Design Optimization of Waveguide Applicator for Microwave Hyperthermia Cancer Treatment

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Abstract: The optimized design and simulation of a waveguide applicator has been presented here for superficial microwave hyperthermia using COMSOL Multiphysics 3.5a. Non-Invasive or external hyperthermia is used to treat tumors that are in or just below the skin (superficial). Non-invasive hyperthermia systems using waveguide applicators are less traumatic to patients which also minimize the risk of mixing abnormal cells with healthy tissues. The dimensions of the waveguide can be optimally selected to focus the energy more specifically over the tumor region. The 3D modeling of the waveguide applicator is performed and the performance is verified by analyzing the resistive heating and temperature distributions in muscle like phantom.

Keywords: Finite Element Method, Waveguide applicator, 3D simulation, Temperature distribution, SAR

1. Introduction

Hyperthermia refers to the rise in temperature of a part or whole body above normal temperature (41-45°C) [1]. Hyperthermia is a type of cancer treatment in which body tissues are exposed to very high temperatures. This is done using external or internal heating devices. High temperatures can damage and kill cancer cells, usually with minimal injury to normal tissues. The blood perfusion increases with increase in the blood temperature as a result the healthy tissue is defended against further temperature rise and damage whereas the tumors with diameter more than 2 cm do not exhibit this defensive mechanism. The temperature in tumor cells grows fast and their damage takes place in short time [2].

The most often used heating sources are electromagnetic and ultrasound radiations. When using electromagnetic radiation, it is possible to work with non-ionizing radiation. It reduces the damage to healthy tissue and does not cause side effects.

2. Methodology

Finite element modeling is performed for the superficial hyperthermia using waveguide as applicator. FEM simulations are accurate and flexible for detailed studies. FEM can be considered as a three step process preprocessing (mesh generation), analysis and then postprocessing. It divides a very complicated problem into small elements that can be solved in relation to each other. In the design of applicator 3D modeling has been done which is more practically realistic hence offering many advantages over 2D modeling.

2.1 Waveguide Applicator Design

The dimensions of the waveguide aperture are calculated using the following equations:

$$a = \frac{1}{2 f_c \sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}} \qquad (1)$$

$$b = \frac{a}{2} \qquad (2)$$

where, a and b are the height and width of the waveguide aperture, f_c is the cut-off frequency, μ_0 *and* μ_r are the permeability of free space and the material inside the waveguide respectively, ε_0 *and* ε_r are the permittivity of free space and the material inside the waveguide respectively.
For calculating the waveguide height, it is necessary to know the wavelength, which is given by the equation:

$$\lambda = z = \frac{1}{f_c\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r}} \quad (3)$$

The position and orientation of the applicator are optimized in order to achieve better distribution of SAR (Specific Absorption Rate) in treated area. SAR determines the quantity of electromagnetic field exposition and it is related to E- field by [3].

$$\mathrm{SAR} = \frac{\sigma\,\mathrm{E}^2}{\rho}\left(\frac{\mathrm{W}}{\mathrm{kg}}\right) \quad (4)$$

Where σ (S/m)is electric conductivity,ρ (kg/m^3) represents the mass density of the tissue and E (V/m) is the RMS value of the time harmonic electric field strength inside the exposed tissue.

On the other hand, the heat transfer inside a biological tissue is described by bioheat equation proposed by Pennes [4,5], which relates TE waves with temperature increase in tissue.
The bioheat equation is defined as:

$$\delta_{ts}\rho C\frac{\partial T}{\partial t} + \nabla.\ (-k\nabla\,\mathrm{T}) = \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \quad (5)$$

Where,
$\delta_{ts}$is a time scaling coefficient
$\rho$is the tissue density
C is the specific heat of tissue
k is the tissue thermal conductivity tensor
$\rho_b$is the density of blood
$C_b$is the specific heat of blood
$\omega_b$is the blood profusion rate
$T_b$is the arterial blood temperature
$Q_{met}$is the heat source from metabolism
$Q_{ext}$is the specific heat source

3. Hyperthermia System Modeling

In this paper, 3D model of waveguide applicator has been created for hyperthermia treatment using COMSOL Multiphysics 3.5. This software allows modeling and simulation of various physical processes by solving partial differential equations. These equations are solved by finite element method. The program has various modules which are used to solve problems of particular physical domain. In this model harmonic propagation of EM waves in radiofrequency module is used [6]. The model is designed to work at frequency of 404 MHz. This frequency is one of the Industrial, Scientific and Medical (ISM) frequencies. The dimensions of the waveguide are 60 x 30 x 58 mm. A water bolus which is 20 mm thick is placed between the waveguide and the surface of agar jelly muscle phantom as shown in Fig, 1. The water bolus serves the purpose of keeping contact between the microwave applicator and the skin surface, homogeneity of temperature and skin cooling which helps prevent skin burns and thermal blisters [7]. The significance of using agar jelly is that its electrical and thermal parameters are similar to the biological tissue [8].

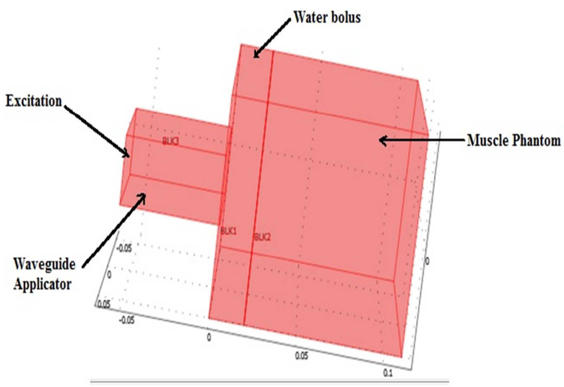

Fig.1. 3D model of hyperthermia system

The wave excitation with P_{in} = 10 mW is applied at the input aperture of the waveguide. Matched boundary conditions are selected for water bolus and muscle phantom. After applying the boundary conditions the meshing is performed. The final mesh obtained is as shown in Fig. 2. Vector Quadratic type elements are used for meshing the geometry. The mesh consists of 5079 element with 34838 degrees of freedom**.** The parametric solver is then used to solve the model. The execution has been performed using Intel Pentium(R) dual CPU E2200 @2.2GHz with solution time of 749.938 s.

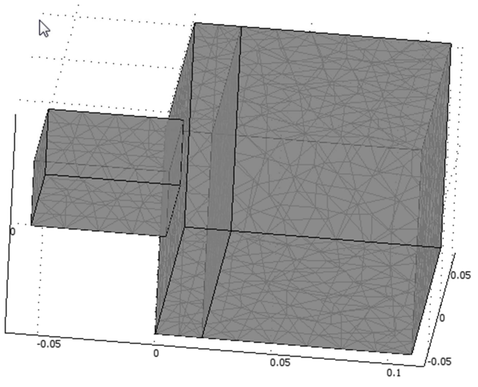

Fig.2. Mesh plot of the hyperthermia system

4. Results and Discussion

The performance of waveguide applicator has been validated by evaluating the heat distribution and S_{11} parameter. Fig. 3 plots the value of S_{11} as a function of frequency. At operating frequency of 404 MHz S_{11} reaches a minimum of -26.7 dB indicating good impedance matching. The applicator frequency bandwidth (S11 < -10 dB) is 57 MHz (from 371 MHz to 428MHz),

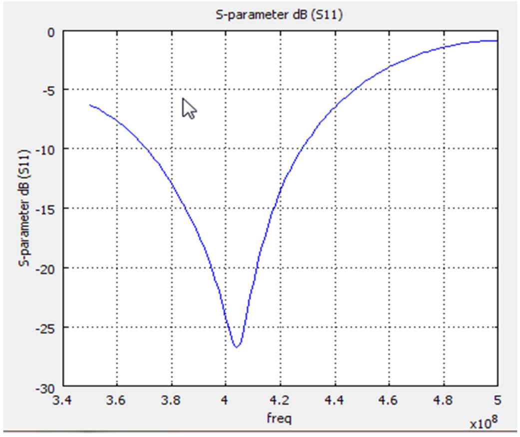

Fig.3. Impedance matching of waveguide applicator

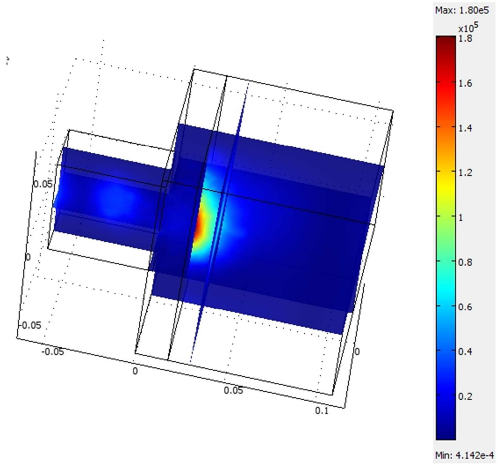

Fig.4. Heat distribution plot of waveguide applicator

Fig. 4 depicts the surface plot of restive heating pattern resulting in heat distribution within the muscle phantom. From the distribution it can be observed that the heating pattern is more localized indicating improved performance. The 2D plot of resistive heating is also presented in Fig. 5.

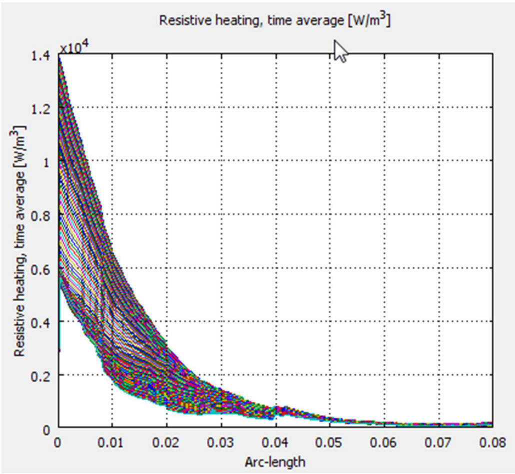

Fig.5. Resistive heating plot

5. Conclusions

A 3D model of waveguide applicator is presented here for hyperthermia treatment. This work also performs the analysis of the distribution of electric field along with the resistive heating distribution. Finite element full-wave modeling has been performed to predict to a high degree of accuracy the performance of 3D model of the applicator. In the next step of research the formulation of 3D model will be done for several tissue types.

6. References

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