WAVEGUIDE APPLICATORS FOR MICROWAVE THERMOTHERAPY: APERTURE AND WATER BOLUS RESONANCES

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Abstract: Paper deals with our new results in the field of external local applicators used for microwave thermotherapy, like e.g. cancer treatment, physiotherapy, etc.

Introduction

In our contribution we describe external local applicators working at 70, 434 and 2450 MHz**.** These applicators were used here in Prague for the treatment of more then 500 cancer patients with superficial or subcutaneous tumours (up to the depth of approximately 6 cm).

Local External Applicators

We have studied waveguide applicators heating pattern for the aperture excitation at above and at under the cut-off frequency. It has helped us to get analytical approximations of the electromagnetic field distribution in the treated area of the biological tissue. In the Figure 1. there is one of very important results - diagram showing the theoretical depth of heating *d* as a function of the used frequency *f* and of the aperture diameter *D* of the applicator. The most important results for the effective heating depth *d* can be characterised as follows:

- at high frequencies (above 1000 MHz) the depth of effective heating *d* is a function of frequency *f* (s,
- bellow 100 MHz *d* is the dominantly function of the diameter *D* of applicator aperture (*d* = 0.386 *D).*

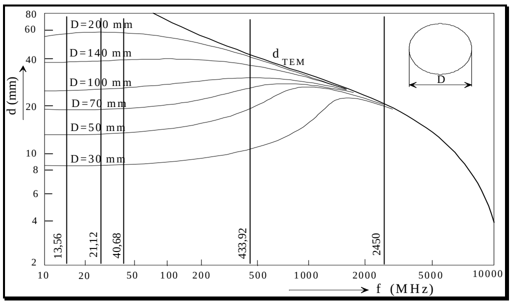


Figure 1: Effective depth of heating *d* for external applicator with respect to frequency f [MHz] and diameter of aperture D [mm].

Local microwave applicators can be either directly coupled to treated area, or they can be coupled through the so called water bolus (i.e. plastic sac).

Resonances in the aperture of waveguide applicator

Another of our research interests is to study what happens, when the frequency *f* of hyperthermia apparatus is either very different (much higher or much lower) from the cut-off frequency f_c of the used waveguide applicator or very near (even equal) to this cut-off frequency f_c.

In our contribution we would like to discuss what happens, when the frequency *f* of hyperthermia apparatus is either very different (much higher or lower) from the aperture resonance frequency f_r or very near (even equal) to the aperture resonance frequency $\underline{f_r}$ of the used waveguide applicator. This special case of our interest can happen when either the hyperthermia apparatus is tunable in broader frequency range or the aperture resonance frequency f_r of the applicator is changed by different dielectric parameters of various types of biological tissues.

There is a substantial difference between the two ways of the waveguide applicator excitation (i.e. above or under the aperture resonance frequency f_r) and in the propagation and „behaviour“ of the EM field inside such applicator also. Basic differences would be explained during the presentation.

For the following discussion we have chosen the case of the rectangular applicator with a flange. But similar results is possible to obtain for other important cases like e.g. rectangular applicators without flange or for the family of circular applicators

In Figure 2, a simple sketch of electric field strength line of the electromagnetic field irradiated from waveguide applicator is shown. It is the basis of our analysis of SAR distribution in front of the aperture of waveguide applicator, radiating into the heated biological tissue. Formulas describing the electric field distribution are given in the right side of this figure.

Waveguide flange is in our approach considered as an electric wall, dashed line going into the biological tissue determines the magnetic wall of our model. The distance between these walls determines the aperture resonance frequency f_r of the applicator aperture. Of course, f_r is influenced by the tissue permittivity also.

Let us take into account the area of biological tissue surrounded by electric and magnetic walls. Then the hybrid waveguide mode HE_{11} (i.e. the lowest possible one) can be defined and excited in the biological tissue in front of applicator aperture and can be specified by the case

$$m = n = 1 \ .$$

In fact, it is a linear superposition of the modes TE_{11} and TM_{11}. Higher order modes can be suppressed by the suitable construction of the applicator. Moreover these modes do not penetrate so deep in the tissue, therefore we need not to take them into account in our analysis.

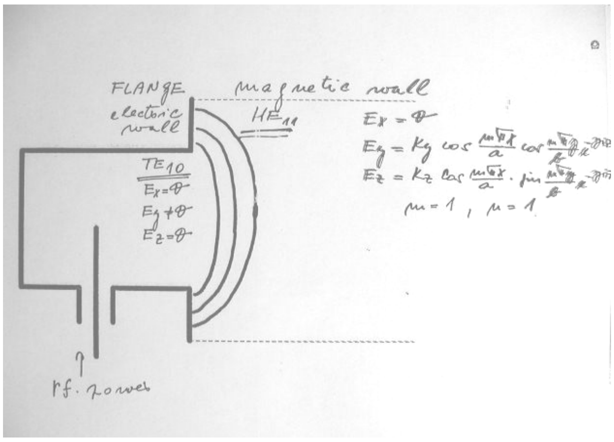


Figure 2: Schematics of the applicator radiating into the biological tissue.

Series of the figures 3a to 3c show the change of the SAR in front of the applicator aperture as a function of working frequency *f* of the hyperthermia apparatus with respect to the f_r. There is big difference between *f* and f_r in the case shown in Figure 3a, instead both frequencies are very near each to other in the figure 3c (the difference between *f* and f_r is going down through the figure series). More detailed description of this theory of the waveguide applicator SAR analysis and more figures we will offer during presentation.

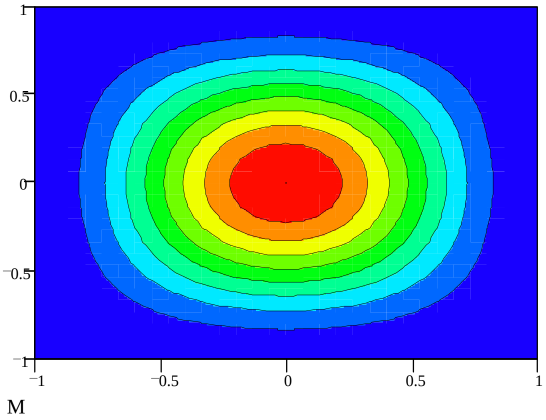
The results we would like to describe in our contribution are important from theoretical point of view of the knowledge about the general properties of the waveguide applicators. And are very important also for the treatment - our results demonstrate very substantial changes of SAR distribution in the treated biological tissue. If *f* is going to f_r then so called hot spots complicating the treatment can arise.

Waveguide flange is considered as an electric wall, dashed line going into the biological tissue determines the magnetic wall of our model.

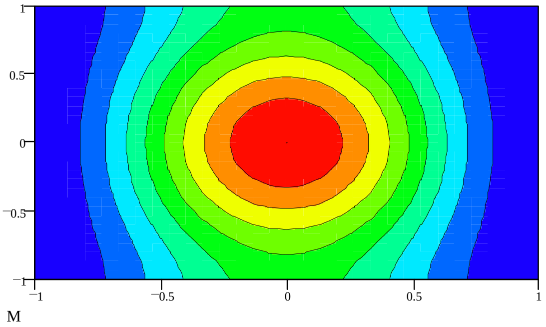
Let us take into account the area of biological tissue surrounded by electric and magnetic walls. Then the hybrid waveguide mode HE_{11} (i.e. the lowest possible one) can be defined and excited in the biological tissue in front of applicator aperture (it is a linear superposition of the modes TE_{11} and TM_{11}). Higher order modes can be suppressed by the design of the applicator. Following 3 cases describe the change of the SAR in front of the applicator aperture as a function of working frequency *f* of the hyperthermia apparatus with respect to the f_c:

- if there is enough big difference between *f* and f_c , then homogeneous heating of the treated area can be expected – see Figure 3a,b,c.

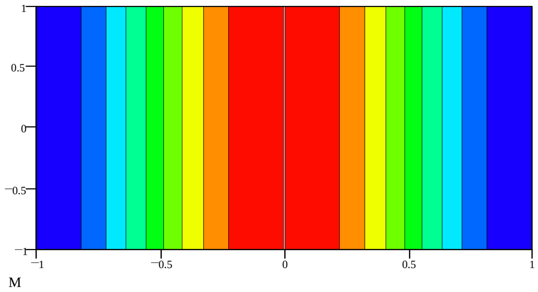
- if the both frequencies are very near each to other (difference between *f* and f_c is going down), then overheating (hot-spots) out of the treated area can arise - see Figure 3d,e.



a)



b)



c)

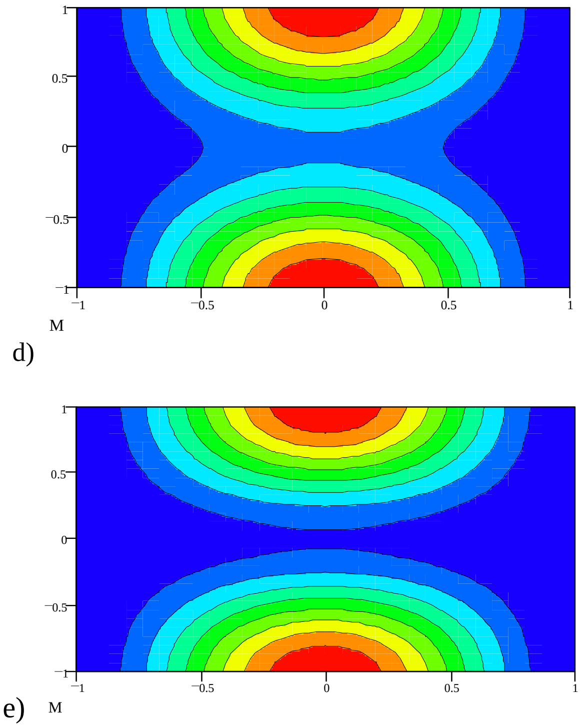


Figure 3: Calculated SAR in the waveguide aperture

Water bolus

Often waveguide applicator is not coupled directly to the biological tissue, but between its aperture and treated are a so called water bolus is being placed – please compare Figure 4 and Figure 5.

There are several reasons to do this. Firstly if waveguide applicator could create so called hot spots (intensive overheating of certain part of the treated area as can be observed in Figure 4) then water bolus can prevent patient from this problem, if water bolus will be used.

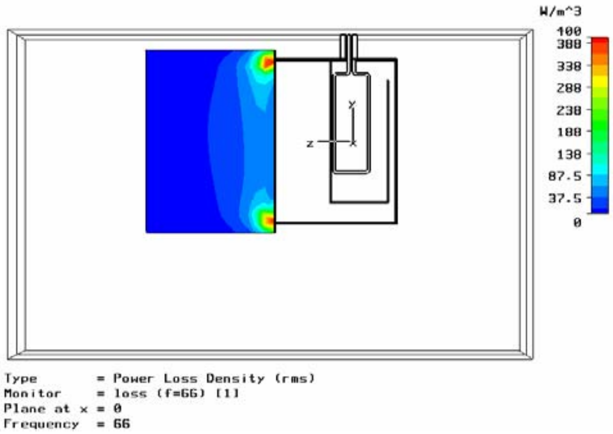


Figure 4: Numerical simulation of the applicator radiating into the biological tissue.

We have studied the influence of water bolus on SAR and temperature in the treated area. In Figure 5 we would like to give an example of SAR and temperature improvement obtained by aid water bolus in comparison to Figure 5.

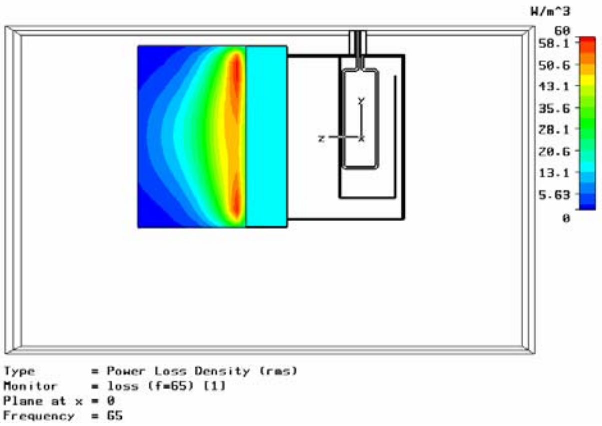


Figure 5: Numerical simulation of the applicator radiating into the biological tissue through the water bolus.

In general, water bolus can often improve both SAR and temperature distributions in the treated area. But sometimes volume resonances can occur and in such case heating pattern can deteriorate significantly. To prevent that, we need to study conditions of resonant modes inside water bolus.

Volume resonances in the water bolus

Further we will discuss possibilities of excitations of volume resonances in the water bolus. For simplicity we will work here only with electrical field strength components

$$\dot{E}(x,y,z)=\frac{E_0\exp(-ikz^*)}{\left[(z^*-a_0)(z^*-b_0)\right]^{1/2}}\cdot\exp\left[\frac{-ikx^2}{2(z^*-a_0)}\right]\cdot\exp\left[\frac{-iky^2}{2(z^*-b_0)}\right]$$

From electromagnetic point of view water bolus can be considered to be a dielectric resonator with a series of the so called resonant modes and their a resonant frequencies. Basic known equation for resonant frequencies of cavity resonator can be expressed as

$$f_{VO}^{mnl}=\frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2+\left(\frac{l}{b}\right)^2+\left(\frac{n}{d}\right)^2}=f_{op}$$

In general we can distinguish volume resonances (in the case when n is different from 0) and aperture resonances (in the case when n is equal to 0).

Previous equation for resonant frequency of resonant modes is valid only for certain type of boundary conditions: metallic wall surrounding dielectric media. In our case situation is more complicated. In order to determine resonant modes and its resonant frequencies we have to take into account following transitions from the studied water bolus to:

- aperture of applicator,
- biological tissue,
- surrounding air.

To describe open wall resonators in microwave technology we often use a model of either so called electric wall or the so called magnetic wall. In both of these cases almost all incident electromagnetic power is being reflected back to water bolus, i.e. energy can be stored in the discussed water bolus and so it can behave like a resonating structure.

Magnetic wall can be a good model for the case of the transitions between water bolus and surrounding air. And for the case of transitions between water bolus and aperture of applicator if this applicator is filled by air as well.

Instead if we take into account either transition between water bolus and water filled applicator or transition between water bolus and biological tissue, then level of reflections is very low, as dielectric constant values are very near each to other in different parts of discussed system.

Influence of losses in water bolus

EM field losses in water bolus in general should be very low, therefore distilled water is mostly used, sometimes even deionised water. That can guarantee us, that we will have good results in transferring almost all the energy into the biological tissue.

If from any reason the losses in water bolus will not be negligible, it can cause a lot of problems. E.g. not all microwave energy will reach the treated area, water in water bolus will be heated and so its temperature will increase. And also for resonant modes in water bolus losses will change its quality factor Q, and so its bandwidth as well

$$\Delta f = f_r / Q,$$

where

$$Q = \frac{\varepsilon\omega}{\sigma},$$

where conductivity of distilled water is 35-45 mS/m and so at frequency 434 MHz quality factor is approximately equal to values level of 40 -50.

Conclusions

Microwave thermotherapy is successfully applied in clinics in the Czech Republic. Technical support is at present from the Czech Technical University in Prague. Our goal for the next technical development is:

- improve the theory of the local applicators design and optimisation,
- innovate the system for the applicator evaluation (mathematical modelling and measurements)

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