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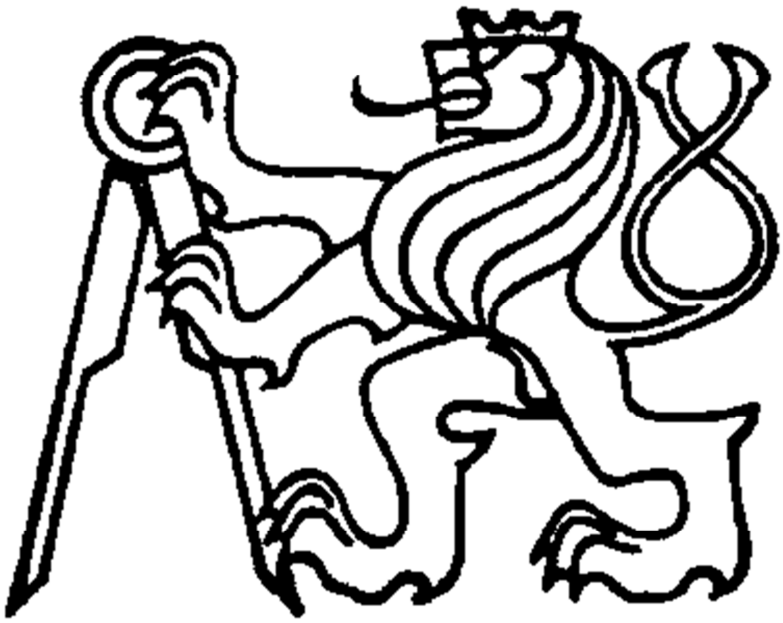

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electromagnetic Field

Ing. Barbora Vrbová

Principles of Applicators Design for Microwave Hyperthermia and Physiotherapy

Ph.D. Programme: Electrical Engineering and Information Technology

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Contents

1. State of the Art in the field of Microwave Thermotherapy

According to the progressive developments in the studies on EMFs, the therapeutic effects of interaction between EMFs and biological systems have been utilised in the fields of oncology, physiotherapy and urology since the late 1970s. Nowadays, microwave thermotherapy is a common cancer therapeutic tool in many countries, including the EU, the USA, Japan and China. Thanks to clinical research undertaken at the 1st Medical Faculty of the Charles University, in combination with technical research undertaken at the Department of EMFs at the Czech Technical University (CTU), microwave thermotherapy was already in use in former Czechoslovakia since 1981, with more than 1000 cancer patients having been successfully treated at Bulovka Hospital in Prague using the process since then. Since 1981 the CTU has worked in close cooperation with the Academy of Sciences of the Czech Republic, and specifically with the Institute of Photonics and Electronics, resulting in basic discussions on Cancer Physics. In 2001, a new cooperation agreement was finalised between the CTU and the Institutes of Microbiology and Physiology. Cooperation in the area of interactions of EM field with biological systems has CTU also with Medical Faculty in Pilsen of the Charles University and with the Technical University in Liberec.

Through the centuries there have been many recorded references to the treatment of human diseases, including cancer, with increased temperature. An already famous aphorism of Hippocrates from 400 BC ends with words:

Those diseases which medicines do not cure, iron (the knife) cures;
those which iron cannot cure, fire cures;
and those which fire cannot cure, are to be reckoned wholly incurable.

Some medical reports written in the 18th , 19th and early 20th century are describing remission of a variety of tumours after body temperature of the patient was increased (e.g. by viroses, etc.), but methods used at that times were mostly uncontrollable and thus providing unpredictable results [1]. Thanks to the rapid development of microwave technology in the seventieth and early eighties we can talk about microwave thermotherapy, which is being used in medicine for the cancer treatment and for treatment of some other diseases.

We can divide medical applications of microwaves into the three basic groups according to purpose:

- treatment of patient (with the use of thermal or non-thermal effects of microwaves),
- diagnostics of diseases (e.g. permittivity measurement, microwave tomography, etc.),
- part of a treatment or diagnostic system (e.g. linear accelerator, etc.).

Microwave thermotherapy is based mainly on thermal effect. Temperatures up to 41^{o}C are used for applications in physiotherapy and this method is called microwave diathermia. Microwave hyperthermia uses the temperature interval between 41^{o}C and 45^{o}C for cancer treatment. Microwave ablation (destruction of cells) occurs, when the temperature is more than 45^{o}C. Such microwave thermo ablation can be used e.g. in cardiology (for heart stimulations, treatments of heart arrhythmias, fibrillations, microwave angioplastics etc.) and in urology for treatment of Benign Prostatic Hyperplasia (BPH), etc.

Microwave thermotherapy in case of cancer treatment is often used in combination with other medical therapeutical methods, like e.g. immunotherapy, chemotherapy, radiotherapy or chirurgical treatment. Some of these therapeutic methods have many undesirable effects, such as e.g. effects of ionizing radiation, etc.

From clinical and biological point of view microwave hyperthermia is based on differences in the behaviour of healthy tissue and tumour tissue under enhanced temperatures. This method is based on the principle of destruction of malignant cells by artificially increasing the temperature above 41°C, while healthy tissue survives temperatures of 45°C [2]. In such case self-protective mechanism of malignant cells fails, they turn to apoptosis. Temperature in the area to be treated grows up in biological tissue due to absorption of power of electromagnetic waves, because biological tissue represents a lossy dielectric environment absorbed energy of electromagnetic wave is thus changed into a thermal energy, which means an increase of temperature. The blood flow in tumour cells decreases with increasing temperature, and so the temperature in tumour cells increases even more rapidly. So in temperature interval between 41 and 45°C only tumour tissue is destroyed (an apoptosis of tumour cells is induced) [3].

Disadvantage of hyperthermia (potential risk) could be creation of hot spots in the treated area, but this can be eliminated by use of a water bolus. This bolus should be inserted between surface of biological tissue and applicator aperture. Water bolus can improve transition of electromagnetic waves into treated area and it can help to optimize the temperature profile in the treated area.

The duration of a single hyperthermia treatment typically does not exceed 50 minutes. The level of the hyperthermic dose depends on temperature and time.

A standard hyperthermia system consists mainly from a high power rf. or microwave generator, set of thermal sensors, and especially, a set of different types and different aperture shapes and dimensions applicators.

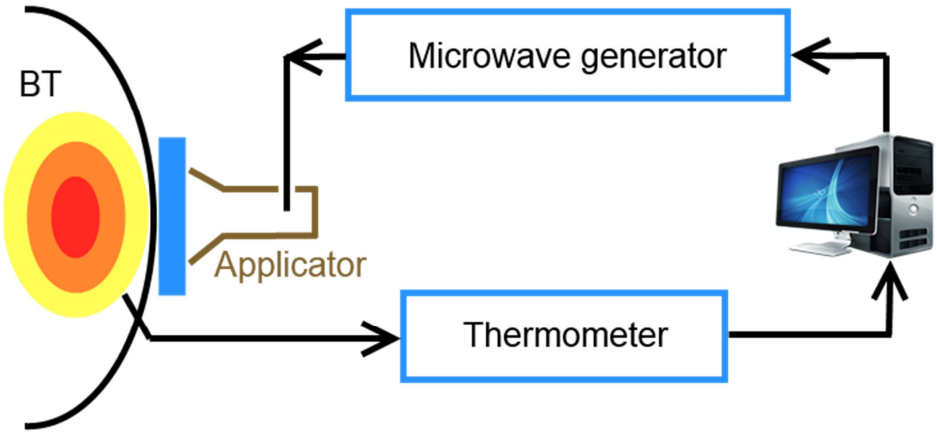


Fig.1 Equivalent scheme of the apparatus for microwave thermotherapy.

2. Main Aims of Doctoral Thesis

I would like to describe the main aims of my doctoral thesis, including information, in which chapter of my doctoral thesis it is possible to find solution of the mentioned problems:

a) New model of microwave hyperthermia system coupled to patient body, based on signal flow graph theory (see Chapter 5, please).
b) Proposal of a new definition for evaluation of the SAR homogeneity during the treatment (see Chapter 6, please).
c) Feasibility study of focusing possibilities for local deep treatment and for case of regional treatment, when EM power is irradiated either into the phantom or into the patient body from several apertures with possibility to set up different amplitudes and phases in each of these apertures (see Chapters 7 and 8, please).
d) Analytical and numerical study of excitations of surface waves, which in therapy can cause so called hot-spots (see Chapter 9, please).
e) Feasibility study of superposition of EM field irradiated both from external and from intracavitary applicators (see Chapter 10 and 11, please).

In my research attention is particularly paid on numerical simulations of SAR distribution and its experimental evaluation by aid of temperature measurements on agar phantoms. Results of this doctoral thesis will be possible to export into clinical practice, e.g. at Institute of Radiation Oncology of the Hospital Na Bulovce.

In following part of this paragraph I would like to describe in more details topics and content of the main parts/chapters of my doctoral thesis. The first chapter ("*Introduction*") specifies orientation of this doctoral thesis to topics of interactions between EM field and biological systems and to medical applications of EM field (especially microwave technologies) to microwave thermotherapy above all.

The second chapter ("*State of the Art in the field of Microwave Thermotherapy*") represents a general introduction into medical applications of microwaves, specifying definitions of the hyperthermia and physiotherapy.

The third chapter ("*Main Aims of Doctoral Thesis*") identifies the main goals (so called "disertable core") of my doctoral thesis first of all. Then description of content of all chapters of this doctoral thesis is given here.

The fourth chapter ("*Applicators for Microwave Hyperthermia and Physiotherapy*") is touching topics of interaction of EM field with biological tissue and defining basic parameters of microwave applicators. Further it deals with description of applicators for local and deep local treatment, basic rules of design of TEM, intracavitary and regional applicators. An original model of studied situation, i.e. applicator coupled to biological tissue, based on oriented graphs theory is proposed here in this chapter. Importance of impedance matching is explained here. Definition of an effective treatment area with respect to SAR distribution and the effective treatment area with respect to temperature distribution is given here. Last but not least, importance of assessment and testing of microwave applicator properties is explained here in this chapter.

In fifth chapter ("*Design of Applicators for Microwave Thermotherapy*") I have proposed a new model of microwave hyperthermia applicator coupled from one side to power generator and from the other side to biological tissue to be treated (based on theory of oriented graphs). This model can be considered as one of my original contributions to the topics of microwave thermotherapy systems. Further in this chapter I described design of applicators used in my work for research activities.

The sixth chapter ("*Microwave Thermotherapy in cancer treatment: Evaluation of Homogeneity of SAR Distribution*") is based on following of my papers [L1,L6]. In this chapter I have propose a new definition of the SAR homogeneity, which is according to my opinion very important parameter for quality assurance of the treatment. Design of applicator and a series of simulations demonstrating usage of homogeneity definition is given here.

The seventh chapter ("*Study of focusing principles for regional treatments by array of applicators in homogeneous phantom*") is based on following of mine papers [L4,L9,L16]. Setups of several applicators used for series of simulations demonstrating homogeneity of SAR in case of dielectrically homogeneous model of area to be treated is given here in this chapter.
The eighth chapter ("*Study of focusing principles for regional treatments by array of applicators in anatomical model*") is based on following of my papers [L2,L3,L10,L11,L17]. Several setups of applicators used for series of simulations demonstrating homogeneity of SAR in case of anatomical model of area to be treated is given here in this chapter. Here used anatomical model were created by me myself. I have described basic points of methodology how to create them from CT or MRI scans.

The ninth chapter ("*Study of Hot-Spots Induced by Electromagnetic Surface Waves*") is based on following of my papers [L8,L18]. This chapter brings analytical and numerical simulations to verify and explain hypothesis of surface waves (they can create so called hotspots) and consequently to show how to eliminate excitations of surface waves. In this case we eliminate surface waves by optimization of dimensions of water bolus.

The tenth chapter ("*Intracavitary Helix Applicator to be used for BPH and for Prostate Cancer Treatment*") is based on following of mine papers [L5,L12]. This chapter deals with new results in area of intracavitary microwave applicators which can be used e.g. for prostate cancer treatment and for Benign Prostatic Hyperplasia (BPH) treatment as well.

The eleventh chapter ("*Feasibility of Treatment Based on Combination of External and Intracavitary Applicators*") brings analytical and numerical simulations to verify possibility to combine external and interstitial applicators for treatment by microwave thermotherapy.

The twelfth chapter ("*Conclusions*") gives a summary of the original results obtained in the frame of this doctoral thesis and then some notes on possible continuation in future research in this field.

In there is a list of my research and scientific activities – i.e. list of published papers, list of research projects which I have participated as a member of a research team, list of my memberships in congress organizing committees.

3. Working Methods

In this part of my Doctoral Thesis Statement (DTS) I would like to describe main part of my work during my doctoral studies mentioned in my Doctoral Thesis (DT). I will describe working methods and main results in following paragraphs.

3.1 Design of Applicators for Microwave Thermotherapy

As it follows from Chapter 3 of my doctoral thesis, its main aims are contributions to theory and design methods of applicators for microwave thermotherapy. As it was mentioned before, design of applicators for microwave thermotherapy should fulfill several important requirements:

1. Delivery of microwave power into the treated area
2. Optimization of SAR distribution in the treated area.
3. Optimization of temperature distribution in the treated area.
4. Minimization of EM field scattered around hyperthermia system.

My work and contributions to these requirements will be discussed in this chapter of the DTS.

- **Impedance matching of microwave thermotherapy applicators**

If we want to deliver major part of microwave power into biological tissue (i.e. area to be treated) we have to take care about how to minimize reflections of EM power in microwave part of hyperthermia system. Microwave theory and technique enables in general to implement systems with very negligible level of reflections.

In literature usually only reflections between applicator aperture and water bolus or surface of biological tissue are mentioned and discussed. In such case usually we get very simple frequency behaviour of reflection coefficient – shape approaching to the shape of resonant peak. But in general situation can be much more complicated. In order to explain that in part 5.2 of my DT there is described typical topology of the waveguide type resp. TEM transmission line type applicator and in part 5.3 of my DT there is a model of such applicator based on theory of signal flow graphs. From this graph then it follows where more complicated response of reflection coefficient frequency behaviour can arise.

- **Topology of applicators for microwave thermotherapy**

According to comments to Fig. 2, the construction of the waveguide type or the TEM wave applicator type is usually based on a section of waveguide or rf. resp. microwave TEM wave uniform transmission line (K). One side of the discussed applicator is short-circuited (Sh) with conductive wall and the other side with opened aperture is attached (bound) to biological tissue (BT) to be treated. To enlarge aperture of discussed applicator we can use a waveguide horn or horn TEM transmission line (H). Very often between applicator itself and the BT there is a water bolus (B).

EM energy, generated by microwave power generator (G), usually enters the applicator through coaxial transmission line (I) which enters into the waveguide or the TEM transmission line via capacitive probe (T) and thus it excites the desired EM mode in the applicator. As this capacitive probe excites EM wave going in two directions - one wave goes in the direction to BT and the other one in the opposite direction. So we have to return that other one wave back to BT by aid of shorting plate (Sh). Correct phase of returned wave can be adjusted by correct length of transmission line section (J).

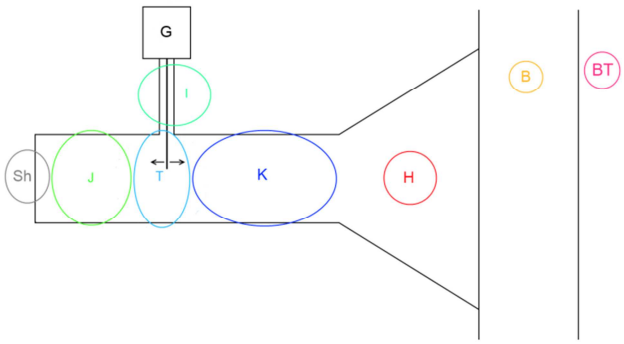


Fig.2 Discussed applicator coupled to biological tissue.

- **Signal flow graph of applicator coupled to biological tissue**

In this paragraph we would like to propose new signal flow graph model for the description of the case described in previous paragraph and Fig. 2. In the literature we have found only a very simple model of this case, here we would like to propose much more sophisticated model displayed on Fig. 3a. As it can be seen in this figure, each of parts mentioned in description to Fig. 2 (i.e. sections G, I, T, J, Sh, K, H, B and BT) are represented in this oriented graph by a number of corresponding one-, two- and three port elements.

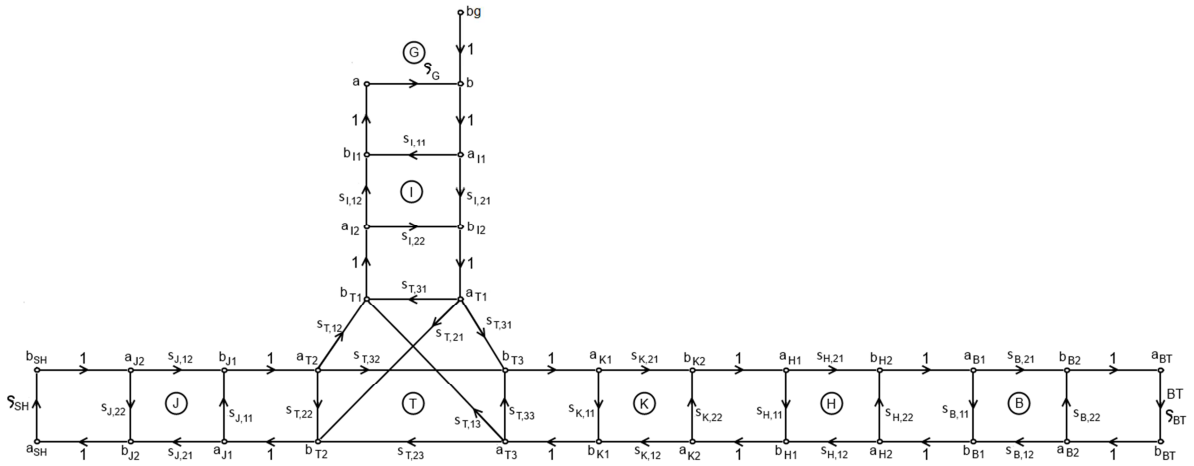


Fig.3a Signal flow graph model of the applicator coupled to the biological tissue.

To analyse behaviour of studied case of the microwave applicator coupled to the biological tissue (described by previous figure) we have to determine scattering matrices of each part of discussed system, i.e. scattering matrices for sections G, I, T, J, Sh, K, H, B and BT:

$$s_G = \begin{bmatrix} s_{G,11} & s_{G,12} \\ s_{G,21} & s_{G,22} \end{bmatrix} \quad (1)$$

$$s_I = \begin{bmatrix} s_{I,11} & s_{I,12} \\ s_{I,21} & s_{I,22} \end{bmatrix} \quad (2)$$

$$s_T = \begin{bmatrix} s_{T,11} & s_{T,12} & s_{T,13} \\ s_{T,21} & s_{T,22} & s_{T,23} \\ s_{T,31} & s_{T,32} & s_{T,33} \end{bmatrix} \quad (3)$$

$$s_J = \begin{bmatrix} s_{J,11} & s_{J,12} \\ s_{J,21} & s_{J,22} \end{bmatrix} \quad (4)$$

$$s_{Sh} = \begin{bmatrix} s_{Sh,11} \end{bmatrix} \quad (5)$$

$$s_K = \begin{bmatrix} s_{K,11} & s_{K,12} \\ s_{K,21} & s_{K,22} \end{bmatrix} \quad (6)$$

$$s_H = \begin{bmatrix} s_{H,11} & s_{H,12} \\ s_{H,21} & s_{H,22} \end{bmatrix} \quad (7)$$

$$s_B = \begin{bmatrix} s_{B,11} & s_{B,12} \\ s_{B,21} & s_{B,22} \end{bmatrix} \quad (8)$$

$$s_{BT} = \begin{bmatrix} s_{BT,11} \end{bmatrix} \quad (9)$$

Scattering matrices for sections G, I, T, J, Sh, K, H and B is possible to determine either by analytical resp. numerical calculation or by measurement (i.e. experimental evaluation). Scattering matrix for section of the BT can be determined by aid of the signal flow graph calculated e.g. for different cases of 1D configurations of the different tissues, described in paragraph 5.4 of my DT and here displayed in Fig. 4.

Second step in procedure to analyse behaviour of studied case of the microwave applicator coupled to the biological tissue we have to determine the transfer functions *T* describing signal transmissions between selected nodes of this signal flow graph (e.g. by aid of so called Mason rule). In our case the transfer function $T_{BT,G}$ (i.e. transfer function from node b_{g} to node a_{BT}) is for us the most important one:

$$T_{BT,G} = \frac{a_{BT}}{b_G} \quad (10)$$

where

a_{BT} is a generalized voltage wave incident on the biological tissue surface,

b_G is the generalized voltage wave going out from the microwave generator.

In case of ideal design of the discussed applicator the previous signal flow graph could be simplified to case displayed by following figure, where both full and dashed lines should be taken into account.

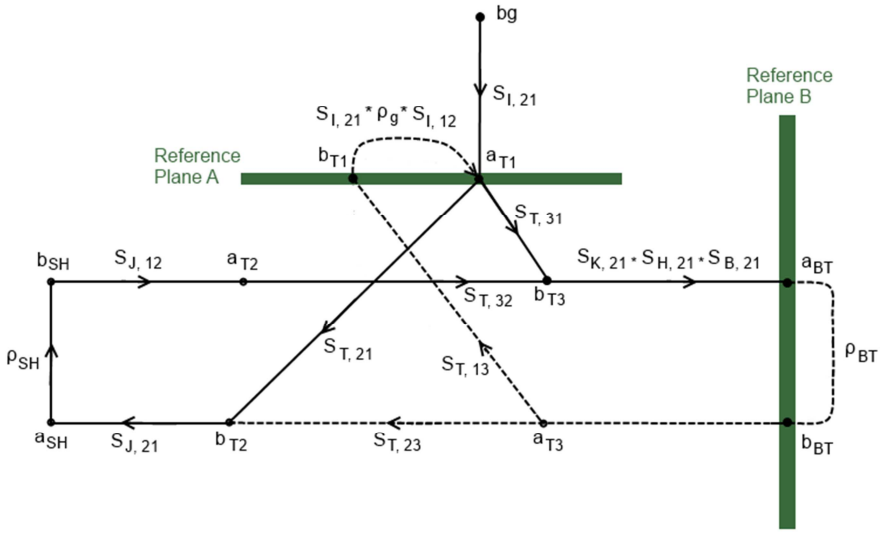


Fig.3b Simplified signal flow graph model of the applicator coupled to the biological tissue.

In this figure are by dashed lines displayed those branches, which can be consequently eliminated by a perfect impedance matching both at a reference plane A of the applicator input (horizontal green line) and at the reference plane B where the applicator is coupled to the BT (vertical green line). Perfect impedance matching at the reference plane A can be guaranteed by the perfect impedance matching of the sections G, I and T each to other (e.g. by aid of impedance transformers). Further, perfect impedance matching at the reference plane B can be guaranteed by the perfect impedance matching of the sections T, K, H, B and BT each to other (e.g. by aid of the impedance transformers plus by filling all those sections by water which has its dielectric parameters very near to those of the BT).

In this case the transfer function $T_{BT,G}$ (i.e. transfer function from node b_g to node a_{BT}) can be written by aid of Mason rule:

$$T_{BT,G} = \frac{a_{BT}}{b_G} = s_{I,21}\left(s_{T,31} + s_{T,21}s_{J,21}\rho_{Sh}s_{J,12}\right)s_{K,21}s_{H,21}s_{B,21} \qquad (11)$$

where all used quantities are mentioned in the signal flow graph displayed in Fig. 3b. From this equation we can see, that for optimal function of the studied applicator following conclusions can be derived:

a) all scattering parameters should represent only a phase shift (i.e. no attenuation),
b) both parts of the expression in parenthesis (i.e. $s_{T,31} and\ s_{T,21}s_{J,21}\rho_{Sh}s_{J,12}$) should be equal each to other (at least approximately).

- **Signal flow graphs of several different configurations of biological tissue**

Delivery of the microwave power does not depend only on the microwave applicator itself, it depends very strongly on real 3D configuration of biological tissue in the treated area as well. In this paragraph we will discuss several possible cases of 1D tissue configuration and we will show the way how to determine the reflection coefficient of the surface plane of the biological tissue in the area to be treated.

In the following picture we can see five basic examples of typical 1D configuration. Here S designates section of skin, F designates section of fat, M designates section of muscle and C designates section of cancer resp. tumour.

To be able to determine reflection coefficient of the surface of biological tissue and to determine the power absorbed in the single layers of the biological tissues in the treated area we have to take into account the real anatomical configuration of the biological tissue in the area to be treated. In this paragraph we would like to propose signal flow graphs for five such typical cases. In opposite to previous paragraph, where we demonstrated, that by the careful design of the microwave applicator it is possible to simplify significantly appropriate signal flow graph, in this case no such simplification is possible.

The first case from Fig. 4 describes typical situation when area of the bilogical tissue has three layers: a skin(S), a fat (F) and a muscle (M). The second case from Fig. 4 describes the situation when there is a surface tumour (C) and the muscle (M) under it. The third case from Fig. 4 describes situation when there is the surface tumour (C) and the fat (F) layer and the muscle layer (M) under it. The fourth case from Fig. 4 describes situation when there is the skin (S) on the surface, under it then the tumour (C) and the fat (F) layer and the muscle layer (M). Very similar is then the case five, where the tumour (C) is between the fat (F) and the muscle (M).

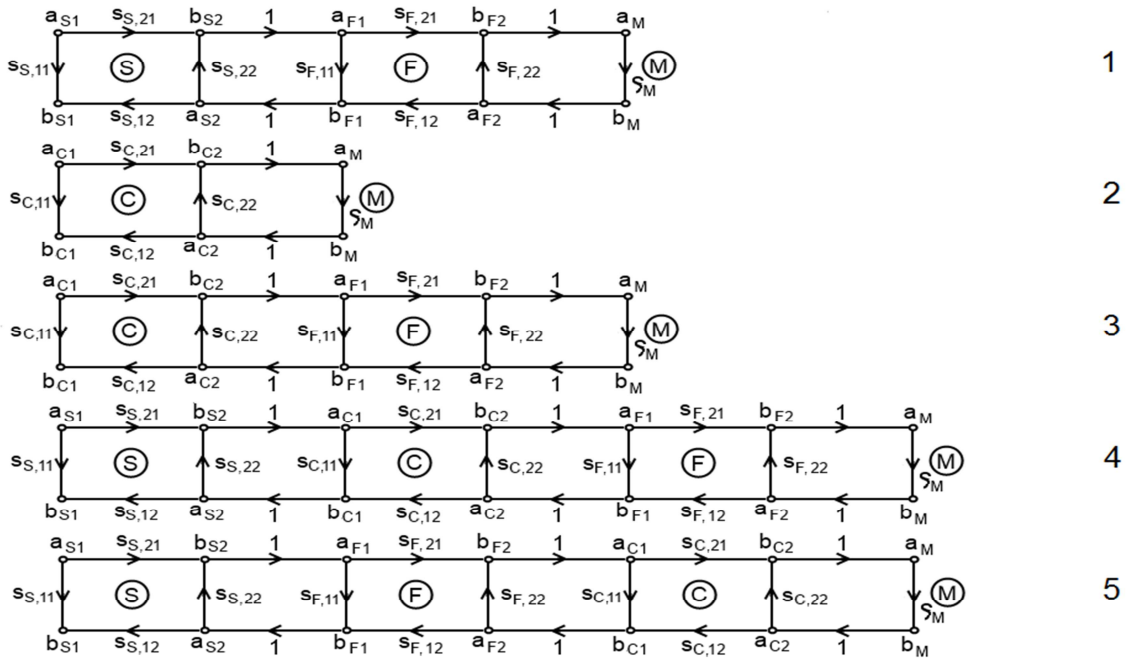


Fig.4 Signal flow graph models of five typical 1D configurations of the biological tissue in the area to be treated.

As it was told before, the second case from Fig.4 describes the situation when there is the surface tumour (C) and the muscle (M) under it. As we are interested in determination of power P_L absorbed in the tumour layer then especially in this case following approximate formula can be used:

$$P_L = \frac{1}{2}[(|a_{C1}|^2 - |b_{C2}|^2) + (|a_{C2}|^2 - |b_{C1}|^2)] \quad (12)$$

where in the first parenthesis we have the power absorbed by the forward propagating wave and in the second parenthesis we have the power absorbed by the reflected wave.

3.2 Microwave Thermotherapy in Cancer Treatment: Evaluation of Homogeneity of SAR Distribution

For the real clinical applications of the microwave thermotherapy in general a very high level of homogeneity of the 3D SAR and temperature distribution obtained during the treatment by aid of the applicators is strongly required. It is essentially important for reaching of a high quality assurance of the mentioned treatments. And a basic condition to reach such goal is a very good level of homogeneity of a SAR 3D distribution generated by the discussed phase array applicators [46]. In paper of Gelvich the homogeneity of SAR distribution is defined as the ratio of the area size with SAR > 75 % to the area size with SAR > 25 % of the maximum SAR value and includes information about the existence of 'hot spots' in SAR patterns [47].

- **Definition of the SAR homogeneity**

I have proposed a new definition for the SAR homogeneity evaluation in my DT. In this paragraph of the DTS I will describe how to evaluate the homogeneity of SAR distribution in the agar phantom. As an EM field exposure system we selected a system which consists of the four microwave stripline type TEM mode applicators of the same type, see Fig. 6 please. All these applicators work at a frequency of 70 MHz and are designed for the deep local or for the regional type cancer treatment by the microwave hyperthermia. This exposure system is in our study coupled to a cylindrical homogeneous agar phantom mimicking the biological tissue (the muscle tissue in our case). To compare the quality of the SAR distribution homogeneity obtained in the several different simulations we need to specify the definition for the SAR homogeneity evaluation.

In following discussion we would like to find out how to describe homogeneity of the SAR distribution. We want to specify a special function *H* describing this quantity and to determine, on which parameters it will depend the value of this function. As a basic definition of such function describing SAR homogeneity we propose to use following equation:

$$H = \mathrm{SAR}_{\mathrm{max}}/\mathrm{SAR}_{\mathrm{min}} \quad (13)$$

where $\mathrm{SAR}_{\mathrm{max}}$ is a maximum value of SAR in the studied volume and $\mathrm{SAR}_{\mathrm{min}}$ is a minimum SAR value in the studied volume. Such definition enables quantitative evaluation of SAR distribution homogeneity over the heated area. Its efficacy in appreciation of SAR patterns quality is demonstrated on idealized and real SAR distributions. The *H* parameter of a series of applicators widely used in clinics can be calculated easily. *H* could be assumed as a useful parameter additional to the qualified effective field size in characterizing the applicator's properties. From Eq. 12 it follows, that we can specify three basic cases of homogeneity quality (and function *H* value):

1) *Perfect homogeneity of* SAR, when in all studied volume SAR_{min} is almost equal to SAR_{max} (i.e. the value of the function *H* is almost equal to 1).
2) *Very good homogeneity*, when in all studied volume $SAR_{min} > SAR_{max}/2$ (i.e. the value of the function *H* is in interval between 1 and 2).
3) *Poor homogeneity*, when in the studied volume there is region in which $SAR_{min} < SAR_{max}/2$ (i.e. the value of the function *H* is bigger than 2).

It is evident, that for such definition the critical value of the SAR homogeneity is a case when $H = 2$. Critical value here means a boundary between acceptable (i.e. at least very good SAR homogeneity) and/or not-acceptable (i.e. very poor SAR homogeneity) distribution of SAR for treatment of selected patient.

We can suppose, that in general the homogeneity *H* of the SAR distribution created by array of the discussed applicators in the homogeneous cylindrical agar phantom is basically a function of frequency *f*, function of complex permittivity ε of the used cylindrical agar phantom, a function of the phantom radius *R* and a function of the phantom axial dimension (its length) *L*, it can be schematically written as follows:

$$H = H(f,\varepsilon,R,L) \tag{14}$$

It can be expected, that up to a certain value of the discussed agar phantom radius there will be created SAR distribution shape with very good level of homogeneity, but with increasing value of the phantom radius the homogeneity of the SAR will decrease very quickly then

- **Description of the Applicator**

For research of above mentioned problem we choose microwave stripline type applicator with the TEM mode [23]. It is displayed in Fig. 5.

Advantage of the applicator filled by the water is at first a better transfer of electromagnetic energy from the discussed applicator into the human body and at second smaller dimensions of the applicator itself. This applicator was designed by the FDTD simulator [38] (e.g. SEMCAD X EM Field simulator from SPEAG, Schmid & Partner Engineering AG, Switzerland).

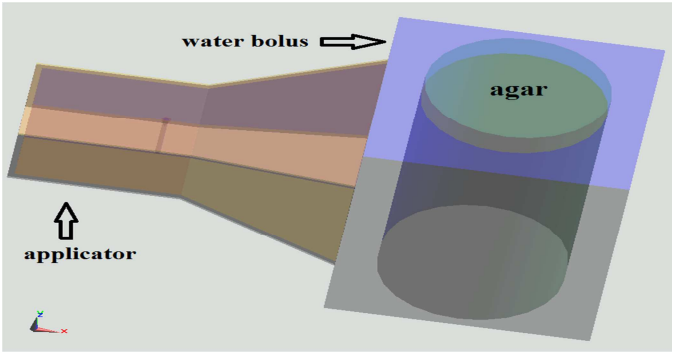
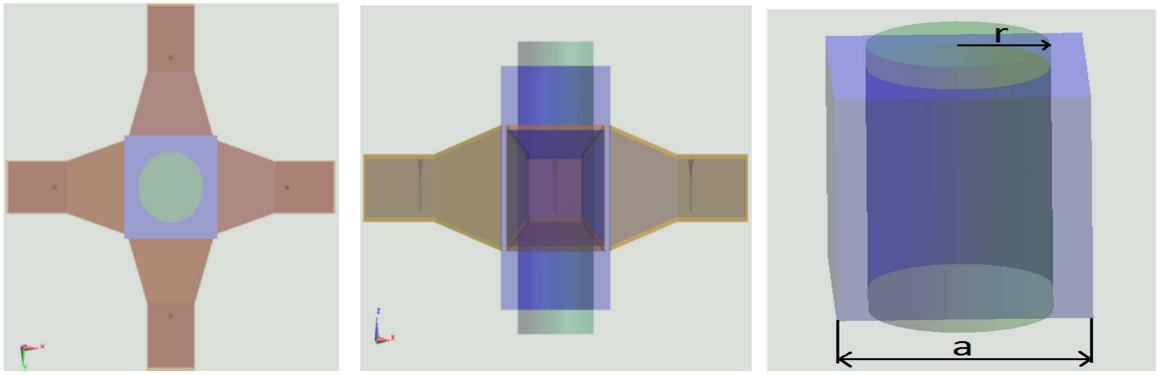


Fig.5 Model of applicator with agar and bolus.

For design and verification of functionality of created applicator the agar phantom is used. This is a homogeneous phantom, which represents only one tissue type. In our case the agar phantom represents muscle tissue.

- **Simulations**

By aid of the SEMACD X EM field simulator we simulated array of TEM mode applicators of the discussed type located around cylindrical agar phantom, which in our work we gradually enlarged in several steps and thus we can compare results of single simulations. Between homogeneous agar phantom and array of applicators a water bolus is inserted for better transfer of electromagnetic energy into agar phantom, which in our case represents muscle tissue, as can be seen in Fig. 6.



(a) (b) (c)

Fig.6 Definition of phantom cross sections: (a) Transversal plane cross section, (b) sagittal plane cross section and (c) dimensions of cylindrical agar and water bolus.

In discussed case, when we have cylindrical phantom surrounded by four above mentioned applicators, then for the thermotherapy the most important component of EM field will be longitudinal component E_z, which in discussed case can be expressed by following equation

$$E_z = K.\, H_0^{(2)}(\gamma r) \tag{14}$$

where

$H_0^{(2)}$ is Hankel function of zero order and second kind,
K is a constant,
r is a radius vector
γ is a constant of propagation.

As cylindrical agar phantom is mimicking muscle tissue, i.e. lossy medium, then argument of Hankel function is a complex number. Comparing Figures 6 and 7 it is evident that diameter $D = 2r$. In following picture (Figure 7) there are displayed four basic cases of possible SAR distribution along the diameter D of the agar cylinder:

a) This curve corresponds to case, when depth of penetration of the studied EM wave is much less than radius of the agar phantom. This typically happens for higher frequencies (i.e. higher attenuation constant) and bigger diameters of the phantom.
b) If frequency is going down (i.e. attenuation constant is decreasing) or diameter of the phantom is decreasing then we can expect to approach to the shape of curve “b”, where just some level of focusing can be seen.

c) If we further continue to go down with the frequency or we continue to decrease diameter of the phantom, then we may have very significant focus of SAR, like e.g. it is shown in the case of curve “c”.
d) If the frequency is very low and depth of penetration at this frequency is comparable or bigger than radius of the phantom, than shape of SAR distribution may be approaching curve “d”.

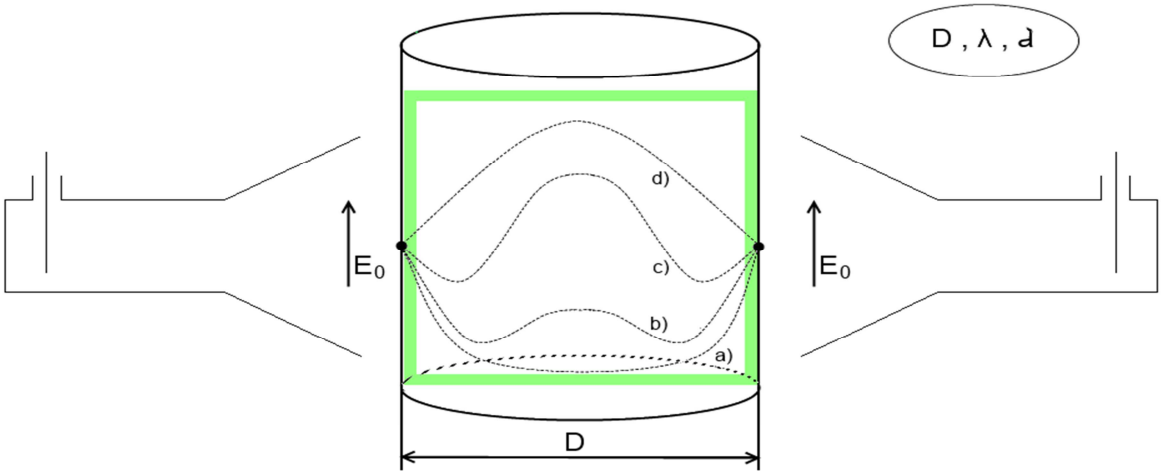
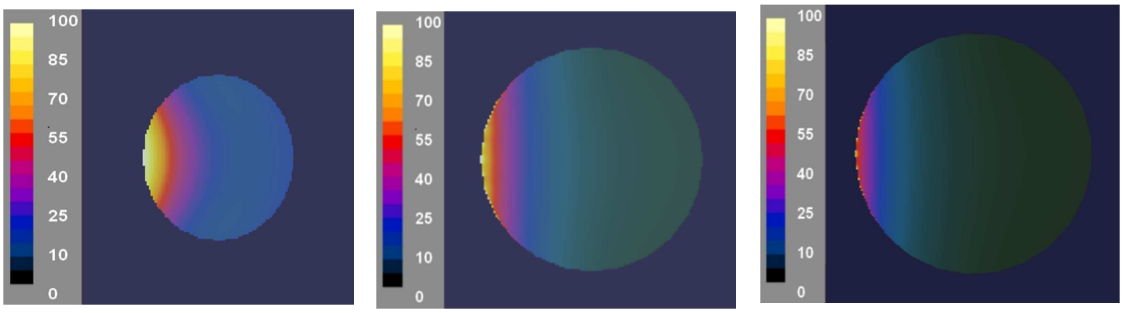


Fig.7 Four different types of the SAR distribution in cylindrical agar phantom.

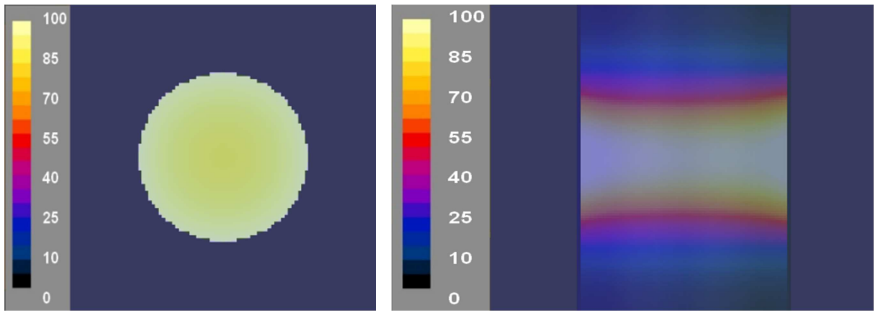
In Figure 8 there is a result of exposition of a cylindrical phantom by only one applicator. So we will have possibility to compare these results with those presented in Figures 9, 10 and 11, when four applicators were placed around cylindrical phantom.



(a) (b) (c)

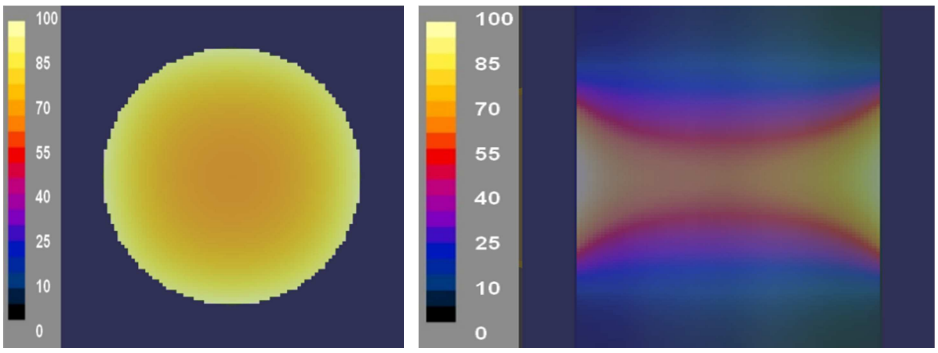
Fig.8 SAR distribution created by one applicator. (a) r = 50 mm, a = 180 mm, (b) r = 75 mm, a = 25 mm, (c) r = 100 mm, a = 25 mm.

In Fig. 9 till 11 there is displayed the SAR distribution created in the cylindrical agar phantom by the array of the four applicators located around the cylindrical homogeneous agar phantom, which has radius changing from 50 to 100 mm.



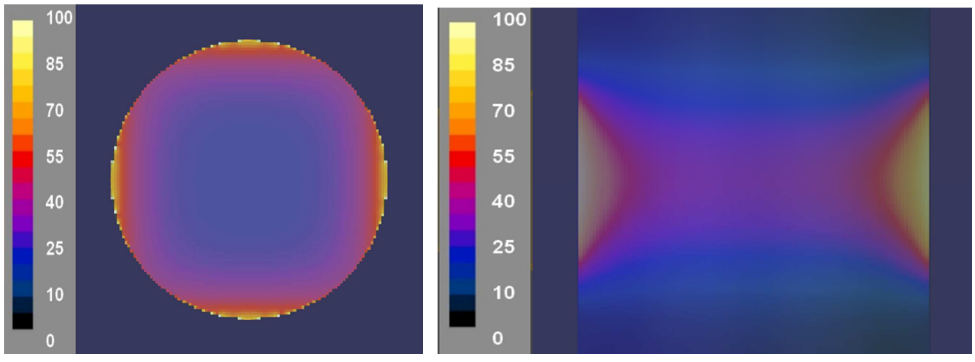
(a) (b)

Fig.9 SAR distribution for case r = 50 mm, a = 180 mm, H = 1.114. (a) in transversal plane cross section and (b) in sagittal plane cross section.



(a) (b)

Fig.10 SAR distribution for case r = 75mm, a = 200 mm, H = 1.444. (a) in transversal plane cross section and (b) in sagittal plane cross section.



(a) (b)

Fig.11 SAR distribution for case r = 100mm, a = 250 mm, H = 3.552. (a) in transversal plane cross section and (b) in sagittal plane cross section.

- **Discussion of presented results**

In my DT I presented much bigger number of such simulations and the results are displayed in following figure.

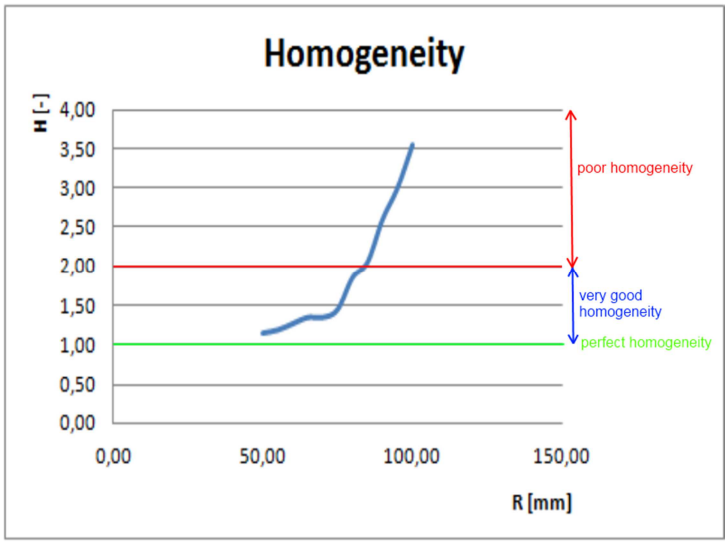


Fig.12 Homogeneity *H* vs. radius *R* of cylindrical agar phantom.

3.3 Study of focusing principles for regional treatments by array of applicators in anatomical model

Introduction

To verify basic functionality of created applicator we can use a homogeneous agar phantom. This homogeneous phantom represents only one type of the tissue in the human body. In reality the human body is very inhomogeneous, and therefore for hyperthermia treatment planning it is necessary to use anatomical precise 3D models with all the types of biological tissues taken into account. Such 3D model can be created e.g. from segmentation of series of several scans from Computer Tomography (CT) or Magnetic Resonance (MR). CT scans are 2 dimensional transversal gray–scale cuts. After then the created 3D model is imported to the software tool, which is used for hyperthermia treatment planning. This software tool must both cooperate well with a segmentation program and in the same moment to enable calculation of SAR distribution.

Methods

In this part of DTS we will present a comparison of the SAR distribution in the homogeneous agar phantom and in the anatomical based biological model. We made 3D anatomical model of thigh (Fig. 13) and of woman's calf (Fig. 14). These models are realized by segmentation program 3D – DOCTOR (vector-based 3d imaging, modeling and measurement software [36]). We should have available DICOM scans from CT [49]. DICOM scans hold the original quality of data. CT provides gray-scale image data in many transverse slices. The gray-scale images first are rescaled to produce appropriate voxels. Each voxel in the images then is identified rigorously as belonging to one type of tissue by assigning each voxel a red-green-blue code that identifies the discrete tissue type of that particular voxel. All identified transverse images then are combined to obtain a three-dimensional numerical model. A fine adjustment generally is required to smoothly connect each slice in the three orthogonal planes (axial, sagittal and coronal). DICOM CT scans for thigh model were obtained from university

hospital Bulovka. This model has the resolution 2mm, meaning voxel size 2 x 2 x 2mm. Each voxel was assigned to one of 3 different tissue types, such as muscle, fat and bone.

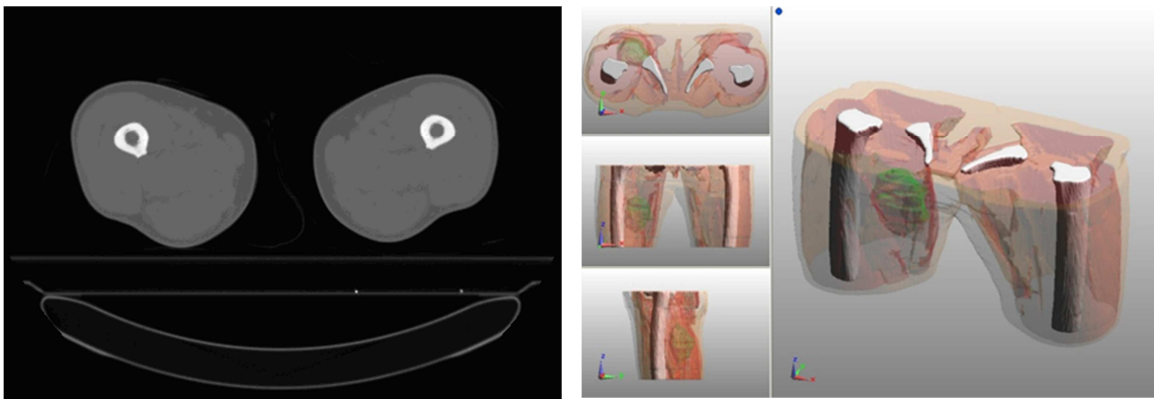


Fig.13 Thigh (a) computed tomography scan [49], (b) 3D anatomical model

Model of woman's calf has resolution of 1 mm and meaning voxel side is 1 x 1 x 1 mm. Like in segmentation of thigh each voxel was assigned also to one of 3 different types of biological tissue (bone, muscle and fat).

Fig. 14 3D anatomical model of woman's calf

The dielectric properties at the frequency of 434 MHz of both anatomical models are shown in the next table:

Name	**Conductivity [S/m]**	**Relative permittivity**
Agar	**0,8**	**54**
Bone Cortical	**0,09**	**13,07**
Muscle	**0,8**	**56,86**
Fat	**0,04**	**5,56**

Tab. 1 Dielectric properties at frequency 434 MHz [44]

For our simulation presented in this chapter we used microwave stripline applicator with TEM mode which works at frequency of 434 MHz and for simulations of SAR distribution we used homogeneous agar phantom, which dielectric parameter are stored in table above. All of several compositions of applicators, agar phantom, 3D model of thigh and of calf were simulated by FTDT program SEMCAD X.

This chapter consists from three parts. In the first part we chose the matrix composition of two applicators of the same type. In the first case of this part we put two applicators on cylindrical agar phantom next to each other (Fig.15a). This homogeneous agar phantom represents thigh of human body. The radius of cylindrical agar phantom is 8 cm. In the second case we put matrix of two applicators on anatomically based biological model (Fig.15b).

In the second part of this chapter we studied composition of 2 and 4 applicators located on homogeneous cylindrical agar phantom and consequently on 3D anatomical model of woman's calf. Cylindrical agar phantom represents muscle tissue of human limb. In our case we simulated muscle tissue of woman's calf with diameter of 8 cm.

The last part of this chapter is to address the influence of two layers on the shape of SAR distribution in homogeneous agar phantom and in anatomic model of woman calf as well. In each layer there is always the same number of applicators. The distance between two layers is gradually enlarged about 5, 10, 15 and 20 mm.

Results

The results of simulations of SAR distribution of the first part

On the following figure are two same applicators put on cylindrical agar phantom and then on 3D model of human thigh.

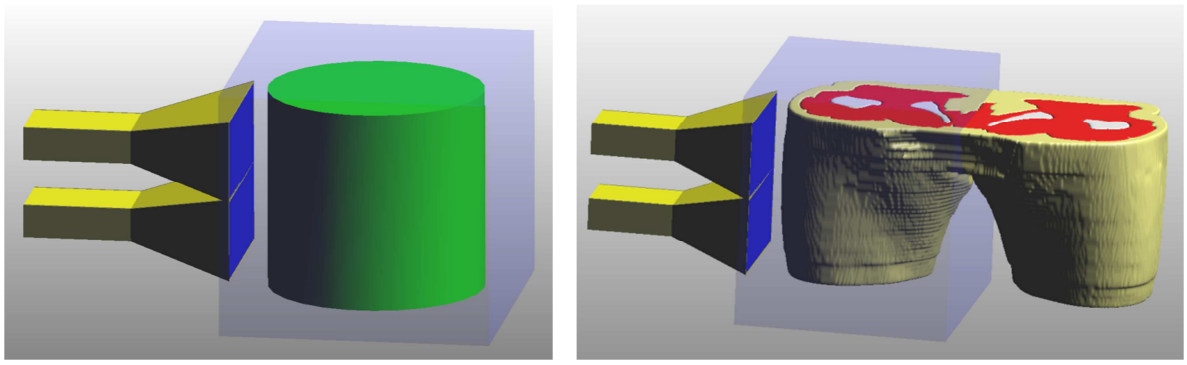


Fig.15 Matrix of two applicators (a) on cylindrical agar phantom, (b) on anatomically based biological model

Maximum of the SAR distribution in the studied case is situated in the middle of two applicators in homogeneous agar phantom. By comparison of SAR distribution in agar phantom and in anatomic model is shown, that the SAR distributions acquire maximum at the same locations, but the shape of SAR distribution in anatomic phantom is influenced by fat and bone.

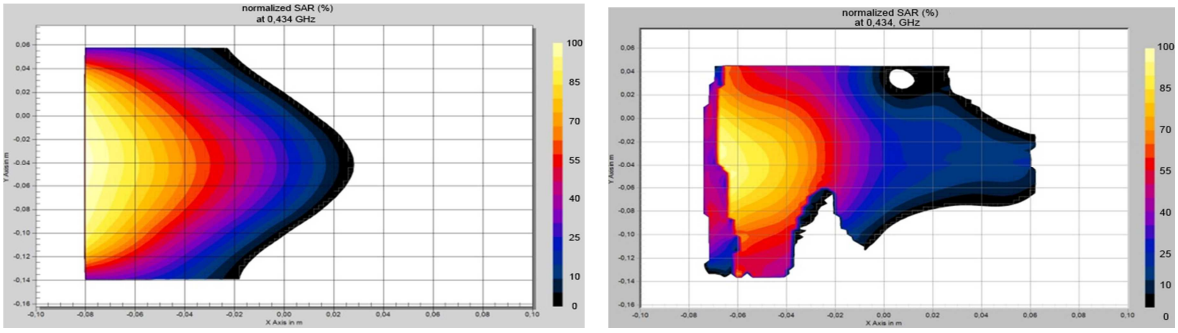


Fig.16 SAR distribution (a) in agar phantom in longitudinal layer, (b) in anatomic model in longitudinal layer

Fat has a lower value of permittivity as a muscle and therefore low part of energy is absorbed in it and the most of energy goes into another layer, into muscle. Muscle behaves as lossy environment, therefore is energy in it absorbed. Also bone affects the shape of SAR distribution as can be seen in transversal section of femur.

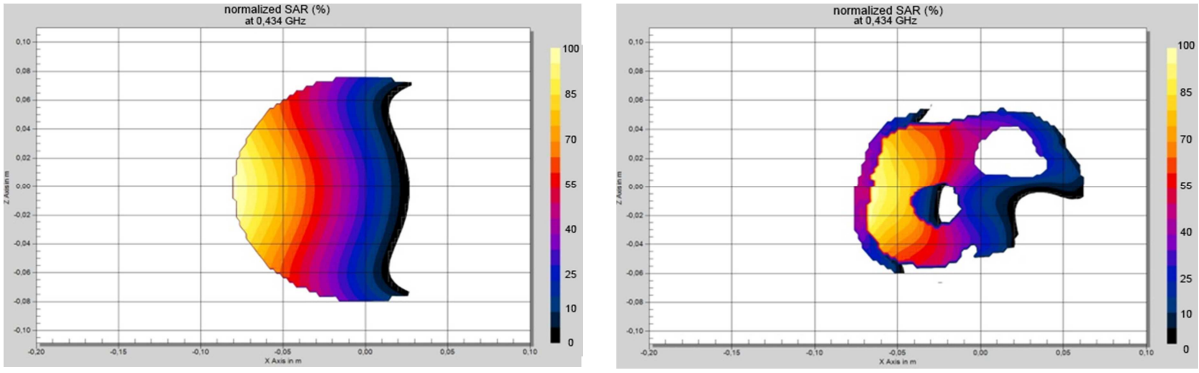


Fig.17 SAR distribution in transversal layer (a) of agar phantom, (b) of anatomic model.

Bone analogous to fat has a low value of permittivity (contains a small amount of water), but value of SAR is in this case approaching to zero (bone behaves almost like a lossless matter).

The results of simulations of SAR distribution of the second part

One of possibilities of composition of applicators is case of 2 applicators on cylindrical agar phantom and on 3D anatomical model of woman's calf shown on Fig. 18.

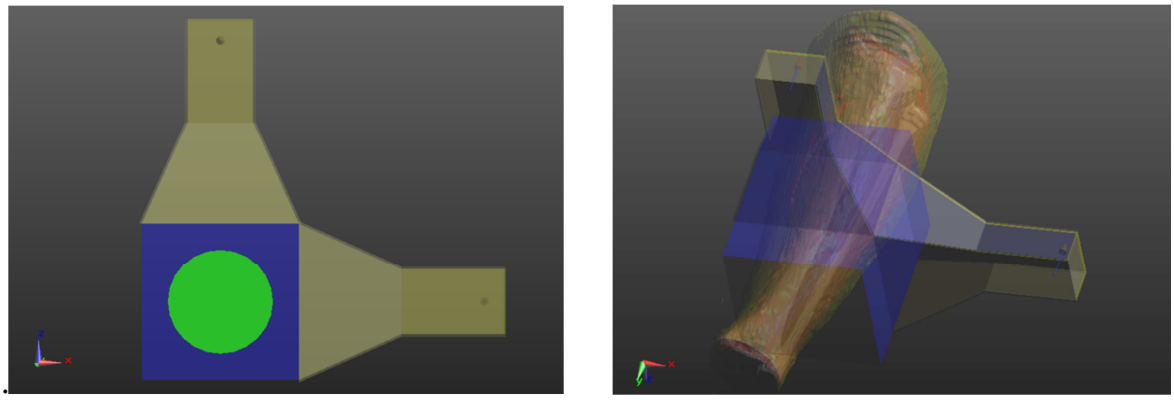


Fig.18 Case of 2 applicators (a) on cylindrical agar phantom, (b) on anatomical model.

From both SAR distributions presented in Fig.19 it follows, that this case of 2 applicators is suitable for treatment of tumours, which cover larger area near to surface of human limb.

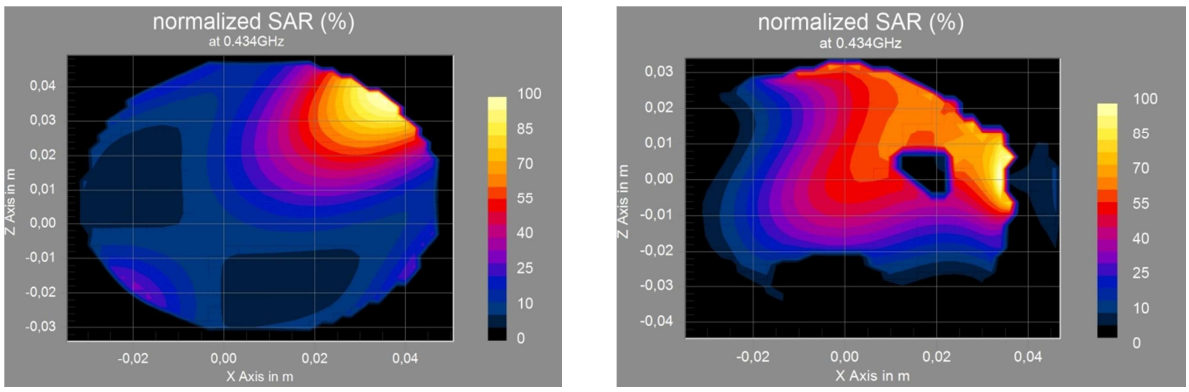


Fig.19 Normalized SAR (a) in agar phantom, (b) normalized SAR in anatomical model

By using 4 applicators we can see on Fig. 20 and 21 that in both cases is a good focusing of SAR distribution near to the cylindrical axis.

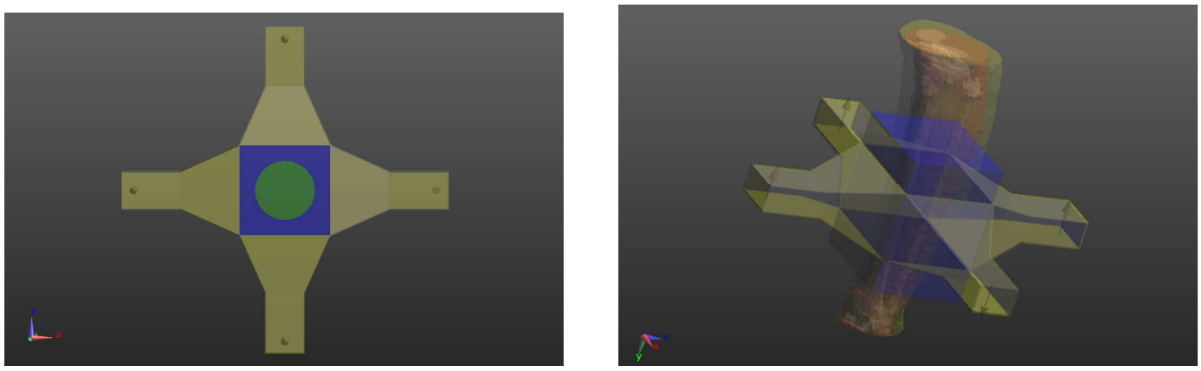


Fig.20 Case of 4 applicators (a) on cylindrical agar phantom, (b) on anatomical model.

By alternation of phases of selected applicators we achieved better focusing in the middle of both homogeneous agar phantom and 3D anatomical model. This composition of 4 applicators could be used for treatment tumors located in the middle of human limb.

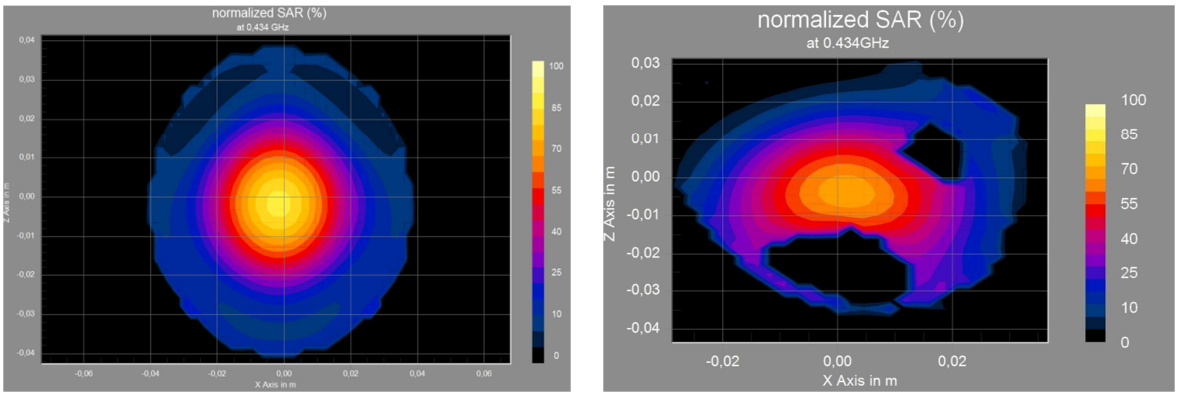


Fig.21 Normalized SAR (a) in agar phantom, (b) normalized SAR in anatomical mode

- **Composition of 8 microwave stripline applicators in two layers**

Idea of using eight applicators brings possibility to scan maximum of SAR along axis of either agar or anatomical model. We can thus speak about 3D focusing. We used the same

procedure as in previous case and we gradually enlarged distance between applicator layers in several steps. If two layers are situated side by side, then in agar phantom and in anatomical model are created maximas of SAR distribution just in the centre of these layers.

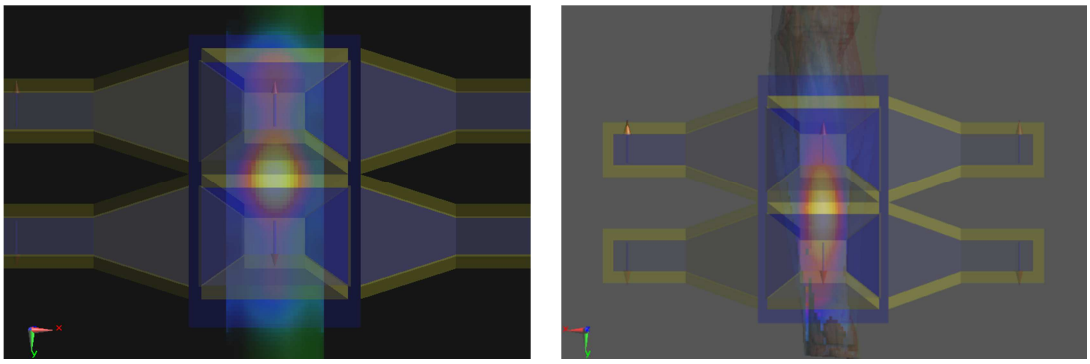


Fig.22 Two layers with four applicators in each layer, distance 0 mm between both layers, coupled a) to agar phantom, b) to anatomical model

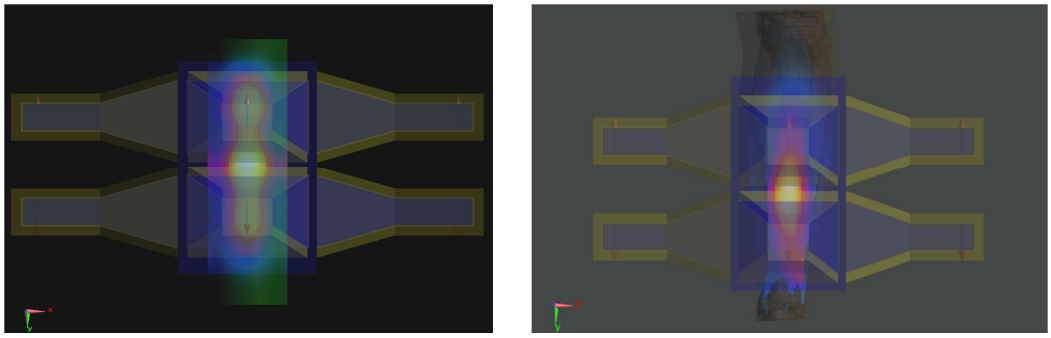


Fig.23 Two layers with four applicators in each layer, distance 5 mm between both layers, coupled a) to agar phantom, b) to anatomical model

In this series of simulations we studied change of SAR distribution with gradually increasing distance of two layers of applicators of the same type located either on homogeneous cylindrical agar phantom or on anatomical model of woman's calf. If two layers are situated side by side on agar phantom or on anatomical model, the shape of SAR distribution is created in the middle of agar phantom / anatomical model. By gradually enlarged distance between two layers of applicators working at the frequency of 434 MHz two local maxima in agar phantom as well as in anatomical model are arising. Shapes of SAR distribution in agar phantom often differ from shapes of SAR distribution created in anatomical model in general. It is due to different pattern of anatomical model, because anatomical model consists of more than one tissue like it is in the case of homogeneous agar phantom.

3.4 Study of Hot-Spots Induced by Electromagnetic Surface Waves

From hyperthermia cancer treatment clinical experiences it is known, that so called hot-spots (i.e. local overheating – burning) can sometimes be observed after the treatment. Mostly it may happen in front of the aperture of the applicator (Fig. 24), but sometimes surprisingly far from its aperture, typically right on the other side with respect to the applicator aperture. Such effect can be explained e.g. by aid of surface waves excited from applicator aperture (Fig. 25).

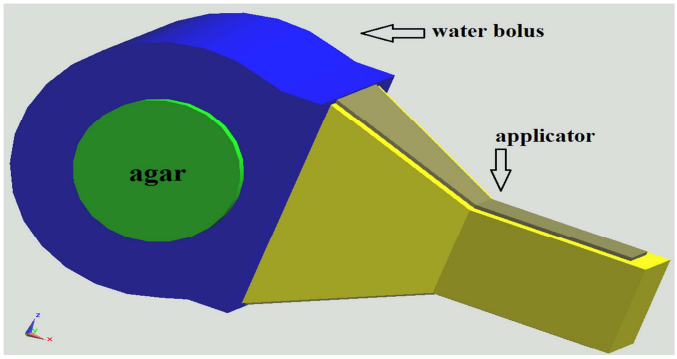


Fig.24 Model of TEM wave stripline type applicator radiating to agar phantom trough the water bolus

According to theory of EM field and waves, either interface between two different dielectric media or interface between dielectric media and conductor can support propagation of the so called surface waves. We can often have such situations in microwave hyperthermia treatment, please see description of discussed case in Fig. 24. Except of the EM wave going directly into the area of the agar phantom the surface waves will travel around the agar phantom either inside water bolus or even outside of it [16,17]. For our study and discussion we have chosen stripline type applicator with TEM mode, which can be used for treatment of cancer patients at frequency 434 MHz (Fig.24). To understand well the discussed problem we studied it both analytically and by aid of numerical solutions.

- **Analytical and numerical simulations**

Our basic approach to develop analytical solution of the discussed problem comes from idea of resonances in water bolus. If the central circle of the water bolus is approximately equal to any of whole number multiple wavelength, then under certain conditions surface waves can create hot spots on the surface of the treated area or on the surface of agar phantom, mostly right on the opposite side with respect to position of the TEM mode applicator in agar phantom (Fig. 25).

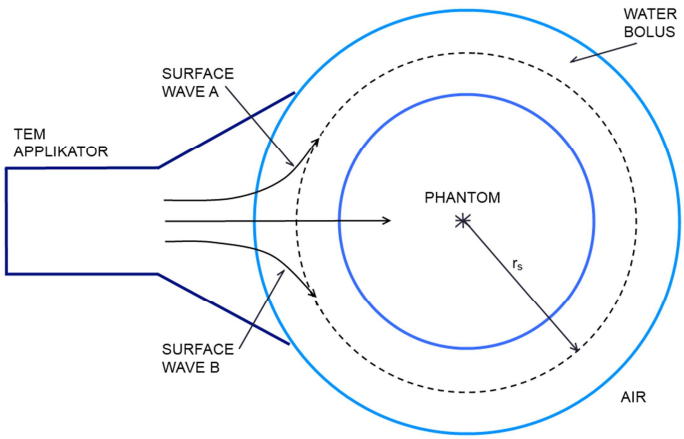


Fig.25 Analytical model of hot-spots created by surface waves

From this figure it follows that there is an EM wave going into the biological tissue and is used for treatment. Contemporaneously there will be excited two surface waves travelling on clockwise (wave A) and the other anti-clockwise (wave B). These two waves can (due to their

superposition) create a hot spot right on the other side of applicator aperture. Under certain conditions these two waves can resonate along central circle of water bolus. This will happen when wavelength (or their *n*-multiples) of the discussed waves will be approximately equal to circle with a radius r_s and length l_s), i.e. when:

$$l_s = 2\pi r_s = n\frac{\lambda_0}{\sqrt{\varepsilon_r}} \tag{15}$$

Result of our numerical simulations is displayed in Fig. 28, hot spot can be observed in this case on the left side of cylindrical agar phantom, i.e. on the other side with respect to position of applicator.

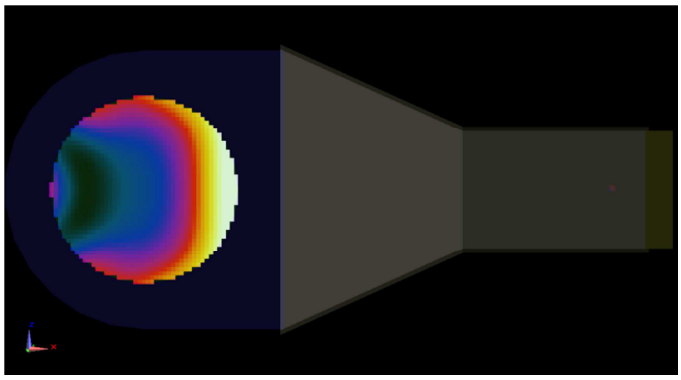


Fig.26 SAR distribution in transversal plane cross section

3.5 Feasibility of Treatment Based on Combination of External and Intracavitary Applicators

Combination of applicators of the same type (most frequently e.g. dipole or waveguide or applicator with evanescent mode etc.) is used quite often in hyperthermia cancer patient treatments. Such applicators are usually set externally on the surface of a patient's body. For treatment of tumours situated near the tubes and/or cavities in the patient body so called intracavitary applicators are used. And for destruction of malignant tumour inside organs, like e.g. liver, so called interstitial applicators can be applied. But sometimes tumours are situated in areas, where it's very difficult or even impossible to deliver microwave energy to these areas in human body either by local external applicators or by intracavitary resp. interstitial applicators. In such cases, sometimes, it could be convenient to use combination of external and either intracavitary or interstitial applicator.

In our feasibility study to verify above mentioned possibility we made at first simulations of SAR distribution of each applicator separately, and then we simulated the shape of SAR distribution from both applicators simultaneously. In all three cases homogeneous agar phantom representing muscle tissue (ε_r = 54, σ = 0.8 S/m) with dimensions 140 x 140 x 74 mm was used. Microwave stripline applicator was located on the surface of this agar phantom and monopole was situated 4 cm under the surface of phantom. Both applicators were powered coherently. Coherent waves allow their mutual interference.

After we obtained very promising results by aid of numerical simulations we decided to verify them experimentally. We created agar phantom with quite the same dimensions as it was in

case of simulations (140 x 200 x 80 mm) with dielectric parameters like muscle tissue. Both applicators were powered by generator UHF-POWER-GENERATOR PG 70.150.2 at the frequency 434 MHz with power P = 100 W.

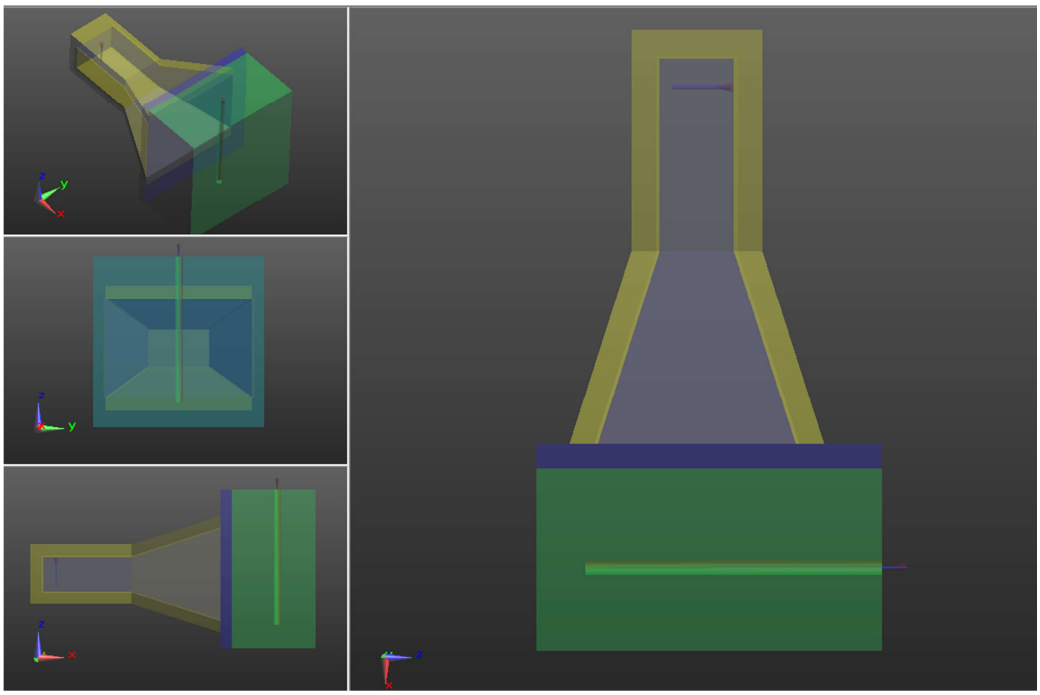


Fig.27 Model of a combination of external and interstitial applicators

By IR camera (Flir P25) we firstly did the measurements of the SAR of the external applicator, after we did the measurement of the SAR of interstitial applicator and then we measured the SAR created by exposition from both these applicators contemporaneously. As a power divider we used coaxial T coupling element, see Fig. 28.

Fig.28 Measurement system

In the Fig. 29 we can see result of this measurement. It is measurement of the SAR resp. temperature distribution obtained by aid contemporaneous exposition from external and interstitial applicator. In comparison with case of external applicator the depth of effective heating is only a half of this one.

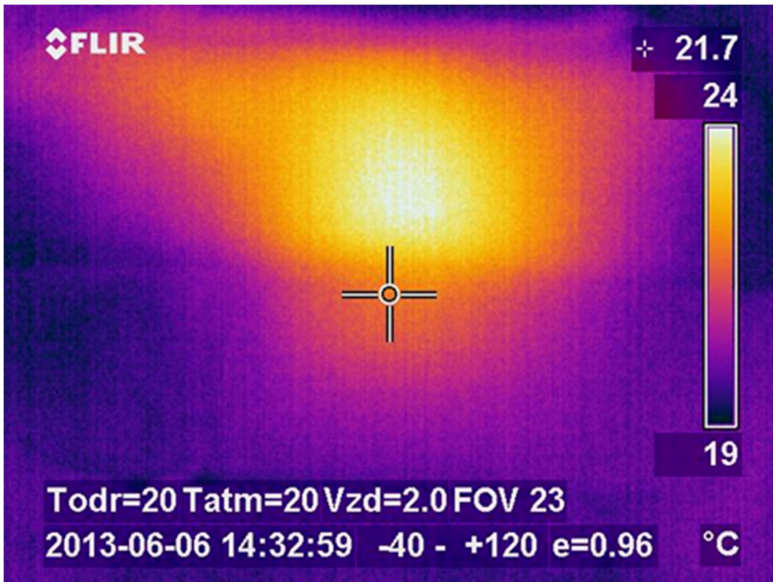


Fig.29 Temperature distribution in agar phantom cross-section

In the Fig. 30 we can see result of the numerical simulation of SAR distribution in agar phantom cross-section.

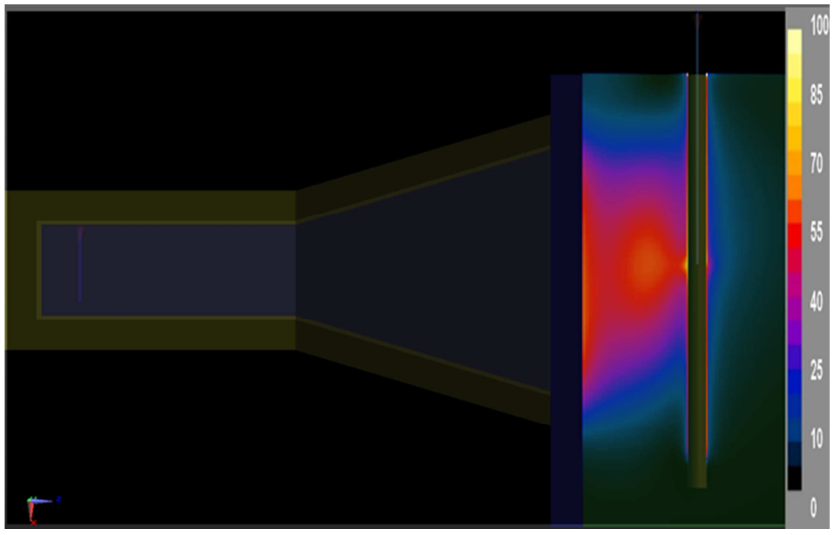


Fig.30 Numerical simulation of SAR distribution in agar phantom cross-section

Comparing result of EM numerical simulation and experimental results it can be told, that there is a very good agreement between both results.

4. Main Results

The main goal of my doctoral thesis was to bring some new scientific contributions to the topics of medical applications of EM field, especially then to microwave thermotherapy. In previous chapter I have described main topics (problems) I have solved in my DT including description of working methods and many significant results. In this chapter I would like to make an overview of the original results obtained in the frame of my doctoral thesis:

a) New model of microwave hyperthermia applicator coupled to patient body.

New model of microwave hyperthermia applicator coupled to patient body has been proposed in this doctoral thesis. This new model is based on theory of signal flow graph and is in details described in Chapter 5 of the doctoral thesis. Firstly a general version of this model has been created and after it an ideal case was derived from the general version. Both from the general model and from its ideal case as well we can determine basic important requirements for optimal design of microwave applicators for hyperthermia cancer treatment.

b) New definition for evaluation of the SAR homogeneity during the treatment.

New definition for evaluation of the SAR homogeneity during the treatment has been proposed in the doctoral thesis (see Chapter 6, please). Results of the study of homogeneity of the SAR distribution created by the array of TEM stripline type applicators of the same type in the homogeneous agar phantom have been described and discussed in the doctoral thesis. The effect of the phantom dimensions on the SAR homogeneity has been demonstrated. In our opinion the techniques selected and tested by us proved to be very accurate and effective. In conclusion it can be stated that up to a certain level radius of agar phantom a very well homogeneous shape of SAR distribution can be created. Here presented results correspond very well to our analytical model of the studied problem.

c) Study of focusing possibilities for deep heating and for case of regional treatment,

Doctoral thesis brings new results based on studies of the shape of the SAR distribution in the homogeneous agar phantom and in the anatomical based biological model (see Chapters 7 and 8, please). Basic results of discussed SAR distribution show that optimized compositions of applicators of the same type could be used for treatment of tumours located in various areas of human extremities. In some cases in order to obtain better results we changed phases and amplitudes of selected applicators. The SAR distributions are influenced by bone and fat tissue in both 3D anatomical models of thigh and calf.

Here used anatomical model were created by me myself. In this thesis I have described basic points of methodology how to create them from CT or MRI scans.

Studies of 3D SAR simulations were done firstly for the case of homogeneous planar resp. cylindrical phantom irradiated by EM wave from by us proposed applicators. Our work was focused on a study of superposition effects by using a matrix of hyperthermia applicators.

Logical continuation then was to study of 3D SAR distribution in true anatomical model of human body, again focusing on the study of superposition effects by using a matrix of

hyperthermia applicators. On the other hand array applicators can be used for treatment of diseases on bigger areas for clinical purposes.

In the last part of these studies we followed influence of change of the SAR distribution with gradually increased distance of two layers of applicators of the same type located either on homogeneous cylindrical agar phantom or on anatomical model of woman's calf. If two layers of applicators are situated side by side on agar phantom or on anatomical model, the shape of SAR distribution is created in the middle of agar phantom / anatomical model. By gradually enlarged distance between two layers of applicators working at the frequency of 434 MHz two local maxima in agar phantom as well as in anatomical model are arising. Shapes of SAR distribution often differ from shapes of SAR distribution created in anatomical model of calf.

d) Analytical and numerical study of excitations of surface waves.

Doctoral thesis brings new ideas about mechanisms which in therapy can cause so called hot-spots (see Chapter 9, please). We have verified the hypothesis that in some cases these hotspots can be created by surface waves excited in the water bolus. Doctoral thesis contains first results of analytical and numerical simulations which can be used to eliminate excitations of surface waves. We propose to eliminate surface waves by optimization of dimensions of water bolus (this possibility was demonstrated in doctoral thesis by aid of a few pictures included in the mentioned chapter).

e) Study of EM field irradiated both from external and from intracavitary applicators.

Another important topic of this doctoral thesis is an initial study and optimization of applicators for intracavitary treatment based on helix structure. As a very original contribution of this doctoral thesis we consider a feasibility study of contemporaneous treatment by external applicator for local treatment in combination with interstitial applicator (see Chapter 10 and 11, please).

Based on these results this doctoral thesis brings a proposal of applicators suitable for medical applications and for biological experiments (including numerical simulations of their SAR distribution and impedance matching and measurements of temperature distribution in agar phantom).

Results obtained by research in the frame of my doctoral thesis were presented in several international scientific conferences (e.g. Annual Meeting of European Society for Hyperthemic Oncology - ESHO 2010 in Rotterdam (NL), ESHO 2011 in Aarhus (DN), ESHO 2013 in Munich (D), Progress In EM Research Symposium - PIERS 2011 in Morocco, ISMOT 2011 in Prague (CZ) and EDALC 2011 in Prague (CZ), PIERS 2012 in Moscow, PIERS 2013 in Stockholm). Some of my results were published in international journal PIER (Progress in EM Research, IF=5,39).

5. Conclusions

This doctoral thesis had as a main aim to bring some new scientific contributions to the topics of medical applications of EM field, especially then to microwave thermotherapy. Therefore it deals with studies of 3D SAR simulations done firstly for the case of homogeneous planar resp. cylindrical agar phantoms, because this can give us basic information about true behaviour of EM wave irradiated from by us proposed applicators, i.e. tools (resp. antennae) for irradiation of EM wave into biological tissue or its phantom in order to create EM field exposure for high quality treatment of patients.

Based on these results this doctoral thesis brings a proposal of applicators suitable for medical applications and for biological experiments (including numerical simulations of their SAR distribution and impedance matching and measurements of temperature distribution in agar phantom).

6. Summary

Our work was focused on a study of superposition effects by using a matrix of hyperthermia applicators coupled to homogeneous agar phantom, mimicking the muscle tissue.

Logical continuation then was to study of 3D SAR distribution in true anatomical models of human body, again focusing on the study of superposition effects by using a matrix of hyperthermia applicators. On the other hand array applicators can be used for treatment of diseases on bigger areas for clinical purposes.

Another important topic of this doctoral thesis is an initial study and optimization of applicators for intracavitary treatment based on helix structure. As a very original contribution of this doctoral thesis we consider a feasibility study of array applicators in combination with intracavitary applicators.

Last but not least, this doctoral thesis describes our analytical and numerical study of surface waves and methods how to eliminate them, because they may cause so called hot-spots problem.

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8. List of candidate's works relating to the doctoral thesis

Publications in impacted journals:

[L1] Vrbová, B.(50%), Vrba, J.: Microwave Thermotherapy in Cancer Treatment: Evaluation of Homogeneity of SAR Distribution. Progress in Electromagnetics Research (IF 2012: 5.298). 2012, vol. 129, p. 181-195. ISSN 1559-8985.

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- Basar, Md R.; Malek, Fareq; Saleh, Mohd I. M.; et al.: A NOVEL, HIGH-SPEED IMAGE TRANSMITTER FOR WIRELESS CAPSULE ENDOSCOPY. In: Progress in Electromagnetics Research. ISSN 1559-8985.
- Basar, M. R.; Malek, F.; Juni, K. M.; et al.: The Use of a Human Body Model to Determine the Variation of Path Losses in the Human Body Channel in Wireless Capsule Endoscopy. In: Progress in Electromagnetics Research. ISSN 1559-8985.

Publications in reviewed journals:

[L2] Vrbová B.(50%), Víšek L.: Simulation of Hyperthermic Treatment by Using the Matrix of Stripline Applicators. In: Journal - Acta Polytechnica. 2010, vol. 50, no. 4/2010, s. 106 - 110. ISSN: 1210-2709.

Chapter in book:

[L3] Vorlíček J., Vrbová B.(33%), Vrba J.: Prospective Applications of Microwaves in Medicine. In ADVANCES IN CANCER THERAPY. Rijeka: InTech, 2011, p. 507-532. ISBN 978-953-307-703-1.

Patent:

No patent

Membership in conference organizing committee, session co-chair-woman:

- Member of organizing committee of ISMOT 2011 (13th International Symposium on Microwave and Optical Technology, June 20 – 23, 2011, Prague, Czech Republic).
- Chairperson of ISMOT 2011 session: Biological Effects and Medical Applications of EM Fields.
- Member of organizing committee of EDALC 2011 (Electrodynamic Symposium of Living Cells, July 1 – 3, 2011, Prague, Czech Republic).

Project participation:

- **MSM6840770012**: "Transdisciplinary Research in the Area of Biomedical Engineering II" of the CTU in Prague, sponsored by the Ministry of Education, Youth and Sports of the Czech Republic.
- **GD102/08/H081**: "Non Standard Applications of Physical Fields", supported by the Czech Science Foundation (Grant Agency of the Czech Republic).
- **SGS10/175/OHK4/2T/13**: "Development of Microwave Applicators", supported by the Czech Technical University in Prague.
- **SGS12/070/OHK4/1T/13**: "Optimalilzation of hyperthermia treatment planning by using microwave diagnostisc and new types of thermotherapeutic superposition applicators", supported by the Czech Technical University in Prague.
- **SGS13/077/OHK3/1T/13**: "Study of Electromagnetic Processes in biomolecules, cells and tissue", supported by the Czech Technical University in Prague.

Web of Science excerpted publications:

[L4] Vrbová B.(50%), Vrba J.: Waveguide-based Applicators for Local Microwave Thermotherapy: Feasibility Study of Matrix Array Treatment, In: Conference Proceedings - Progress in Electromagnetics Research Symposium (PIERS 2010 Xi\'an). Cambridge, MA: The Electromagnetics Academy, 2010, p. 1394 – 1397. ISBN 978-1-934142-12-7.

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Other publications:

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[L18] Vrbová B.(50%), Vrba J.: Study of Hot-Spots Generated by Electromagnetic Surface in Microwave Thermotherapy. In: 28th Annual Meeting of the EUROPEAN SOCIETY for HYPERTHERMIC ONCOLOGY, June 19 – 22, 2013, Munich, Germany.

List of candidate's other publications

Publications in impacted journals:

No other publications

Publications in reviewed journals:

No other publications

Patent:

No patent

Project participation:

- **P102/11/0649:** "Research and Measurements of Signals Generated by Nanostructures", supported by the Grant Agency of the Czech Republic.
- **TA02010854**: "The development of high-performance broad-spectrum light sources for use in medicine".

Web of Science excerpted publications:

No other publications

Other publications:

No other publications

Abstrakt

Hlavným cielom disertačnej práce je priniesť nové vedecké príspevky k témam lekárskych aplikácií v EM oblasti, predovšetkým v mikrovlnnej termoterapii. Preto sa zaoberá štúdiom 3D simulácií SARu, jednak pre prípad homogénneho rovinného resp. valcového agarového fantómu, pretože to nám môže dať základné informácie o skutočnom správaní EM vlny vyžiarenej z nami navrhnutých aplikátorov, tj. zariadení (resp. antén) pre vyžarovanie EM vlny do biologického tkaniva alebo jeho fantómu za účelom vytvorenia EM expozície pre vysokú kvalitu liečby pacientov. Práca bola zameraná na štúdium superpozičných účinkov pomocou matice hypertermických aplikátorov.

Logickým pokračovaním bolo štúdium 3D SAR distribúcie v anatomickom modeli ľudského tela, opäť so zameraním na štúdium účinkov superpozície pomocou matice aplikátorov. Na druhú stranu matica aplikátorov môže byť použitá na liečbu ochorení u väčších plôch pre klinické účely.

Ďalšou dôležitou témou tejto dizertačnej práce je pôvodná štúdia a optimalizácia aplikátorov pre intrakavitárnu liečbu. Ako veľmi originálny prínos tejto dizertačnej práce považujeme štúdiu uskutočniteľnosti kombinácie externého a intersticiálneho aplikátoru.

V neposlednom rade táto dizertačná práca popisuje analytické a numerické štúdie povrchových vĺn a metód ako ich odstrániť, pretože môžu spôsobiť tzv. hot-spot problém.

Na základe týchto výsledkov dizertačná práca prináša návrh aplikátorov vhodných na lekárske aplikácie a pre biologické experimenty (vrátane numerických simulácií ich SAR distribúcie a meranie rozloženia teplôt v agarom fantóme).