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MICROWAVE THERMOTHERAPY IN CANCER TREATMENT: EVALUATION OF HOMOGENEITY OF SAR DISTRIBUTION

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Abstract—Medical applications of microwaves (i.e., a possibility to use microwave energy and/or microwave technique and technology for therapeutical purposes) are a quite new and very rapidly developing field. Microwave thermotherapy is being used in medicine for cancer treatment and treatment of some other diseases since early eighties. This paper is a contribution to a theory of phase array applicators to be used for a microwave thermotherapy (microwave hyperthermia) in a cancer treatment. It deals with a study and theoretical evaluation of homogeneity of *SAR* distribution in cylindrical agar phantom for several different values of its radius. Discussed *SAR* distribution is in our case created by simulations of EM field exposure done by aid of four microwave stripline type TEM mode applicators of the same type.

1. INTRODUCTION

This paper describes the results achieved in the field of microwave thermotherapy. It represents a contribution to the theory of phase array applicators for microwave hyperthermia cancer treatment [1–14]. Hyperthermia is a thermotherapeutical method used for fulguration of cancerous cells by artificially increasing temperatures due to electromagnetic field exposure [15–19]. There is a number of scientific papers related to this topics and to necessary technologies [1–41]. For real clinical applications of the microwave thermotherapy in general a very high level of homogeneity of a 3D temperature distribution obtained by aid of the discussed phase array applicators is strongly required. It is essential to ensure that the treatment is of the highest quality. One of the basic condition to reach such a goal is a very

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good level of homogeneity of a SAR 3D distribution generated by the discussed phase array applicators [20, 21]. In the paper by Gelvich et al., 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 [22]. In our opinion, this definition does not correspond well with usual requirements for Quality Assurance for microwave thermotherapy in cancer treatment. In such cases, the criteria for efficient treatment is as follows: level of SAR in the tumour should be at least on the level of 50% of its maximum value. This criteria is a basis for in Section 3 of this paper introduced definition of homogeneity function H. From this then follows the three stated levels of homogeneity.

This paper therefore deals with the study and evaluation of homogeneity of SAR distribution in cylindrical agar phantom for several different values of its radius. Discussed SAR distribution is in our case created by EM field exposure done by the aid of four microwave stripline type TEM mode applicators of the same type.

2. CLINICAL USE OF MICROWAVE THERMOTHERAPY

Thanks to the rapid advances in technology and especially those in medical technology during the early eighties we can now talk about microwave thermotherapy. It is currently being used in cancer treatment and it is also used when treating some other diseases. Medical applications of microwaves are divided 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., by aid of permittivity measurement, microwave tomography),
- part of a treatment or diagnostic system (e.g., linear accelerator).

Microwave thermotherapy, which is mostly used in medical applications of EM fields, is based on thermal effect [23]. Temperatures up to 41°C are used for applications in physiotherapy and this method is called microwave diathermia [24]. Microwave hyperthermia uses the temperature interval between 41°C and 45°C for cancer treatment [25, 26]. Microwave ablation (destruction of cells) occurs, when the temperature is more than 45°C [27]. Such microwave thermo ablation can be used in cardiology (for heart stimulations, treatments of

heart arrhythmias, fibrillations, microwave angioplastics), and in urology (for treatment of Benign prostatic Hyperplasia — BPH) [28]. Microwave thermotherapy is often used in combination with other medical therapeutical methods, like e.g., immunotherapy, chemotherapy, radiotherapy or chirurgical treatment, for cancer treatment.

3. DEFINITION OF *SAR* HOMOGENEITY

This section describes how to evaluate the homogeneity of SAR distribution in agar phantom. As EM field exposure system we selected a system which consists of four microwave stripline type TEM mode applicators of the same type, described in more details in Section 4 of this paper [29, 30]. The Discussed microwave applicators work at a frequency of 70 MHz and are designed for deep local and regional type cancer treatments by microwave power [31–34]. In our study, the exposure system is coupled to a cylindrical homogeneous agar phantom mimicking the biological tissue (muscle tissue in our case). Our Study presents a sequence of several simulations of SAR distributions with different values of the radius of the cylindrical agar phantom changing in the range from 50 up to 100 mm. To compare the quality of the homogeneity obtained in different simulations we need to specify what the definition of the parameter of homogeneity is.

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

$$H = SAR_{\max}/SAR_{\min} \tag{1}$$

where $SAR_{\max}$ is a maximum value of SAR in the studied volume and $SAR_{\min}$ is a minimum SAR value in a studied volume. Such a 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. (1) 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., function H is almost equal to 1).

2 *Very good homogeneity*, when in all studied volume $SAR_{\min} > SAR_{\max}/2$ (i.e., function H is in interval between 1 and 2).

3 *Poor homogeneity*, when in studied volume there is region in which $SAR_{\min} < SAR_{\max}/2$ (i.e., function H is bigger than 2).

It is evident that for such a definition a critical value of 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:

$$H = H(f, \varepsilon, R, L) \tag{2}$$

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

4. DESCRIPTION OF THE APPLICATOR

When researching the above mentioned problem we chose a microwave stripline type applicator with TEM mode [35]. Our goal is to create in the cylindrical agar phantom the SAR profile with the best possible homogeneity. In order to achieve this we selected for our studies TEM

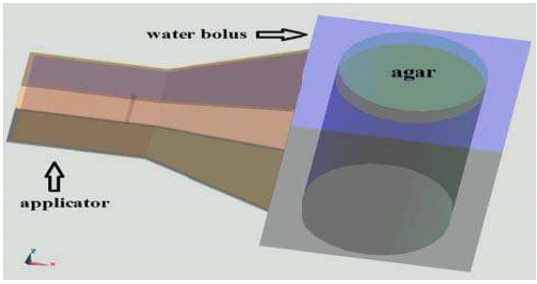


Figure 1. Model of applicator coupled to water bolus and to agar phantom.

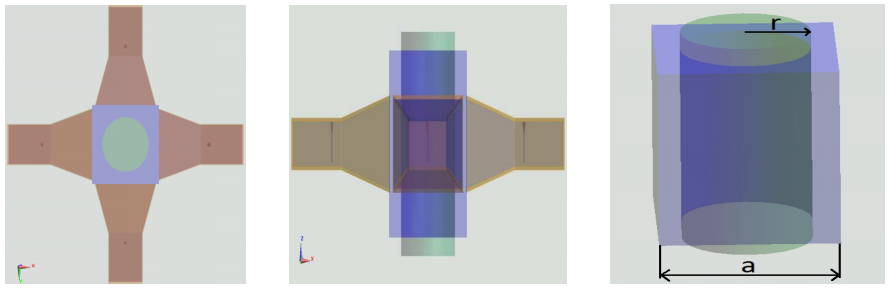
stripline type applicator, because from its aperture a plane wave is irradiated, i.e., EM field with the best possible homogeneity goes from applicator into the phantom. This applicator was developed at the Department of Electromagnetic Field of the Czech Technical University in Prague [36]. It is displayed in Figure 1.

The electromagnetic field in this applicator was excited by a capacitive probe, which is located inside the applicator. The EM wave propagation from applicator into the treated tissue depends on dielectric parameters, such as relative permittivity ε and conductivity σ of that tissue. This discussed EM wave propagates along a strip-line type transmission line, (upper and bottom part of applicator consists of one piece of highly conductive material, in our case it is made from copper). Transversal dimensions of this applicator are 100×60 mm. Lateral sides of the applicators are made from a dielectric material such as acrylic glass. Aperture of this applicator has a stripline type horn shape — its dimensions are 240×200 mm and its length equals approximately one quarter of wavelength. Wavelength of TEM wave on transmission line depends on frequency and on permittivity of dielectric material used to build the discussed transmission line (in our case $\varepsilon_{H20} = 85$). Whereas 70% of human body consists of water, applicator is filled with distilled water. The Advantage of the applicator filled by water is a better transfer of electromagnetic energy from the applicator into human body. This applicator was designed and optimized by the FDTD simulator [37–41] (e.g., SEMCAD X EM Field simulator from SPEAG, Schmid & Partner Engineering AG, Switzerland).

To evaluate the created applicator a homogeneous agar phantom mimicking muscle tissue has been used. The detailed reasons for this are explained in Section 5. Between applicator aperture and phantom there is a so called water bolus, which fulfills several important functions, e.g., mechanical matching of surface of phantom to aperture of the discussed applicator, impedance matching between phantom and applicator, surface cooling of the treated area and by this possible elimination of the so called hot spots.

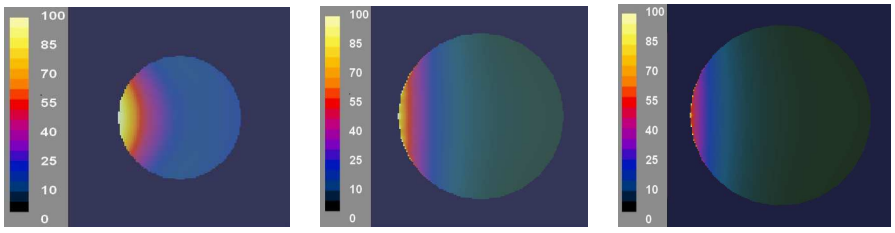
5. SIMULATIONS

By the aid of SEMACD X simulator, we simulated the array of TEM mode applicators of the discussed type located around cylindrical agar phantom of biological tissue, which in our work we gradually enlarged in several steps, and thus we can compare results of single simulations. We selected this particular biological phantom for the following two reasons: Firstly, a cylindrical shape is a very good approximation for the shapes of various parts of human body (e.g., arm, leg, thorax,



(a) (b) (c)

Figure 2. (a) Transversal plane cross section, (b) sagittal plane cross section and (c) definition of basic dimensions of cylindrical agar phantom and water bolus: a and r.



(a) (b) (c)

Figure 3. SAR distribution created by only one applicator. Dimensions: (a) $r = 50\,\text{mm}$, $a = 180\,\text{mm}$, (b) $r = 75\,\text{mm}$, $a = 200\,\text{mm}$, (c) $r = 100\,\text{mm}$, $a = 250\,\text{mm}$.

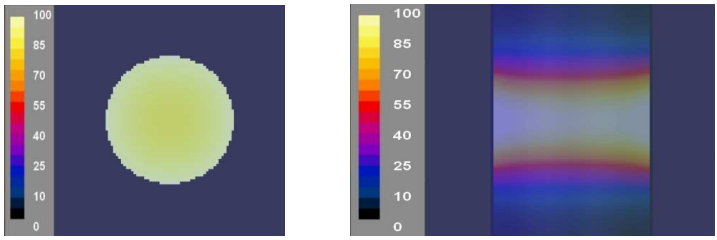
abdomen, etc.). And secondly — the simple homogeneous structure is the best one for the studies of homogeneity of the SAR distribution primarily related to the studied applicators. It should be the first step when new types of the applicators are being studied. In case of the true anatomical phantoms homogeneity of SAR distribution is significantly influenced by selected anatomical part of human body. In our simulations we took into account dielectric properties of muscle tissue. Real cancer cells have somewhat lower values of complex permittivity, but the SAR distribution is influenced by square root of complex permittivity, so the mentioned difference does not play a significant role. Between homogeneous agar phantom and array of applicators a water bolus is inserted for better transfer of electromagnetic energy into agar phantom, as can be seen in Figure 2.

In order to be able to evaluate effect of SAR superposition created by array of four applicators, we did some simulations of the case, when only one of four applicators was active (see Figure 3). Here simulations of 3 cases ($r = 50\,\text{mm}$, $r = 75\,\text{mm}$ and $r = 100\,\text{mm}$) are displayed.

Figures 4 to 14 display 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 in 11 steps from 50 to 100 mm. The range of radius from 50 to 100 mm is very typical to different parts of the human body which we potentially expect to be treated by microwave thermotherapy — e.g., arm, leg, thorax, abdomen, etc. The SAR distribution scale in Figures 4 to 14 has no units. In all these figures we display normalized value of SAR, i.e., real value in discussed point divided by maximum value in the studied area. And then multiplied by 100, thus we have result in percent with respect to the SAR maximum value. Doing this we can easily find 50% Iso-SAR curve, which is boundary of the area, where we can expect successful treatment.

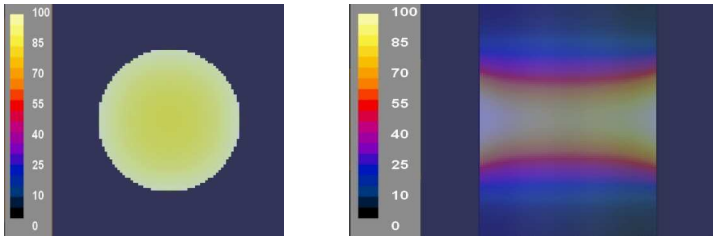
6. DISCUSSION OF PRESENTED RESULTS

In Figures 4 to 14, when comparing the homogeneity of SAR of all the different cases an almost perfect homogeneity of the studied



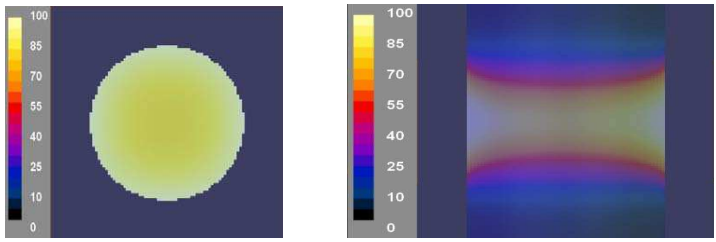
(a) (b)

Figure 4. 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.



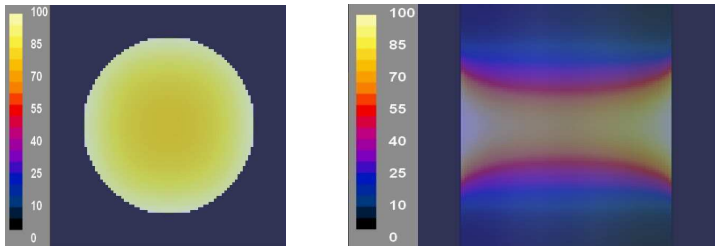
(a) (b)

Figure 5. SAR distribution for case $r = 55$ mm, $a = 180$ mm, $H = 1.182$. (a) In transversal plane cross section and (b) in sagittal plane cross section.



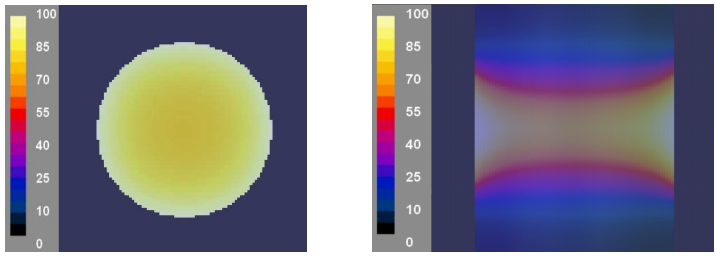
(a) (b)

Figure 6. SAR distribution for case $r = 60\,\text{mm}$, $a = 180\,\text{mm}$, $H = 1.258$. (a) In transversal plane cross section and (b) in sagittal plane cross section.



(a) (b)

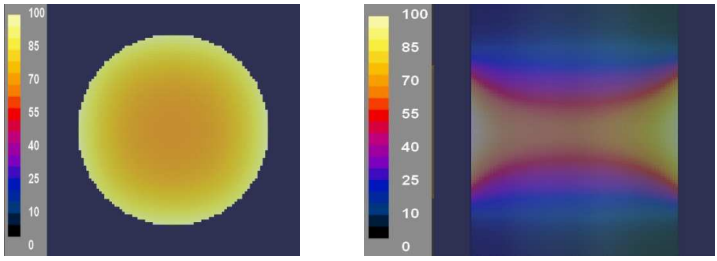
Figure 7. SAR distribution for case $r = 65\,\text{mm}$, $a = 180\,\text{mm}$, $H = 1.3448$. (a) In transversal plane cross section and (b) in sagittal plane cross section.



(a) (b)

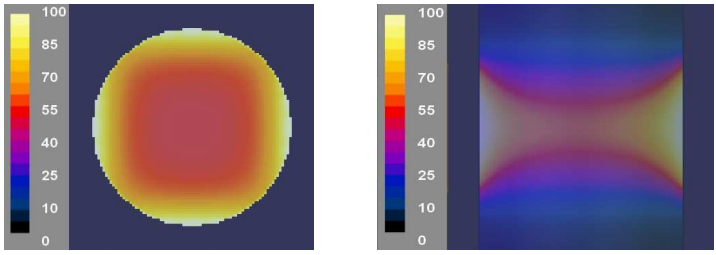
Figure 8. SAR distribution for case $r = 70\,\text{mm}$, $a = 180\,\text{mm}$, $H = 1.3448$. (a) In transversal plane cross section and (b) in sagittal plane cross section.

SAR distribution (i.e., SAR almost perfectly constant in all phantom volume) can be observed only for case of the agar phantom radius up to 60 mm. With respect to the SAR maximum (i.e., level of 100%) the SAR value is above the 50% level here in all the agar phantom volume.



(a) (b)

Figure 9. SAR distribution for case $r = 75\,\text{mm}$, $a = 200\,\text{mm}$, $H = 1.444$. (a) In transversal plane cross section and (b) in sagittal plane cross section.



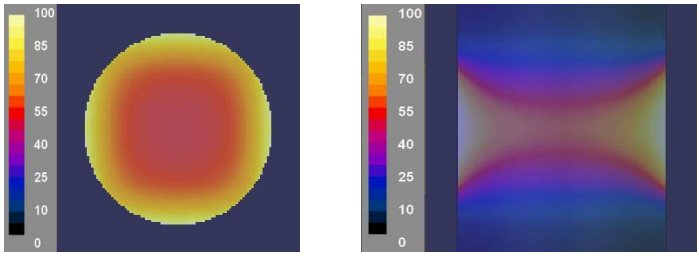
(a) (b)

Figure 10. SAR distribution for case $r = 80\,\text{mm}$, $a = 200\,\text{mm}$, $H = 1.857$. (a) In transversal plane cross section and (b) in sagittal plane cross section.

When we enlarged in several steps the radius of cylindrical agar phantom up to value of 100 mm (and we will repeat simulations for all these cases, of course) then we can compare homogeneity of SAR created in agar for all these cases, what can be seen very well in all SAR distributions displayed in all cases of Figure 4 till 14.

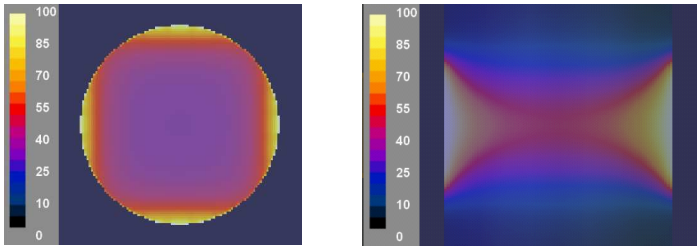
Increasing the value of agar phantom radius, we can see that homogeneity of 3D SAR distribution in agar phantoms deteriorates very quickly. Just at radius of 80 mm homogeneity of SAR approaches to its critical value (see please Figure 9 — there is very evident decrease to level of 50% with respect to the SAR maximum), i.e., $H = 1.857$ in this case.

Figure 11 to 14 show that the quality of homogeneity of SAR is deteriorating, i.e., level of SAR is below the level of 50% (with respect to the SAR maximum, which corresponds to 100%) in a substantial part of studied agar phantom volume. Comparing all the studied cases



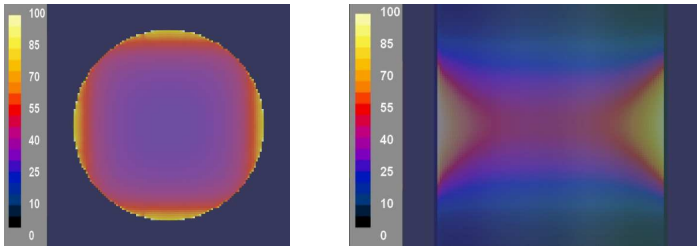
(a) (b)

Figure 11. *SAR* distribution for case $r = 85\,\text{mm}$, $a = 220\,\text{mm}$, $H = 2.05$. (a) In transversal plane cross section and (b) in sagittal plane cross section.



(a) (b)

Figure 12. *SAR* distribution for case $r = 90\,\text{mm}$, $a = 220\,\text{mm}$, $H = 2.599$. (a) In transversal plane cross section and (b) in sagittal plane cross section.

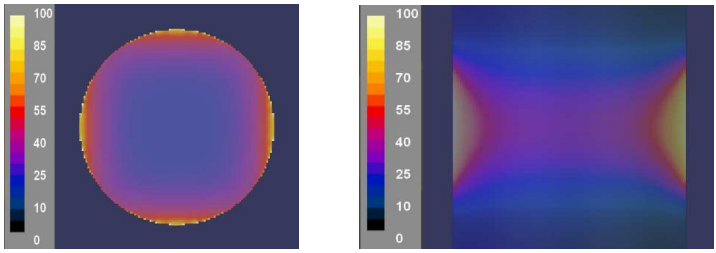


(a) (b)

Figure 13. *SAR* distribution for case $r = 95\,\text{mm}$, $a = 240\,\text{mm}$, $H = 3$. (a) In transversal plane cross section and (b) in sagittal plane cross section.

in the Figure 4 to 14, we can arrive at the conclusion given by a graph displayed in Figure 15.

The quality of the current software tools for numerical simulations



(a) (b)

Figure 14. SAR distribution for case $r = 100\,\text{mm}$, $a = 250\,\text{mm}$, $H = 3.552$. (a) In transversal plane cross section and (b) in sagittal plane cross section.

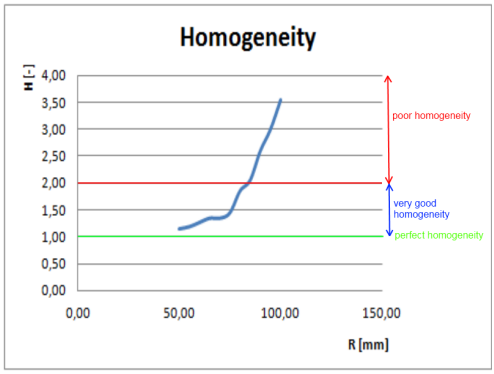


Figure 15. Homogeneity H vs. radius R of cylindrical agar phantom.

of the EM field is considered on prototyping level now, and theirs results in general are considered to have high level of confidence. Margin of error in the presented results is less than 5%. That is why in this phase we do not consider it necessary to compare presented results with measurements. But of course, we will prepare for laboratory measurements for the near future.

7. CONCLUSIONS

Results of the study of homogeneity of SAR distribution created by the array of TEM stripline type applicators of the same type in homogeneous agar phantom have been described and discussed in this paper. The effect of the phantom dimensions on 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. Main conclusion of our work is that from the point of view of real treatments of cancer patients a significant reduction in homogeneity of SAR can be observed for radii more than 85 mm.

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