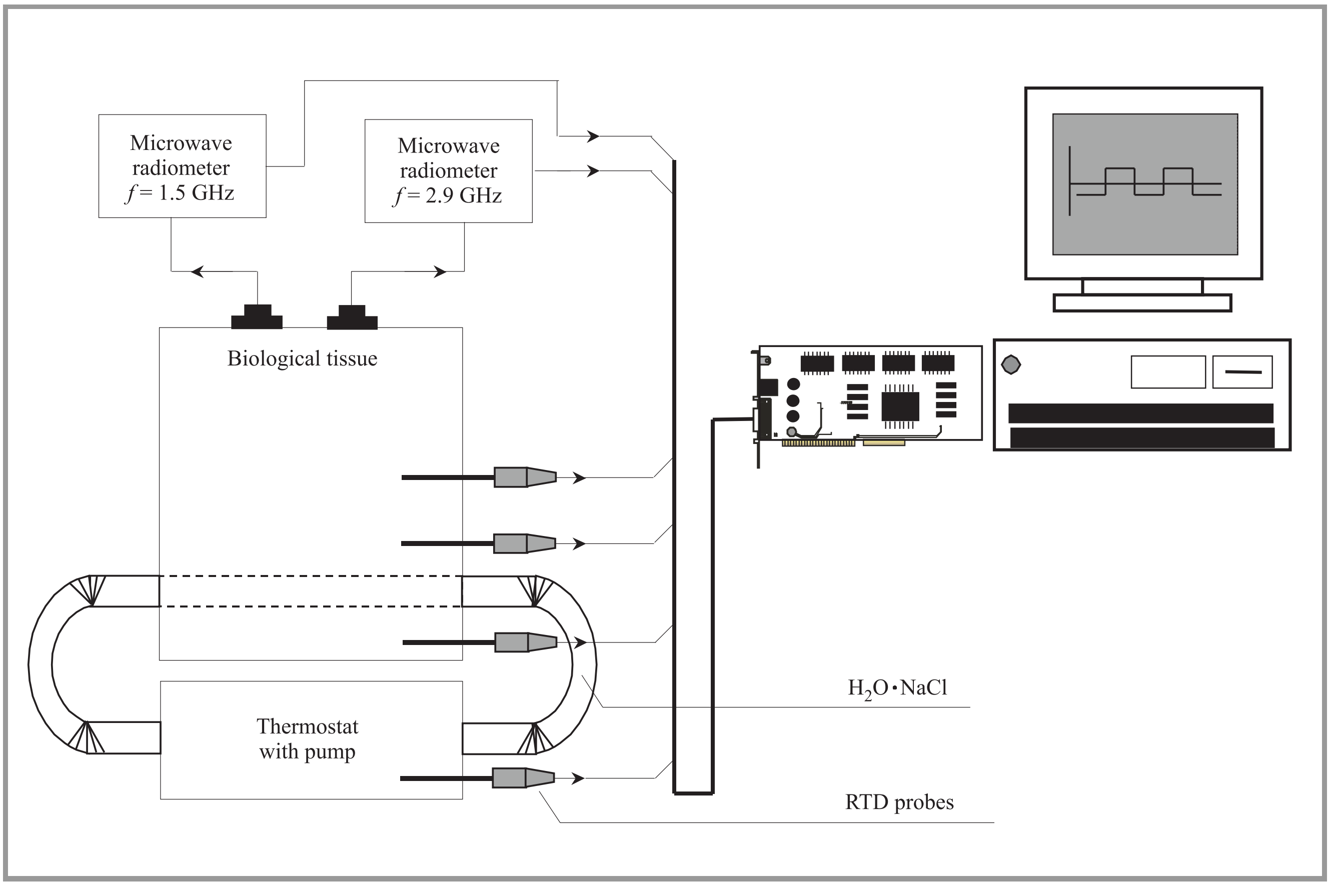


Fig. 2. Scheme of the measurement.

Integration of the relation with respect to z from 0 to ∞ is equivalent to the integration of the relation with respect to ξ in a range $< 0, 1 >$ and consequently, for

$$d_g \leq d_{g\,\min} = 2\sigma + \frac{\sigma^2}{2\delta_g}, \tag{6}$$

the effective temperature of noise on border of gland and fat is defined as:

$$T_g = \frac{T_S \sigma \sqrt{\pi}}{\delta_g} \exp\left(\frac{\sigma^2 - 4\delta_g d_g}{4\delta_g^2}\right). \tag{7}$$

Because of the slender thickness of the skin layer in tested place, one can treat it as a thin layer. Thus, in radiometers constructed in Military University of Technology in Warsaw $\Gamma_f = 0$ [8], the dependence (3) takes the following form

$$T_f = \frac{T_S \sigma \sqrt{\pi}}{\delta_g} \exp\left(\frac{\sigma^2 - 4\delta_g d_g}{4\delta_g^2}\right) K, \tag{8}$$

where

$$K = t_{gf} \exp\left(-\frac{d_f}{\delta_f}\right). \tag{9}$$

Knowing the coefficient K (appointed in a calibration process for three radiometers working on different frequencies and their respective power penetration distances) one can estimate the real distribution of temperature realising multi-frequency measurement. Solving the set of Eq. (8) for three frequencies f_1, f_2, f_3 we obtain expressions describing the real distribution of temperature in investigated tissue:

$$d_g = \frac{\alpha\, \delta_{g1}^2(\delta_{g2}^2 - \delta_{g3}^2) - \beta\, \delta_{g3}^2(\delta_{g1}^2 - \delta_{g2}^2)}{\delta_{g1}^2(\delta_{g2} - \delta_{g3}) - \delta_{g2}^2(\delta_{g1} - \delta_{g3}) + \delta_{g3}^2(\delta_{g1} - \delta_{g2})},$$

$$\sigma = 2\delta_{g1}\delta_{g2}\sqrt{\frac{d_g(\delta_{g2}^{-1} - \delta_{g1}^{-1}) - \alpha}{\delta_{g1}^2 - \delta_{g2}^2}}, \tag{10}$$

$$T_S = \frac{T_{f1}\delta_{g1}}{\sigma K_1 \sqrt{\pi}} \exp\left(\frac{4\delta_{g1} d_g - \sigma^2}{4\delta_{g1}^2}\right), \tag{11}$$

where:

$$\alpha = \ln\left(\frac{T_{f1} K_2\, \delta_{g1}}{T_{f2} K_1\, \delta_{g2}}\right), \quad \beta = \ln\left(\frac{T_{f2} K_3\, \delta_{g2}}{T_{f3} K_2\, \delta_{g3}}\right). \tag{12}$$

Entire depth of heat source definite is sum

$$d = d_g + d_f + d_s. \tag{13}$$

3. Temperature measurement experiments

In measurements, beef meet has been used as a tissue. The polypropylene tube of diameter 5 mm, with 1.5% saline solution NaCl has been used as the heat source. A thermostat has regulated the temperature of the liquid. In the range of temperatures (30°C−45°C) the conductivity of the solution is about 2 S/m, and relative permittivity falls into a range (70 − 75). Such parameters assure very good coefficient of power transmission on the solution and tissue interface. In measuring range of frequency it is equal to 0.99. Side of tube can be omitted in analysis because its thickness is equal to 0.1 mm.

Measuring position is presented schematically in Fig. 2. To inspection of distribution of temperature inside the tissue mini hypodermic probes with platinum RTD element have been used. To test the noninvasive thermometry based on the principles described in this paper, we have developed an experimental two – band radiometer system that measures the brightness temperature at 1.5 and 2.9 GHz. Measurements have been made automatically and results have been displayed on the computer CRT in real time.

Experiment has been realised for two widths of layer the muscle with use of wide distribution of temperature. Distribution should be sufficiently wide in relation to dimensions of tube, so that its influence on results was prevailing, and simultaneously not too wide because of an error of integrating [condition (6)].

In Fig. 3 the results of the measurements and theoretical characterisations – Eq. (8) – describing behaviour of the effective temperatures illustrated by radiometers versus width distribution of the temperature for two distances antennas – heat source are shown.

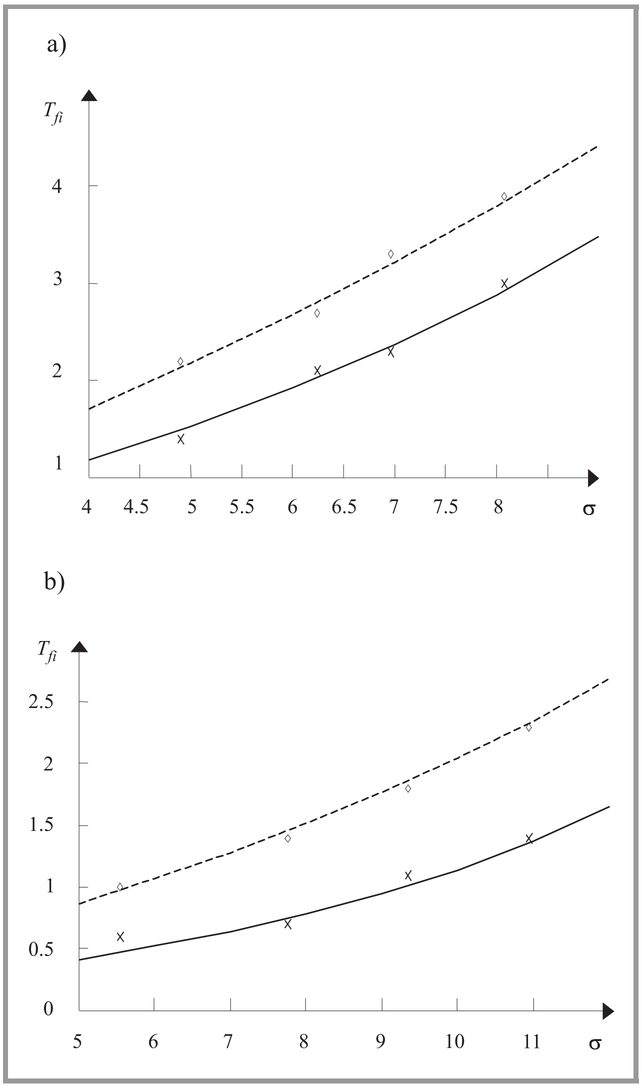


Fig. 3. Results of measurements and calculations for radiometers working on frequencies 1.5 GHz (dashed line) and 2.9 GHz (continuous line) for $d_g = 24.5$ mm (a) and $d_g = 34.5$ mm (b).

4. Conclusion

The aim of this work is elaboration of a measurement method permitting the construction of a spatial microwave thermograph. The paper presents problems related to thermal radiation of human bodies in microwave range and description of transmission properties of living tissues. The correctness of the presented analysis is confirmed by the experiment described in the paper. The results of the work point at a possibility of detecting and measurement of temperature, depth and size of heat sources inside human body, by means of multifrequency microwave thermograph [7].

The idea of spatial microwave thermography, resulting from theoretical analysis and results of experiments, is described in the paper. The theoretical analysis and experiments confirmed initial expectations, which has formed a base to an attempt of estimation of spatial temperature distribution inside biological tissues. At present, most promising is a construction of a thermograph as a multichannel receiver, with each channel being separate radio receiver. Also, a delivery of signal simultaneously to all channels by one wide-band antenna would be advisable. In practice, however, the above postulate is difficult to realise.

References

[1] L. Dubois, J. Pribetich, J. Falbre, M. Chive, and Y. Moschetto, "Non-invasive microwave multifrequency radiometry used in microwave hyperthermia for bidimensional reconstruction of temperature patterns", *Int. J. Hyperther.*, vol. 9, pp. 415–431, 1993.

[2] S. Mizushina, T. Shimizu, K. Suzuki, M. Kinomura, H. Ohba, and T. Sugiura, "Retrieval of temperature-depth profiles in biological objects from multifrequency microwave radiometric data", *J. Electromagnet. Wav. Appl.*, vol. 7, pp. 1515–1548, 1993.

[3] H. Ohba, M. Kinomura, M. Ito, T. Sugiura, and S. Mizushina, "Multifrequency microwave radiometry for non-invasive thermometry using a new temperature profile model function", in *Asia Pacific Microw. Conf.*, Tokyo, Japan, 1994, vol. 17-1, pp. 401–404.

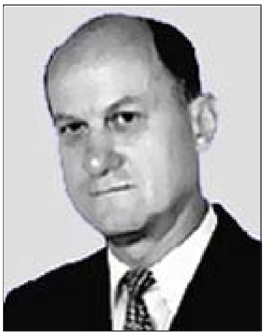
[4] B. Stec and A. Dobrowolski, "Analiza własności transmisyjnych tkanek biologicznych w zastosowaniu do przestrzennej termografii mikrofalowej", in *VIII Symp. URSI'96*, Wroclaw, Poland, 1996, pp. 277–280.

[5] B. Stec and A. Dobrowolski, "Przestrzenna termografia mikrofalowa", in *Symp. KST'97*, Bydgoszcz, Poland, 1997, pp. 442–448.

[6] B. Stec and A. Dobrowolski, "Analiza własności transmisyjnych tkanek biologicznych w zastosowaniu do przestrzennej termografii mikrofalowej", *Biul. WAT*, no. 11, pp. 31–40, 1997.

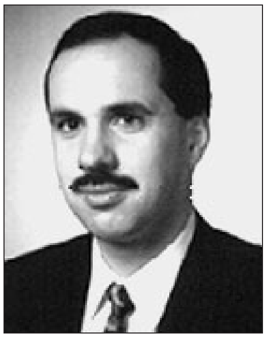
[7] B. Stec and A. Dobrowolski, "Wieloczęstotliwościowa termografia mikrofalowa", *Kwart. Elektron. Telekomun. PAN*, vol. 45, no. 2, pp. 225–233, 1999.

[8] B. Stec and M. Żurawski, "Compensated microwave thermometer for medical applications", in *Asia Pacific Microw. Conf.*, Tokyo, Japan, 1994, vol. 17-2, pp. 405–408.



Bronisław Stec has worked at the Military University of Technology since 1962. He participates in works of Scientific Council of the Faculty of Electronics and the Senate of the Military University of Technology, Warsaw, Poland. He implemented a microwave frequency detector, a monopulse finding direction system and a microwave thermograph for non-invasive measurement of temperature distribution inside biological objects. A military warning device and a recognise receiver of satellite telecommunications were created under his leadership. From 1980 to 1994 he was a Deputy Director and Director of the Institute of Electronic Circuits. In 1991 he became an Associate Professor at the Military University of Technology.

Faculty of Electronics
Military University of Technology
Kaliskiego st 2
00-908 Warsaw, Poland



Andrzej Dobrowolski was born in 1966. He received the M.Sc. degree in the field of radiolocations and the Ph.D. degree in the field of telecommunications, both from the Military University of Technology, Warsaw, Poland, in 1990 and 2001, respectively. Currently, he works at the Institute of Fundamentals of Electronics, Military University of Technology. His current scientific interests focus on applications of digital signal processors in a microwave thermograph.

e-mail: ADobrowolski@wel.wat.waw.pl
Faculty of Electronics
Military University of Technology
Kaliskiego st 2
00-908 Warsaw, Poland