A Simulation Study of Microwave Ablation with Single Slot, Double Slot and Multi-slot Coaxial Antenna for the Treatment of Hepatocellular Carcinoma

Shilpa Nagod[1], Dr. S.V Halse[2]

[1] Research Scholar, Dept. of Electronics, Akkamahadevi Women's University, Vijayapura, Karnataka, shilpa.nagod@gmail.com

[2] Registrar, Davangere University, Davangere, Karnataka, drsvhalse@rediffmail.com

Abstract

Thermal Ablation is the treatment method for cancer wherein the body tissue or the tumor is exposed to high temperature for a certain amount of time. Researches have shown that the high temperature kills the cancerous cells. The techniques of thermal ablation include Microwave Ablation, Radiofrequency Ablation, Laser Ablation etc. Microwave ablation procedures are gaining a lot of attention past few years. In comparison to the radiofrequency ablation, the microwave ablation technique induces faster heating, kills large volume of caner cells in shorter duration and is effective in tissues with high impedance such as lungs or charred tissue. Microwave ablation procedure includes application of EM field through microwave antenna into the tumor to induce dielectric heating. There are different types of microwave antenna used such as coaxial antenna, monopole antenna, dipole antenna. Coaxial antenna can be designed with single slot, dual slot or even multi-slot. In this paper we would be discussing about how there is an impact of slot of MCA (Microwave Coaxial Antenna) in the heat transfer and ultimately in the ablation process of a liver tumor. A comparative analysis of temperature distribution, SAR, cell necrosis in a single slot, double slot and multi-slot antenna is done.

Keywords: Thermal Ablation, Microwave ablation, Hepatocellular Carcinoma, Microwave Coaxial Antenna, Single slot antenna, Double Slot antenna, Multi-slot antenna

1. Introduction

Thermal Ablation is the treatment method for cancer wherein the body tissue or the tumor is exposed to high temperature for a certain amount of time. Researches have shown that the high temperature kills the cancerous cells [1]. The techniques of thermal ablation include Microwave Ablation, Radiofrequency Ablation, Laser Ablation etc. In the process of ablation the cancer cells' protein structure is damaged, leading to their death [2], in the due course, the tumor shrinks heavily or completely vanishes.

A typical percutaneous surgical procedure for MWA (Microwave Ablation) involves insertion of an antenna, into the tumor area with image guidance. A power generator supplies a power of around 0-300W depending on the number of antennae employed and the frequency used [3, 4, 5]. Microwave ablation produces heat utilizing dielectric hysteresis property. Electromagnetic field, typically at 900–2500 MHz. is applied to heat the tissues beyond lethal temperature for its destruction to occur. Water molecules in tissue are forced to continuously realign with the oscillating electric field, increasing their kinetic energy and, hence, the temperature of the tissue as well, this is depicted in Fig. (1). Tissues with more percentage of water are best suitable for this technique. The temperature profile, or the ablation zone, is primarily influenced by the tissue properties and the microwave interaction with the tissue [5].

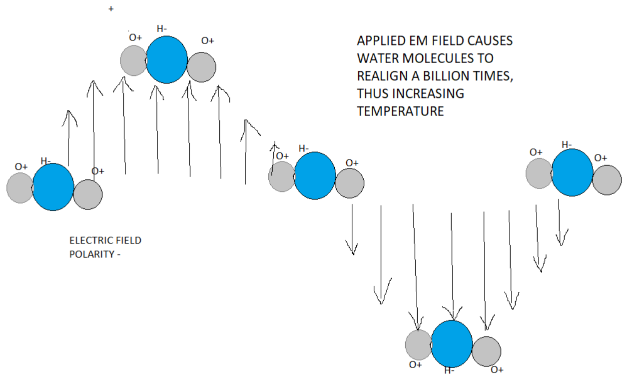


Fig. (1) Interaction of water molecules with applied EM field

.2. Theory

The microwave ablation technique is based on the electromagnetic energy transformation and is characterized by Maxwell's equations given by

$$\nabla \times \boldsymbol{E} = -j\omega\mu\boldsymbol{H} \quad (1)$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + j\omega\varepsilon\boldsymbol{E} \quad (2)$$

$$\nabla \cdot \boldsymbol{D} = 0 \quad (3)$$

$$\nabla \cdot \boldsymbol{B} = 0 \quad (4)$$

where E is the electric field intensity (V/m), H is the magnetic field intensity (A/m), ω is the angular frequency, μ is the permeability (H/m) and ε is the complex permittivity or dielectric constant (F/m), B is the magnetic flux density (Wb/m2), D is the electric flux density (C/ m2). And J is the current density (A/m2).

A description of heat transfer in tissues can be realized using Pennes' formulation of the heat equation [6]:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k_t \nabla T) + Q_h - Q_p + Q_m \quad \left[\mathrm{W/m^3}\right] \quad \ldots\ldots\ldots (5)$$

where cp is the specific heat capacity of the tissue (J/kg·K), kt is the thermal conductivity (W/m·K), T is the temperature (K). Qm is the metabolic heat generated from the tissue (W/ m3) but usually ignored due to its minimal impact compared to the other heat terms. Qp represents heat loss through blood perfusion given by,

$$Q_p = \omega_{bl} c_{bl} (T - T_{bl}) \quad \left[\mathrm{W/m^3}\right] \ldots\ldots\ldots(6)$$

where ωb is the blood perfusion velocity (kg/m3·s), cbl is the specific heat capacity of blood (J/kg·K) and Tbl is the blood temperature (K). The remaining term of equation (5) is the heat absorbed by the electromagnetic field into the tissue,

$$Q_h = \frac{\sigma}{2}\|\mathbf{E}\|^2 \quad \left[\mathrm{W/m^3}\right] \ldots\ldots(7)$$

where E is the electric field (V/m) solution found previously through solving Maxwell's equations, and σ is the tissue conductivity (S/m) [7,8].

3. Model Development and Simulation

A single slot, dual slot and multi-slot MCA is designed and simulations are carried out in Comsol Multiphysics to study the temperature distribution, heat transfer analysis and cell necrosis in all three designs. Following MCAs are inserted into the liver tumor and the frequency applied is 2.45GHz, input power used is 10 watts.

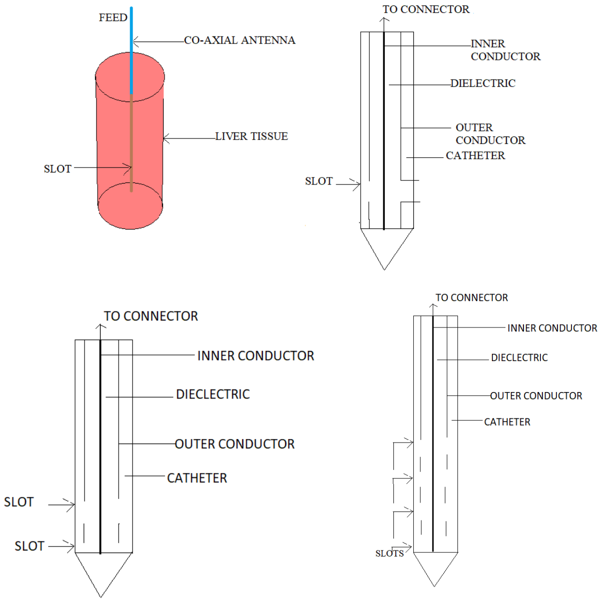


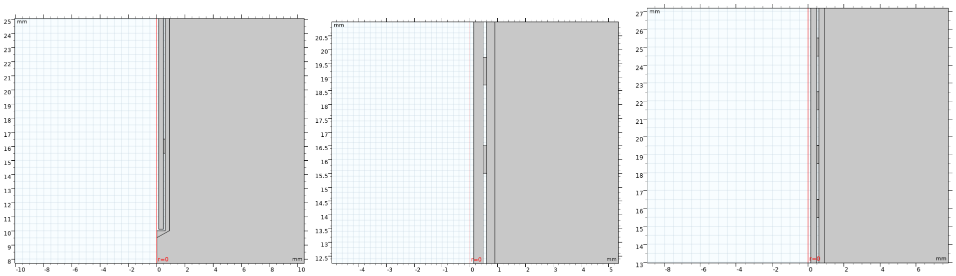
Fig. 1 Microwave Ablation Design Model with Single slot, Dual Slot and Multi-slot MCA

The design metrics are listed in the table below

Property	*Value*
Diameter of Catheter	*1.79mm*
Outer Diameter of the outer conductor	*1.19mm*
Inner Diameter of the outer conductor	*0.94mm*
Diameter of the central conductor	*029mm*
Slot height	*1mm*

Table 1: Model Design Metrics

The geometry of the model depicting the three antenna design under the study, modeled in Comsol Multiphysics are as as below:



(a) (b) (c)

Fig. 2 (a) Single slot MCA (b) Double slot MCA (c) Multi-slot MCA

Parameters used in the design are listed in the table below:

PARAMETERS	*VALUE*	*DESCRIPTION*
rho_blood	*1000 kg/m3*	*Blood density*
Cp_blood	*3639J/(Kg*K)*	*Specific heat of blood*
omega_blood	*0.0036 1/s*	*Blood perfusion rate*
T_blood	*310.15K*	*Blood Temperature*
eps_liver	*43.03*	*Relative permittivity of liver*
sigma_liver	*1.69 S/m*	*Electrical Conductivity of liver*
eps_diel	*2.03*	*Relative permittivity of dielectric*
eps_cat	*2.6*	*Relative permittivity of catheter*
F	*2.45GHz*	*Input Microwave Frequency*
P_in	*10W*	*Input Microwave power*

Table 2: Design Parameters

The material properties used in the design are listed in the table below:

Properties of Liver	*Value*
Heat capacity at constant pressure	*3540[J/(kg*K)]*
Density	*1079[kg/m^3]*
Thermal conductivity	*0.52[W/(m*K)]*
Frequency factor	*7.39e39*
Activation energy	*2.577e5*
Relative permittivity	*43.03*
Relative permeability	*1*
Electrical conductivity	*1.69[S/m]*

Property	*Value*
Relative Permittivity of Dielectric	*2.03*
Relative Permittivity of Catheter	*2.6*

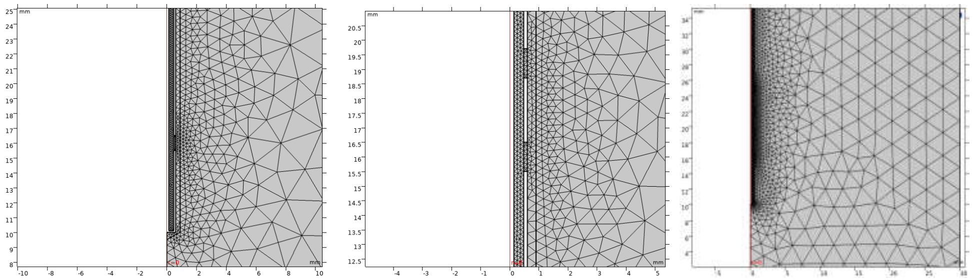
Table 3: Material Properties

3.1 Meshing

The free triangular meshing is used and statistics of meshing in each of the antenna design is mentioned in the table below.

Mesh elements	*Single Slot MCA*	*Double slot MCA*	*Multislot MCA*
Vertices	*3492*	*3571*	*3735*
Triangles	*5810*	*5973*	*6309*
Edge Elements	*1365*	*1382*	*1420*
Vertex Elements	*17*	*21*	*29*

Table 4: Meshing Details



(a) (b) (c)

Fig. 3 (a) Single slot MCA Mesh (b) Double Slot MCA Mesh (c) Multi-slot MCA Mesh

4. Results

4.1 Temperature Distribution

As the EM waves interact with water molecules of the tumor, there is a continuous realigning of water molecules leading to the elevation of temperature. Temperature is maximum around antenna and gradually gets reduced as we move farther. Using the bioheat equation the temperature distribution is calculated. Following figures show the temperature distribution in different antennas under our study.

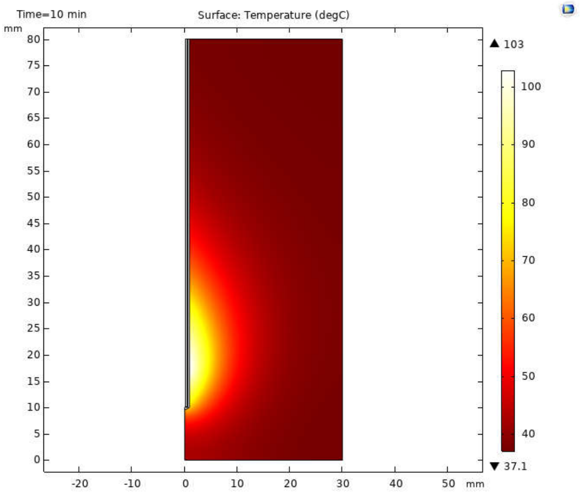


Fig. 4a) Temperature Distribution of single slot MCA

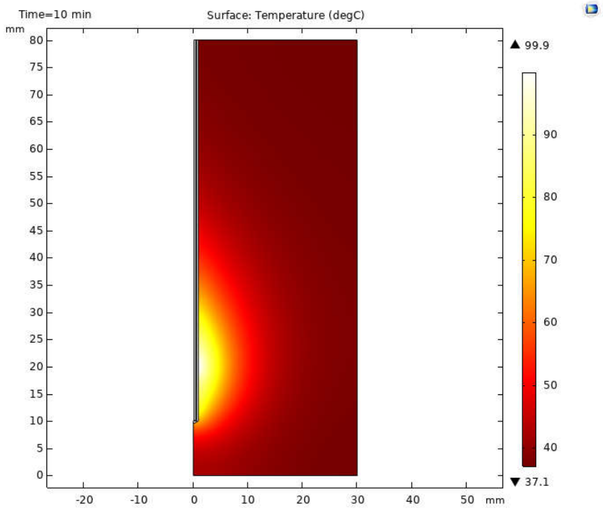


Fig. 4b) Temperature Distribution of Double slot MCA

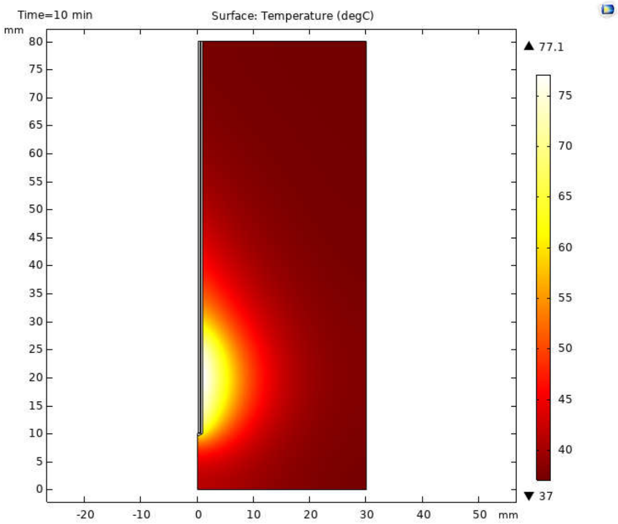


Fig. 4c) Temperature Distribution of Multi-slot MCA

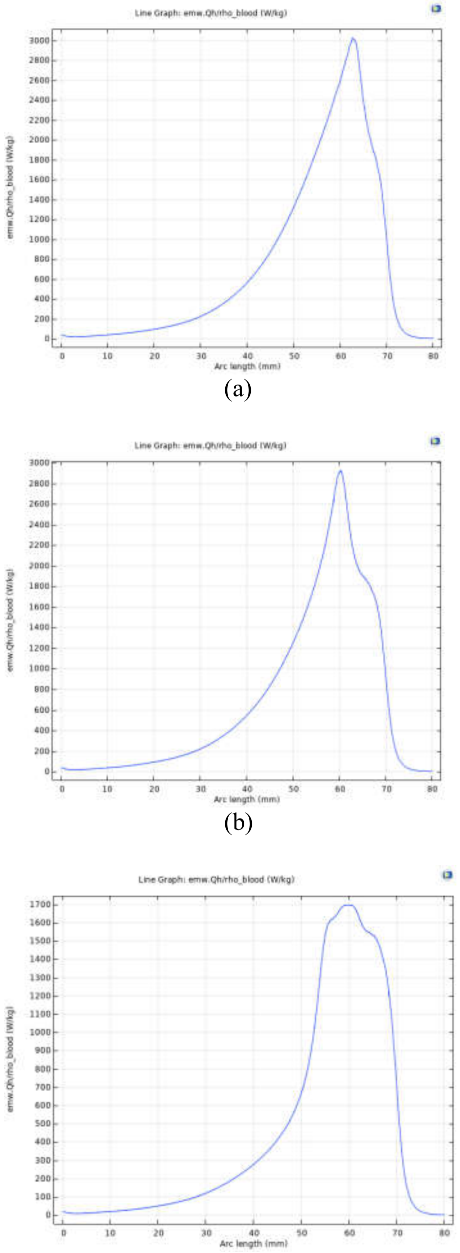
The temperature distribution in single slot is maximum, 103 degree Celsius.

4.2 SAR

SAR represents the electromagnetic power deposited per unit mass in tissue(W/kg) and can be defined mathematically as

$$\text{SAR}=\frac{\sigma}{2\rho}|\bar{E}|^2 \quad [\text{W/kg}] \qquad \ldots\ldots (8)$$

where σ is tissue conductivity (S/m) and ρ is tissue density (kg/m3) [9]. The SAR profile in tissue provides a fair estimation of the heating profile since the direct deposition of electromagnetic energy has been shown to be the major contributing factor to heat transfer in tissue during microwave ablation [10]. Following figures show SAR distribution for 3 antennas under study



(a)

(b)

(c)

Fig. 5 SAR distribution in (a) Single slot MCA (b) Double slot MCA (c) Multi-slot MCA

It can be seen from the resultant plot that SAR distribution is the best for single slot MCA here. In all the three cases it is elongated in ‘z’ direction, this is called ‘teardrop’ shaped distribution. It can be clearly observed and deciphered that it is smooth and sharp for single slot antenna.

4.3 Thermal Damage

Figure (6) below shows the fraction of damaged tumor for different antenna designs. It basically depicts the process of necrosis. The ones that appear red are ablated completely. In the closest proximity of antenna the tumor is gets damaged heavily. Tissue damage due to heating is a function of the amount of increase in temperature as well as the duration of this increase. It has been studied in thermal ablation techniques of various organs. Reviews of methods for tissue damage calculation post the increase of temperature through heat transfer are available [11-13].The damage of cells in tissue exposed to elevated temperature is calculated using Arrhenius equation given by,

$$\Omega(t) = \ln\left\{\frac{C(0)}{C(t)}\right\} = \int_0^\tau A \exp\left(-\frac{E_a}{RT(\tau)}\right) dt \qquad \text{……..(8)}$$

where $C(0)$ is the original concentration of undamaged cells prior to heating, $C(t)$ is the concentration of undamaged cells after heating, Ω is a dimensionless thermal damage parameter, A [1/s] is frequency factor, E_a[J/mol] is the activation energy required to transform tissue from normal to damaged state, R [J/(mol.K)] is the universal gas constant and T [K] is absolute temperature. Activation energies for various tissue types have been measured and are available in the literature [12]. The tissue injury integral increases as the time of exposure is increased.

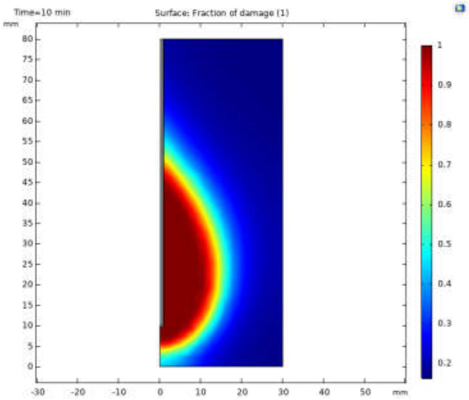
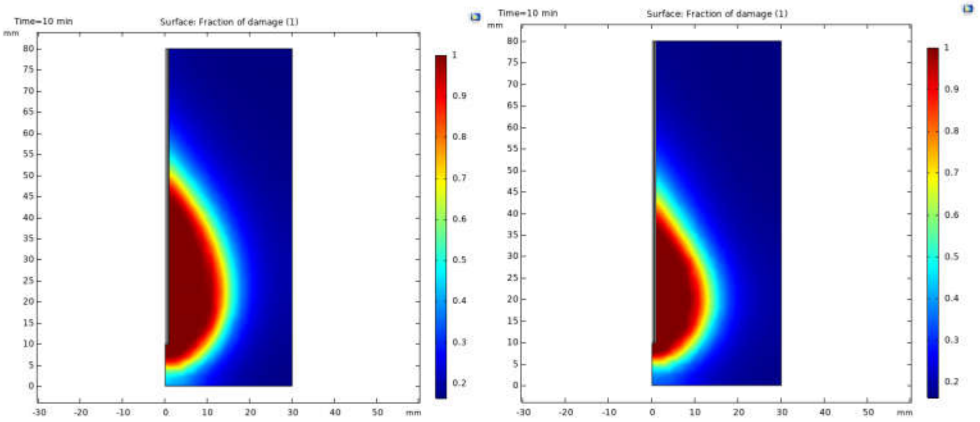


Fig. 6 a) Damage of tumor in single slot MCA



b) Damage of tumor in double slot MCA

c) Damage of tumor in multi slot MCA

It can be visualized that the damage is maximum in single slot antenna when compared with the other two designs. This is quite true from the fact that the temperature is maximum for single slot antenna itself. This larger temperature leads to maximum damage of the tumor.

5. Conclusion

This study comprised of designing a single slot, a double slot and a multi-slot MCA used in technique of Microwave ablation and studying its simulations to decipher the behavior of each of the design in terms of temperature distribution, heat transfer and finally the damage integral of the liver tumor as a part of cell necrosis. It is analysed from the results that the single slot antenna is better in performance when compared to the other two antennas. Future work would be on focusing about how the slot spacing can affect the overall technique of ablation. The performance of double slot and multislot MCA can be further improvised by proper positioning of the slots in antenna

References

[1] Van der Zee J. Heating the patient: A promising approach? Ann Oncol 2002; 13:1173-84.

[2] Hildebrandt B, Wust P, Ahlers O, et al. The cellular and molecular basis of hyperthermia. Crit Rev Oncol Hematol 2002; 43: 33-56.

[3] Hinshaw, J. L., Lubner, M. G., Ziemlewicz, T. J., Lee Jr, F. T., & Brace, C. L. Percutaneous tumor ablation tools: microwave, radiofrequency, or cryoablation—what should you use and why?. Radiographics, 2014,34(5),1344-1362.

[4] Brace, C. L. Radiofrequency and microwave ablation of the liver, lung, kidney, and bone: what are the differences?. Current problems in diagnostic radiology, 2009,38(3), 135-143.

[5] Prakash, P. Theoretical Modeling for Hepatic Microwave Ablation. The Open Biomedical Engineering Journal, 4, 2010, 27-38.

[6] Pennes HH. Analysis of tissue and arterial blood temperatures in the resting human forearm. J Appl Physiol. Aug ; 1948 1(2):93–122. [PubMed: 18887578]

[7] Brace CL. Microwave Tissue Ablation: Biophysics, Technology, and Applications. 2010; 38(1): 65–78.

[8] Lin J, Hirai S, Chiang C-L, Hsu W-L, Su J-L, Wang Y-J. Computer Simulation and Experimental Studies of SAR Distributions of Interstitial Arrays of Sleeved-Slot Microwave Antennas for Hyperthermia Treatment of Brain Tumors. IEEE Trans Microwave Theory Tech. 2000; 48:2191

[9] Clibbon KL, Mccowen A: Efficient computation of SAR distributions from interstitial microwave antenna arrays. IEEE Trans Microw Theory Tech 1994, 42:595-600

[10] Y. Liu, X. Yang, Q. Nan, J. Xiao, and L. Li, "Phantom experimental study on microwave ablation with a water-cooled antenna," Int. J. Hyperthermia, vol. 23, 2007,381-6

[11] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues," Phys. Med. Biol., vol. 41, 1996,. 2271-93

[12] W. C. Dewey, and C. J. Diederich, "Hyperthermia classic commentary: 'Arrhenius relationships from the molecule and cell to the clinic' by William Dewey, Int. J. Hyperthermia, 10, 1994,457-483

[13] F. Henriques, "Studies of thermal injury. V. The predictability and the significance of thermally induced rate processes leading to irreversible epidermal injury," Arch. Pathol., vol. 43, 1947,489-502