FINITE ELEMENT ANALYSIS FOR OPTIMIZING ANTENNA FOR MICROWAVE COAGULATION THERAPY

MAINI SURITA*, MARWAHA A., MARWAHA S.

Sant Longowal Institute of Engineering & Technology,
Longowal (Deemed University) Distt. Sangrur, Punjab, India
*Corresponding Author: suritamaini@gmail.com

Abstract

Microwave coagulation therapy (MCT) is emerging as an attractive modality for thermal therapy of soft tissues targeted in short periods of time, making it particularly suitable for ablation of hepatic and other tumors. In this field of microwave coagulation therapy, the use of minimally invasive antenna is recognized as a very promising technique for the treatment of small tumors because a very thin antenna can be easily inserted inside the body and precisely localized using the advanced 3D imaging techniques and surgical robots. The authors investigated the microwave coaxial antenna operating at 2.45 GHz by varying the slots size for the removal of liver tumor. The analysis was done using 2D finite element modeling. By several optimization steps the antenna is simulated and optimized by comparing the values of specific absorption rate (SAR), mesh statistics and temperature distributions in tissue generated by the antenna with the variations of dimensions of slot from 1 mm to 1.7 mm.

Keywords: Antenna design, FEM model, Microwave coagulation therapy, Specific absorption rate, Microwave ablation, Coaxial antenna.

1. Introduction

Many perceived advantages of microwaves in medical applications have drawn the attention of researchers in the recent years [1]. The use of microwave hyperthermia [2] and microwave coagulation therapy (MCT) [3] for medical treatment of cancer has been widely investigated and reported. Ito et al. have been studying the coaxial-slot antenna [4], which is one of the thin microwave antennas implemented for the interstitial MCT. The propensity of the tissue to produce heat in the presence of the time variable electric field is determined by the values of its electric properties [5], the electric conductivity, and the dielectric permittivity,

462

Nomenclatures

B	Magnetic field, T
c	Specific heat capacity, J/kg.K
D	Electric flux density, C/m^2
E	Electric field strength, V/m
H	Magnetic field density
J	Temperature, K
k	Thermal conductivity, W/m.K
Q	absorbed electromagnetic energy, W/m^3
Q_m	Metabolic heat generation, W/m^3
Q_p	Heat loss due to micro-vascular blood perfusion, W/m^3
T	Current density, A/m^2

Greek Symbols

ρ	Mass density of the tissue, kg/m^3
ρ_{free}	free charge density, C/m^2
σ	Electrical conductivity, S/m

Abbreviation

MCT	Microwave coagulation therapy
SAR	Specific absorption rate, W/kg

---

by other physical properties. The dosimetric quantity that relates to heat generation in tissues is the Specific Absorption Rate (SAR), defined as:

$$SAR = \frac{\sigma E^2}{\rho} \tag{1}$$

ρ represents the mass density of the tissue and E is the rms value of the time harmonic electric field strength inside the exposed tissue. In this paper, SAR distributions for all cases were calculated and compared the results to determine the potential heating patterns of the antennas.

To assist in antenna design for MWA, many researchers have employed the use of mathematical models rooted in computational electromagnetics (CEM). Computer modeling techniques for the simulation of hyperthermia treatment are invaluable tool. The complex geometries and tissue properties involved in simulation of MCT, especially perfusion term, makes computer simulations an ideal choice over analytical solutions which require many simplifying assumptions. The present work is based on electromagnetic (EM) numerical analysis approach of finite element method, because FEM uses piecewise approximation to solve the governing bioheat transfer equation. Geometric irregularities and regional heterogeneity are more easily handled by finite element method. FEM models can provide users with quick, accurate solutions to multiple systems of differential equations and as such, are well suited to heat transfer problems like ablation.

The ultimate goal of computer models for microwave tissue ablation is to induce tissue damage, which is a function of the time-temperature, and for this

accurate prediction of the temperature profile in tissue is necessary. The temperature profile in tissue during an ablation procedure depends upon two physical phenomena: (1) interaction of microwaves with tissue and (2) heat transfer in tissue [6].

While considering the interaction of microwaves with tissue, propagation and absorption of microwaves in tissue is governed by Maxwell's equations, stated in Eqs. (2)-(5).

$$\nabla \cdot D = \rho_{free} \tag{2}$$

$$\nabla \cdot B = 0 \tag{3}$$

$$\nabla \times E = -\frac{\partial B}{\partial T} \tag{4}$$

$$\nabla \times H = J + \frac{\partial D}{\partial T} \tag{5}$$

The electromagnetic fields radiations radiated in a given tissue by an appropriate antenna can be determined by solving the Maxwell's equations, with the knowledge of tissue electromagnetic properties (permittivity and conductivity) and appropriate initial and boundary conditions, in order to develop accurate models of the ablation process.

For the heat transfer in the tissue, the temperature profile in tissue during ablation is obtained by solving a bioheat equation (6). The most widely used bioheat equation for modeling thermal therapy procedures is the Pennes bioheat equation [7].

$$\rho c \frac{dT}{dt} = \nabla \cdot k \nabla T + Q - Q_p + Q_m \tag{6}$$

The Pennes bioheat equation does not take in to account of heat loss due to blood flow through large, discrete vessels – "the heat sink effect." The liver is a highly perfused organ having many large blood vessels. Ablations performed in proximity to these vessels are susceptible to the heat sink effect. The heat transfer due to blood flow in large vessels near tumors must be taken into account during planning of treatments with theoretical models.

2. Methods

2.1. Antenna design

A 2D finite element model (FEM) is developed to determine the absorbed power and the temperature distribution surrounding the single thin microwave coaxial antenna using COMSOL multiphysics [8].

Developed antenna model for FM analysis consists of a thin coaxial cable with a 1 mm wide ring shaped slot cut on the outer conductor 6 mm from the short-circuited tip. For hygienic purposes, the antenna is enclosed in a sleeve (catheter) made of PTFE (polytetrafluoroethylene a biocompatible dielectric material). The antenna is operated at 2.45 GHz, a frequency widely used in microwave coagulation therapy. The geometry of the antenna is modeled in 2D, and analyzed with variable dimensions of slot having, 1 mm, 1.2 mm, 1.5 mm and 1.7 mm distances from the tip. The geometry with 1.5 mm slot of the coaxial antenna is shown in Fig. 1.
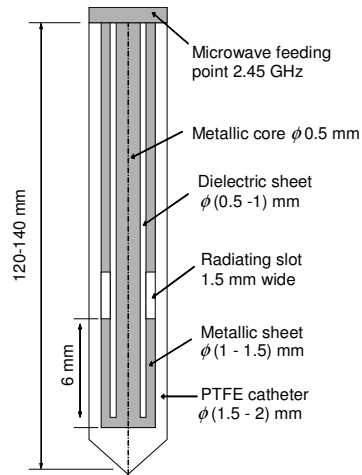
Fig. 1. Microwave Coaxial Antenna Design.

2.2. Numerical analysis

Finite element method was employed for the numerical modeling and analysis of the antenna. The specific absorption rate (SAR) distribution produced by the microwave coaxial antenna has been rigorously investigated.

Figure 2 shows the antenna fed at 2.45 GHz, inserted in a volume of material with parameters as shown in Table 1. The antenna is placed axisymmetrically with liver tissue. The external surface of the liver tissue acts as boundary for the computational domain. In this problem, a low reflecting boundary condition is set on the surfaces, so that boundary does not disturb the EMF distribution. It is assumed that in the heat transfer problem the boundary is thermally isolated.
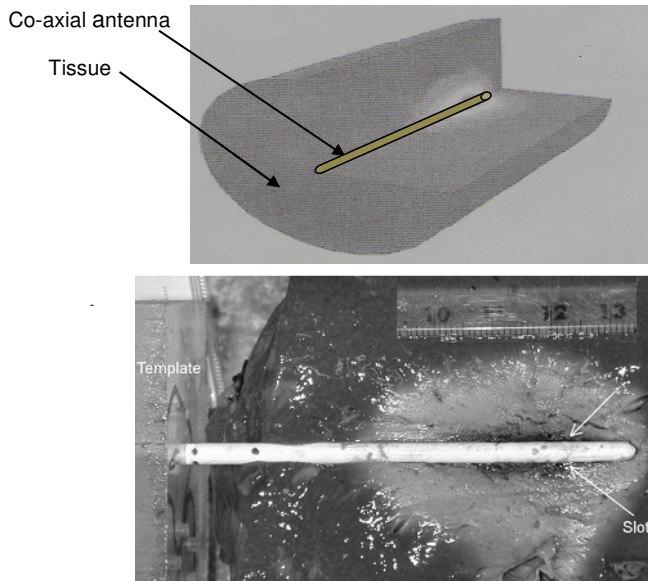

Fig. 2. Antenna Inserted into Liver Tissue.

The microwave source is set at the upper end of the coaxial cable. Taking advantage of the axial symmetry of the domain, a much more economical 2D FEM model is produced and intensively used in the preliminary study of the antenna design and in the primary estimates of the EMF parameters and temperature. Figures 3 and 4 show the temperature and surface distribution in the liver tissue with 2D modeling at the end of the heating process (the steady state), in a longitudinal plane. It is clear that the temperature field follows the heat source distribution quite well. Further the heat lesion is strong near the antenna, which leads to high temperatures, while far from the antenna, the heat lesion is weaker and the blood manages to keep the tissue at normal body temperature.

The finite element method (FEM) involves dividing a complex geometry into small elements for a system of partial differential equation, evaluated at nodes or edges. Figure 5 shows the axisymmeteric finite element mesh, with 1.5 mm slot, generated by FEMLAB using the free mesh parameters with the maximum element 0.003 mm. The mesh consists of 8495 triangular elements with 24552 degrees of freedom (D.O.F).

Table 1. Liver Parameters.

Name	Values	Expressions
K_liver	0.56 [W/(kg.K)]	Thermal Conductivity, liver
Rho_blood	1000[kg/m^3]	Density, blood
C_blood	3639 [J/(kg.K)]	Specific heat, blood
Omega_blood	3.6 e-3[1/s]	Blood perfusion rate
T_blood	37 [Deg^{o}C]	Blood Temperature
P_in	10 [W]	Input microwave power
Nu	2.45 [GHz]	Microwave frequency
eps_diel	2.03	Relative permittivity, dielectric
eps_cat	2.6	Relative permittivity, catheter
eps_liver	43.03	Relative permittivity, liver
sig_liver	1.69 [S/m]	Electrical conductivity, liver
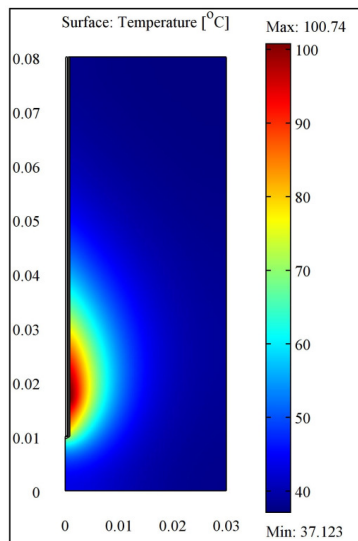
Fig. 3. Temperature Distribution in the Tissue (2D Model.)
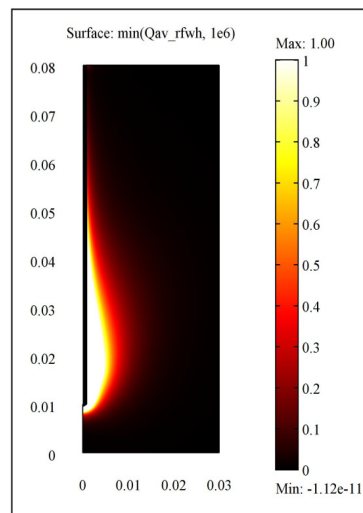
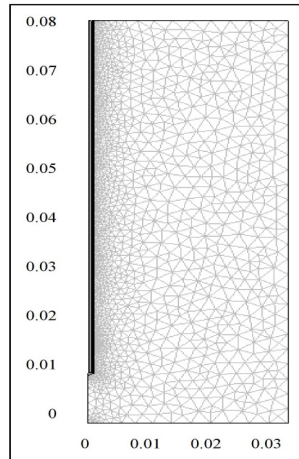**Fig. 4. Surface Temperature in the Tissue.**

Fig. 5. Meshing for 1.5 mm Slot.

3. Results and Discussion

From the temperature distribution patterns it has been analyzed that a well defined focusing point of the EM fields is evidenced near the sensing tip of the wired sensor that could be responsible of a hot spot in the temperature distribution inside the tissue. Heating power deposited in the liver tissue is computed for different designs with varying slot dimensions as shown in Figs. 6 to 9.

It has been observed that with 10 W input power the amount of power absorbed (SAR) is around 9.4 for the slot of 1 mm (Fig. 6), 9.5 for 1.2 mm slot (Fig. 7), 9.9 for 1.5 mm slot (Fig. 8), and 9.7 for 1.7 mm slot (Fig. 9). The numerical results show that with the slot of 1.5 mm, maximum power (approx. 99%) is absorbed in the liver tissue. The antenna has been shown to give good specific absorption rate (SAR) with the slot of 1.5 mm and is suitable for MCT with respect to the other slots such as 1, 1.2, 1.5, and 1.7 mm. Table 2 shows all the mesh statistics for all sizes of slots. From this table it has been observed that the antenna with slot 1.5 mm has large numbers of degree of freedoms, no. of mesh points, no. of elements, boundary elements and minimum element quality. This antenna is also able to produce large number of elements.

Table 2. Mesh Statistics.

| Mesh Parameters	1 mm	1.2 mm	1.5 mm	1.7 mm
Number of D.O.F	23780	24089	24552	23860
Number of mesh points	4678	4738	4838	4658
Number of elements	8171	8294	8495	8137
Triangular	8171	8294	8495	8137
Quadrilateral	0	0	0	0
Number of boundary elements	1374	1375	1380	1383
Number of vertex elements	18	18	18	18
Minimum element quality	0.625	0.7	0.697	0.692
Element area ratio	0.001	0.001	0.001	0.001
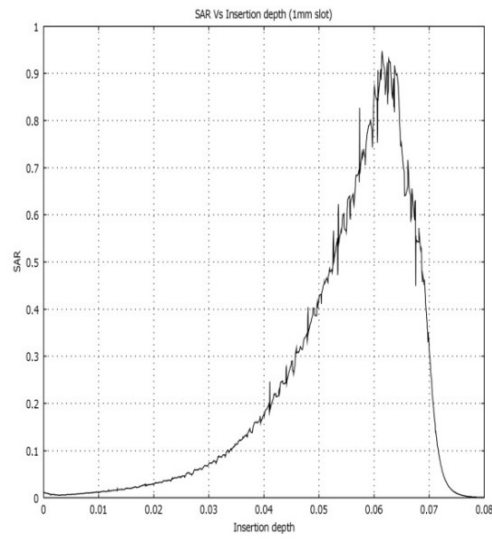
Fig. 6. SAR Distribution vs. Insertion at Depth 1 mm.
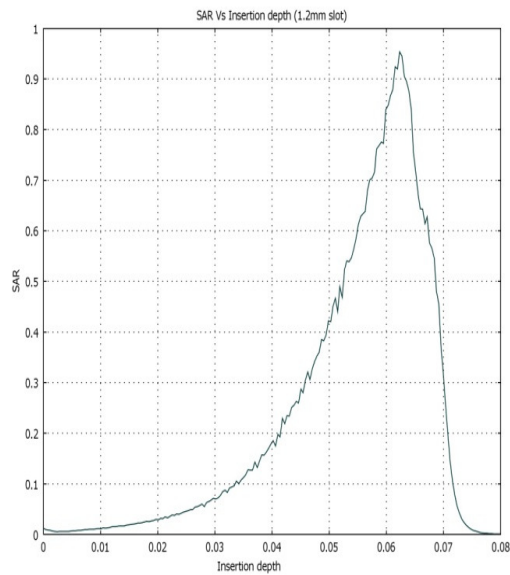
Fig. 7. SAR Distribution vs. Insertion at Depth 1.2 mm.
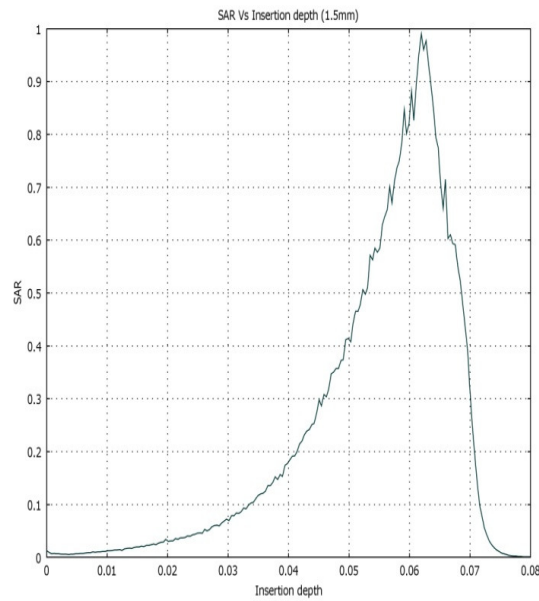
Fig. 8. SAR Distribution vs. Insertion at Depth 1.5 mm.
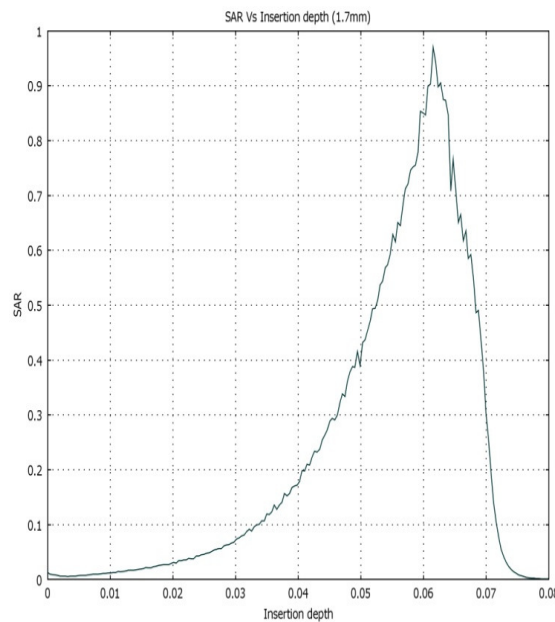
Fig. 9. SAR Distribution vs. Insertion at Depth 1.7 mm.

4. Conclusion

A thin microwave coaxial antenna for hepatic MWA is simulated using an axisymmetric electromagnetic model implemented in COMSOL multiphysics. The

model is rigorously analyzed on the basis of mesh statistics, SAR patterns, and temperature distributions in tissue generated by the antenna with the variations of dimensions of slot. The particular geometry with 1.5 mm slot of the coaxial antenna is the result of an optimization process with regard to the efficiency of the energetic transmission from the antenna to the exposed tissue.

References

1. Sterzer, F. (2002). Microwave medical devices. *IEEE Microwave Magazine*, 3(1), 65-70.

2. Seegenschmiedt, M.H.; Fessenden, P.; and Vernon, C.C. (1995). *Thermoradiotherapy and thermo-chemotherapy*. Springer-Verlag, 1995.

3. Seki, T.; Wakabayashi, M.; Nakagawa, T.; Itoh, T.; Shiro, T.; Kunieda, K.; Sato, M.; Uchiyama, S.; and Inoue, K. (1994). Ultrasonically guided percutaneous microwave coagulation therapy for small carcinoma. *Cancer*, 74(3), 817-825.

4. Ito, K.; Ueno, K.; Hyodo, M.; and Kassi H. (1989). Interstitial applicator composed of coaxial ring slots for microwave hyperthermia. *Proceedings of International Symposium on Antennas and Propagation*, 253-256.

5. Habash, R.W.Y.; and Alhafid, H.T. (2006). Key developments in therapeutic applications of RF/microwaves. *International Journal of Scientific Research*,16, 451-455.

6. Yang, D.; Converse, M.C.; Mahvi, D.M.; and Webster, J.G. (2007). Expanding the bioheat equation to include tissue internal water evaporation during heating, *IEEE Transactions on Biomedical Engineering*, 54(8), 1382-1388.

7. Haemmerich, D.; dos Santos, I.; Schutt, D.J.; Webster, J.G. and Mahvi, D.M. (2006). In vitro measurements of temperature-dependent specific heat of liver tissue. *Medical Engineering and Physics*, 28(2), 194-197.

8. COMSOL Multiphysics™, v. 3.5. (2010). *Users' Guide*. Electromagnetic Module, Heat Transfer Module.