



Accurate Investigation of Coaxial-Slot Antenna for Invasive Microwave Hyperthermia Therapy

Ms. Neeru Malhotra^{a*}, Dr. Anupma Marwaha^b, Dr. Ajay Kumar^c

^a *Research Scholar, Ph.D, Punjab Technical University, Jalandhar -144008, India*

^b *Assoc. Prof., ECE Department, SLIET, Longowal - 148106, Distt. Sangrur, India*

^c *Assoc. Prof., ECE Department, BCET, Gurdaspur-143521, India*

^a *neeru_ins@yahoo.com*

^b *marwaha_anupma@yahoo.co.in*

^c *ajaykm_20@yahoo.co.in*

Abstract

Invasive microwave hyperthermia is a technique applied for treatment of cancer in which body tissue is exposed to high temperatures. The effectiveness of hyperthermia depends upon the temperature achieved during the therapy and the distribution of microwave thermal field; which further depends upon the type of microwave radiative antenna. Microwave ablation (MWA) or high temperature hyperthermia is a minimally invasive technique used to treat liver cancer, the effectiveness of which depends on highly localized spherical shaped lesion with minimum back radiations near the tumor cells. The present work performs investigation of single slot coaxial antenna operating at 2.45 GHz in the ISM (Industrial, Scientific, and Medical) band through 3D simulation for more realistic liver tissue using Finite element method (FEM) based software package; HFSS. The field distributions and specific absorption rate (SAR) obtained for the antenna are exported to ANSYS software for determining temperature distribution in the liver tissue. The results concordant with the theory are obtained using HFSS. Therefore, it is suggested that this research could be a reference for clinical therapy and operation scheme.

Keywords: Microwave Hyperthermia; Microwave Ablation (MWA); Coaxial Slot Antenna; Finite Element Method (FEM); Liver Cancer, Specific Absorption Rate (SAR).

* Corresponding author.

E-mail address: neeru_ins@yahoo.com

1. Introduction

Microwave Hyperthermia is a thermal therapy for cancer treatment in which body tissue is exposed to high temperatures. By killing cancer cells and damaging proteins and structures within cells, hyperthermia may shrink tumors [1]. The effectiveness of hyperthermia depends upon the temperature achieved during the therapy and the distribution of microwave thermal field; which further depend upon the type of microwave radiative antenna. The frequency-dependent reflection coefficient and SAR pattern in tissue are significant for the performance of interstitial Antennas. The operating frequency is usually 2.45 GHz, which is one of the ISM (Industrial, Scientific, and Medical) dedicated frequencies [1]. FEM has been extensively used in simulations of cardiac and hepatic radiofrequency (RF) ablation [2]. FEM models coupled with robust solution methods provide users with fast and accurate solutions making it one of the most efficient tools for electromagnetic problems and as such, is even well suited to coupled heat transfer problems like ablation [3]. Differential equation methods are particularly suitable for modelling small full three dimensional volumes that have complex geometrical details, particularly smaller closed region problems involving inhomogeneous media having lossy dielectrics e.g. for biological issues. The number of unknowns to be solved in differential equations is proportional to the volume under consideration. To analyze the biological effects of microwaves and microwave therapy, the radiator, which is also called antenna, is used to radiate the electromagnetic energy of the microwave oscillator to the exposed biosystem. The advantages such as direct exposure into the tissue of pathological changes, high efficiency of heating and easy control of power, make invasive microwave antenna more suitable clinically.

In the recent years, invasive microwave hyperthermia for cancer treatment has been widely investigated. Jaehoon inserted an antenna into the human body and calculated the distribution of SAR by FDTD [4]. Zouheir developed an electro-thermal cordis duct model to distinguish RF and microwave energetic transmission [5]. Mono-antenna made by coaxial wire was inserted into myocardium for heating, and SAR was calculated by finite element modeling. Mikaya established the precise model of antenna by GBM [6]. Francesca Rossetto calculated the distribution of SAR of 915 MHz microwave antenna by FDTD and simulated on three different human tissues that is of importance to clinic [7]. Keane evaluated the thermal profiles of a 2450 MHz monopole antenna and microwave ablation experiments were performed in-vivo in the ventricles of goats [8]. Some optimum frequency and pattern of antenna in way of heating phantoms by helical and whip shape antennas were obtained [9-11]. In the present work a minimally invasive coaxial-slot antenna operating at frequency of 2450 MHz has been designed to investigate the distribution of thermal field and optimum antenna pattern in invasive microwave thermal therapy. The antenna is modeled and simulated using FEM based HFSS software. HFSS utilizes differential equation based FEM full wave solver requiring little analytical preprocessing. 3D model of the antenna is created for more realistic simulation. Other useful feature of HFSS is its automatic adaptive mesh generation and refinement. Hierarchical basis functions with mixed order h-p refinement automatically distribute element order based on element size and generate an optimum combination of hierarchical basis functions. After investigating the electromagnetic fields induced by microwave radiative antenna, the distribution of thermal field and SAR of invasive coaxial-slot antenna are obtained and analyzed for optimized performance.

MWA, the use of radiofrequency and high-intensity focused ultrasound, are gaining attentions as an alternative to standard surgical therapies. Each of these techniques works differently to heat tissue to a temperature 50°C or above to destroy cells within a localized section of a tumor [12]. In the present work, the results show that much spherical lesion is obtained with the optimized coaxial slot antenna design facilitated by 3D modeling using HFSS. Hence the technology of invasive microwave hyperthermia therapy heats the cancer regions around 44°C thereby making as little damage as possible to normal tissues with the advantage of finally killing the tumor cells.

2. Materials and Methods

In the microwave mesenchymal thermal therapy, the radiative antenna is linear antenna in which the length is far more than the transverse diameter. The invasive system distribution energy is obtained from the thermotherapeutic probe or duct energy source of powerful small antenna. Moreover it should have smaller volume, stronger radiative capability and considerable intensity. The interstitial antenna consists of a micro coaxial cable with a ring shaped slot cut on the outer conductor. For hygienic purposes, the antenna is enclosed in a catheter. The radiative slot is opened in some distance from the top of 50 Ω coaxial wire and slot point is exposed from the media layer. In addition, exterior and interior conductor is connected on the top of the antenna. The structure and size of coaxial-slot antenna are shown in Fig. 1. The thermal and dielectric properties used for the antenna are listed in Table 1.

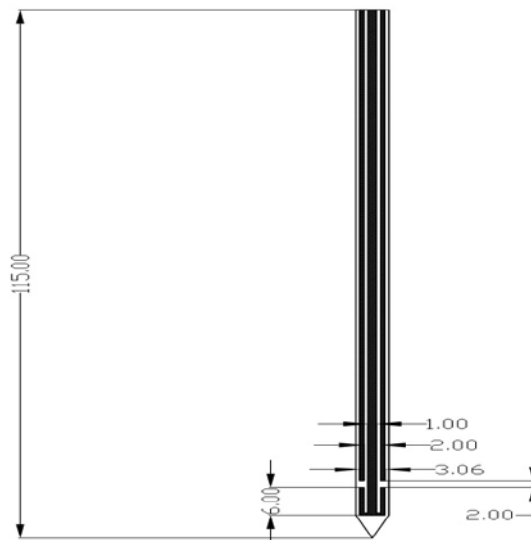


Figure 1: Structure of Coaxial-slot Antenna (All Units in mm)

Table1: Pork liver tissue and antenna parameters

Parameter	Numerous	Demonstration
ϵ_{ri}	2.03	Medium layer relative dielectric constant
ϵ_{rc}	2.60	sheath relative dielectric constant
ϵ_r	43.03	hepatic tissue relative dielectric constant
Σ	1.69(S/m)	hepatic tissue electrical conductivity
K	0.512(W/m.K)	hepatic tissue heat conductivity
P	1060(Kg/m ³)	hepatic tissue density
C	3.60 (J/Kg.K)	Hepatic tissue specific heat
ρ_b	1000(Kg/m ³)	blood density
C_b	4.18 x 10 ³ (J/Kg.K)	blood specific heat
ω_b	3.6 X 10 ⁻³ (s ⁻¹)	Blood perfusion rate

The most widely used bioheat equation for modeling thermal therapy procedures is the Pennes bioheat equation, which demonstrates the balance between heat conduction of perfused tissues, heat loss from blood flow, metabolic heat from heating and energy deposition [13-14]. Pennes bioheat equation is given by

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \quad (1)$$

where the term $\omega_b C_b (T_b - T)$ indicates the heat transfer due to hemoperfusion. In the expression k is the tissue heat conductivity in W/m·K, ρ_b is the blood density, C_b is the blood specific heat, ω_b is the blood perfusion rate. T_b is the body temperature, T is the final temperature, Q_{met} is the heat source from metabolism and Q_{ext} is absorbed microwave radiation energy per tissue unit from external heat source. The external heating term for microwave ablation is given by

$$Q_{ext} = \frac{\sigma}{2} |E|^2 \quad (2)$$

where $|E|$ is electric field intensity (Vm⁻¹) and σ is the effective conductivity (Sm⁻¹).

More over careful examinations of both the antenna's specific absorption rate (SAR) pattern and frequency-dependent reflection coefficient in tissue are essential parameters for the optimization of antennas for hepatic MWA as in Eq. 3. SAR represents the electromagnetic power deposited per unit mass in tissue (W/kg) and can be defined mathematically as [1].

$$SAR = \frac{\sigma E^2}{2\rho} \quad (3)$$

where σ is tissue conductivity (S/m) and ρ is tissue density (kg/m^3). The treatment of deep-seated hepatic tumors requires the SAR pattern of an interstitial antenna to be highly localized near the distal tip of the antenna [15-16]. Antenna efficiency can be quantified using the frequency dependent reflection coefficient (S_{11}), which can be expressed logarithmically. The SAR takes a value proportional to the square of the electric field generated around the antenna and is equivalent to the heating source created by the electric field in the tissue which causes the tissue temperature to rise. The tissue temperature increase therefore is caused by direct MW heating (from SAR) and tissue thermal conduction. MW heating thermal effects can be roughly described by Pennes Bioheat equation as in Eq. 1.

In the present work, the numerical modeling has been done considering static temperature conditions. Fig. 2 shows the 3D model of the coaxial slot antenna generated in HFSS. The relative permittivity and electrical conductivity are however temperature dependent, making the microwave tissue heating process a coupled electro-thermal problem.

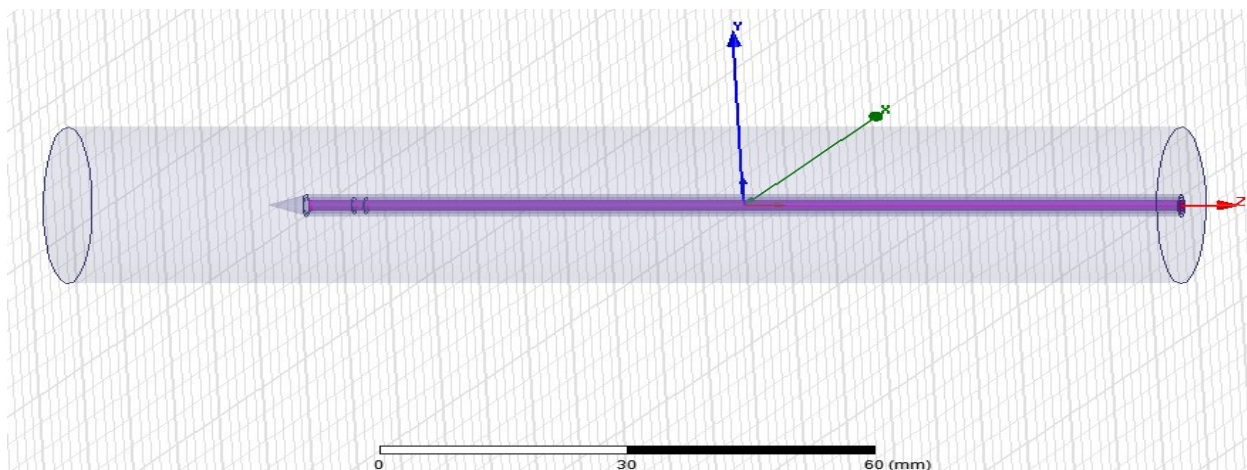


Figure 2: 3D view of coaxial slot antenna model created in HFSS

The problem was solved using HFSS and was further linked with ANSYS for performing the thermal analysis of the model. The thermal and physical properties were assumed constant over temperature to isolate and study the effects of the dielectric models independently. In the present analysis the energy generated by metabolism and taken away by blood perfusion has been neglected for ex-vivo modeling.

3. Results and Discussion

The far-field radiation pattern for the coaxial slot antenna, determined using HFSS, is shown in Fig. 3. In this figure, the normalized magnitude of the electric field versus angle θ is shown with θ varying from 0° to 180° . A 360° azimuthal rotation of this pattern yields a full 3-D doughnut-shaped pattern. The coaxial slot shows a circular-shaped pattern with maximum directivity occurring at $\theta = 90^\circ$, as expected. The Antennal duty ratio of output power is 25% (15s/60s).

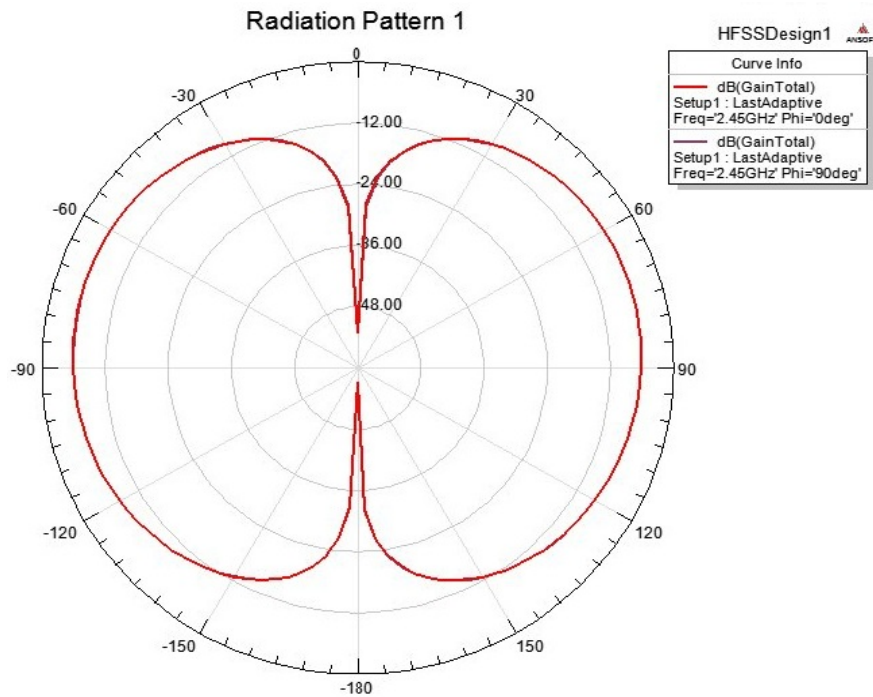


Figure 3: Radiation pattern of coaxial slot antenna

Fig. 4 plots the SAR distribution for coaxial-slot antenna. The plot shows much improved energy absorption with near spherical leison indicating reduced backward radiations in comparison to [17] where the 2D modeling of the coaxial-slot antenna is presented causing the SAR leison to be ellipsoidal.

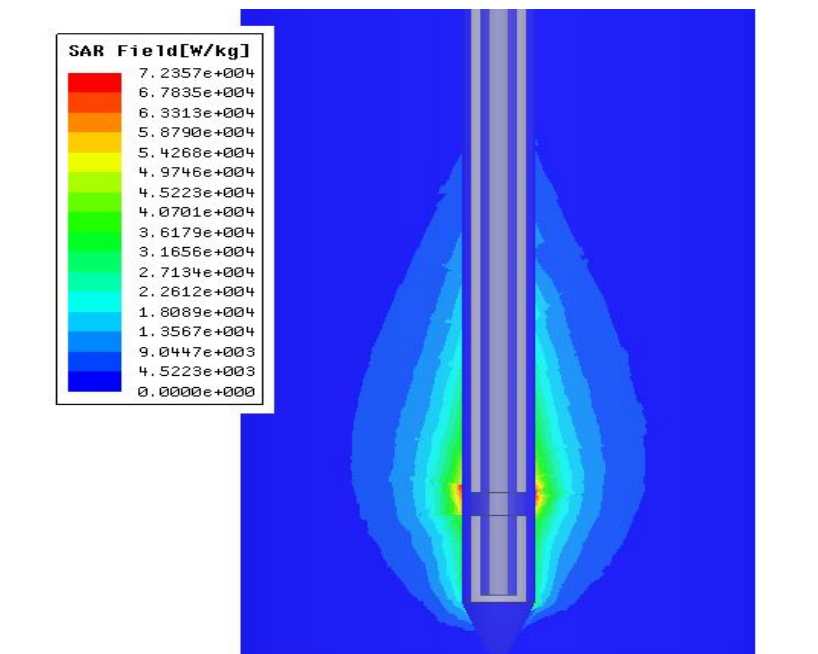


Figure 4: SAR distribution after heating for 240s.

Further, Fig. 5 shows the corresponding temperature distribution obtained after heating the liver tissue for 240s. From this plot it is seen that the technology of invasive microwave hyperthermia therapy heats the cancer regions round 44°C and simultaneously make as little damage as possible to normal tissues, finally killing the tumor cells.

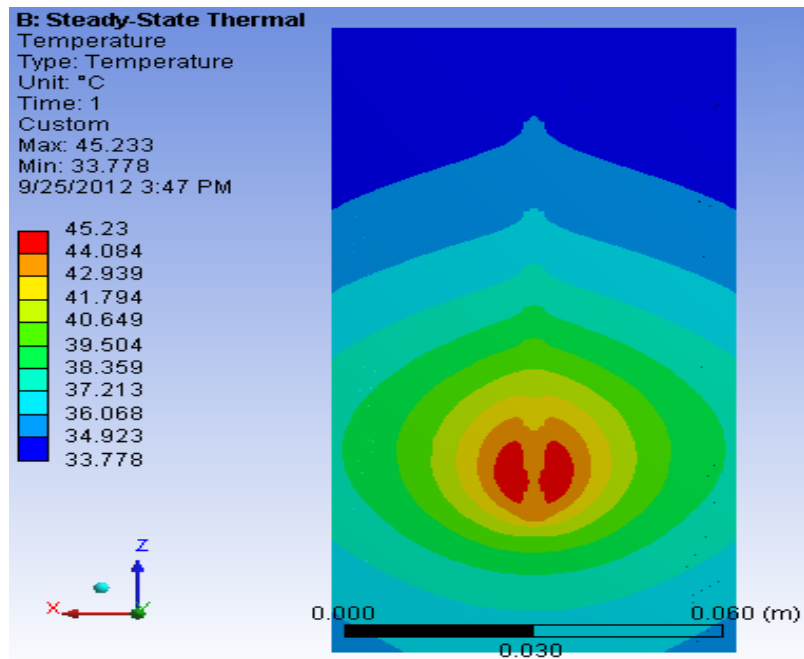


Figure 5: Temperature distribution plot after heating for 240s.

The coaxial-slot antenna hot area range produces lesion of about 2.6cm×3.5cm. The antennas shows good impedance matching with S_{11} parameter achieved to be -30.6452dB on solution frequency of 2450MHz as shown in Fig. 6.

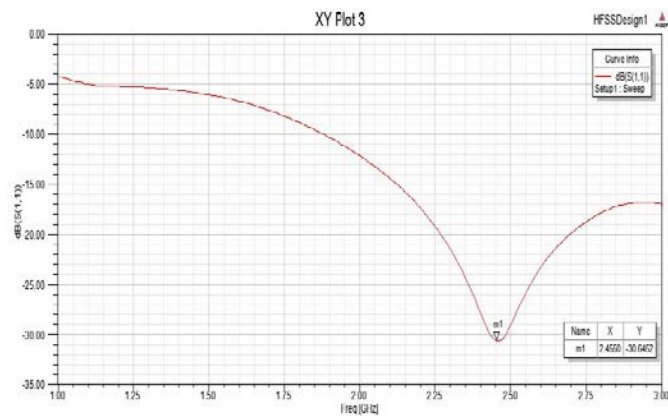


Figure 6: S_{11} plot for coaxial slot antenna

The respective VSWR is achieved at 1.0606 at solution frequency as depicted in Fig. 7.

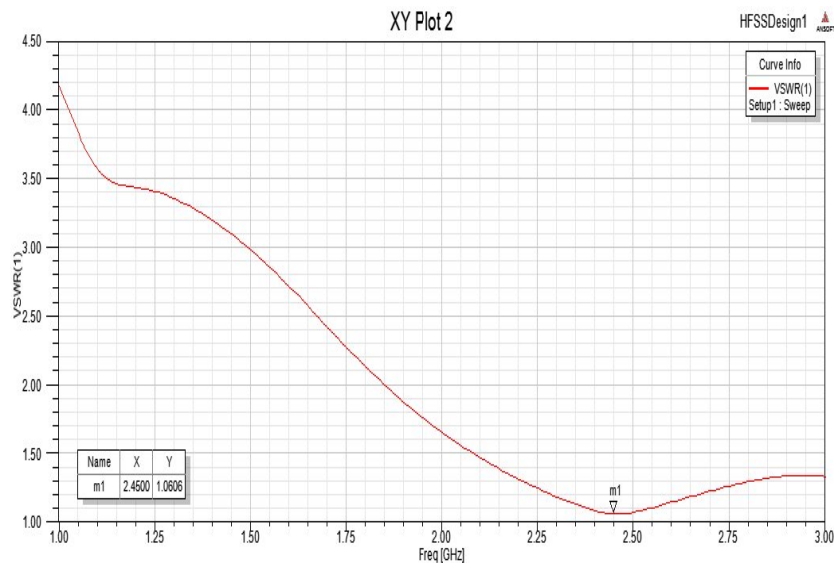


Figure 7: VSWR plot for coaxial slot antenna

4. Conclusions

3D modelling of minimally invasive single slot microwave coaxial antenna is presented for liver cancer treatment. The formulation of electro-thermal coupled problem is done by using FEM based software HFSS with thermal analysis performed on ANSYS software. The antenna results show temperature distribution of coaxial-slot antenna entirely homogeneous, near spherical and cause better heating effect. The temperature may rise around the antenna; the top temperature however does not exceed 200°C. So the phenomenon of part hyperpyrexia near the antennas will not occur. And after heating, tissue will not be scorched and the technology of invasive microwave hyperthermia therapy heats the cancer regions at much less temperature around 44°C thereby making as little damage as possible to normal tissues with the advantage of finally killing the tumor cells. Therefore, it is suitable for clinical thermotherapy.

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