The Effect of Choke on the Efficiency of Coaxial Antenna for Percutaneous Microwave Coagulation Therapy for Hepatic Tumor

Surita Maini

Abstract**—**There are many perceived advantages of microwave ablation have driven researchers to develop innovative antennas to effectively treat deep-seated, non-resectable hepatic tumors. In this paper a coaxial antenna with a miniaturized sleeve choke has been discussed for microwave interstitial ablation therapy, in order to reduce backward heating effects irrespective of the insertion depth into the tissue. Two dimensional Finite Element Method (FEM) is used to simulate and measure the results of miniaturized sleeve choke antenna. This paper emphasizes the importance of factors that can affect simulation accuracy, which include mesh resolution, surface heating and reflection coefficient. Quarter wavelength choke effectiveness has been discussed by comparing it with the unchoked antenna with same dimensions.

Keywords**—**Microwave ablation, tumor, Finite Element Method, Coaxial slot antenna, Coaxial dipole antenna.

I. INTRODUCTION

HEPATOCELLULAR carcinoma (HCC) is one of the most common malignant tumors with an estimated 1,000,000 worldwide deaths per year. Primary and secondary malignant hepatic tumors are among the most common tumors [1]-[4]. Chemotherapy and radiation therapy are ineffective to treat liver tumors. Surgical resection is the gold standard for the treatment of patients with HCC, but in most of the patients, tumors may be too close to the major hepatic blood vessels thus cannot be surgically removed, or too many tumor spots to be removed, which is again a big difficulty. Hence such patients cannot be surgically treated and the patients without treatment usually die within 5 years. Ablative treatments have become viable alternative methods to treat patients with HCC which cannot be treated surgically. The use of microwaves in therapeutic medicine has increased dramatically since the last few years to treat tumors, cancer, arrhythmias, tachycardia, benign prostatic hyperplasia, and sleep apnea, but our main concern is liver tumor.

The basic principle of microwave ablation (MWA) is to apply microwave power to the liver tissue through the microwave antenna. A microwave generator produces microwaves, typically around 2.45 GHz, with 60 W power. Interstitial antenna is inserted into the liver tissue, guided by ultrasound or other medical imaging device. The microwave power absorbed by the liver, heats the tissue above 60°C. Although MWA is a novel therapy but has several theoretical advantages like larger lesion zone, higher temperatures, and the ability for ablation with multi probes. Currently MWA is in clinical experimentation in a number of Asian centers [5], [6]. Recently, advances in antenna design have led to a new MWA system in which power feedback is markedly reduced, allowing for longer times of application, greater power deposition, and larger ablation lesion sizes. Several types of coaxial-based antennas, including the coaxial slot antenna [7], [8], coaxial dipole antenna [9], [10], coaxial cap-choke antennas [11], and others, have been designed for MWA. Many researchers are doing effort to develop less invasive interstitial antennas for microwave ablation for treating the liver tumor. These antennas are capable of producing highly localized patterns of electromagnetic power deposition in tissue [12]-[14].

In this paper the quarter wavelength choke effectiveness of miniaturization sleeve choke antenna is discussed and designed with COMSOL Multiphysics [15] version 3.5, which has been used as primary computer simulation tools. COMSOL Multiphysics is a commercial software package, which solves partial differential equations using the finite element method (FEM).

In Section II, the numerical method and model design of unchoked and choke antenna is described. In Section III meshing, surface heating and reflection coefficient has been investigated using FEM. Finally, conclusions are presented in Section IV.

II. METHODS AND MODELS

A. Numerical Method

The finite element method (FEM) involves dividing a complex geometry into small elements for a system of partial differential equations and obtaining the solution at nodes or edges. Bio-heat equation has been used to determine the thermal-electrical effect within the domain of model. The most widely used bio-heat equation (1) for modeling thermal therapy procedures is the Pennes bio-heat equation [16].

$$\rho c\frac{\partial \mathrm{T}}{\partial t} = \nabla\cdot k\nabla \mathrm{T} + SAR - \rho_{b1}c_{b1}w_{b1}(\mathrm{T}-\mathrm{T}_{b1}) \qquad (1)$$

where T is the tissue temperature (K), ρ is the charge density for tissue (kg/m^3), c is specific heat capacity (J/kg.k), k is thermal conductivity (W/m.k), ρ_{b1} is blood density (kg/m^3),

---

Surita Maini is with the Sant Longowal Institute of Engineering and Technology, Longowal, Sangrur, Punjab, India (phone: 91-1672-253244; fax: 91-1672-253245; e-mail: suritamaini@gmail.com).

c_{b1} is the specific heat capacity of blood (J/kg.k), w_{b1} is blood perfusion rate (kg/m^3.s), T_{b1} is blood temperature (K), SAR is the microwave power per unit volume applied by MWA (W/m^3). The Pennes bio-heat equation does not take in to account 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.

More over careful examinations of both the antenna's specific absorption rate (SAR) pattern and frequency-dependent reflection coefficient in tissue are essential for the optimization of antennas for hepatic MWA as in (2). SAR represents the electromagnetic power deposited per unit mass in tissue (W/kg) and can be defined mathematically as:

$$P = \frac{\sigma E^2}{2\rho} \qquad (2)$$

where σ is tissue conductivity (S/m) and ρ is tissue density (kg/m3) [17]. For the treatment of deep-seated hepatic tumors, the SAR pattern of an interstitial antenna should be highly localized near the distal tip of the antenna. Antenna efficiency can be quantified using the frequency dependent reflection coefficient, which can be expressed logarithmically: where Pr indicates reflected power (W) as in (3). The frequency where the reflection coefficient is minimum, referred as resonant frequency and should be approximately same as the operating frequency of the generator used. Antennas operating with high reflection coefficients (especially at higher power levels) can cause overheating of the feedline possibly leading to damage of the coaxial line or of the tissue due to the thin outer conductor [18].

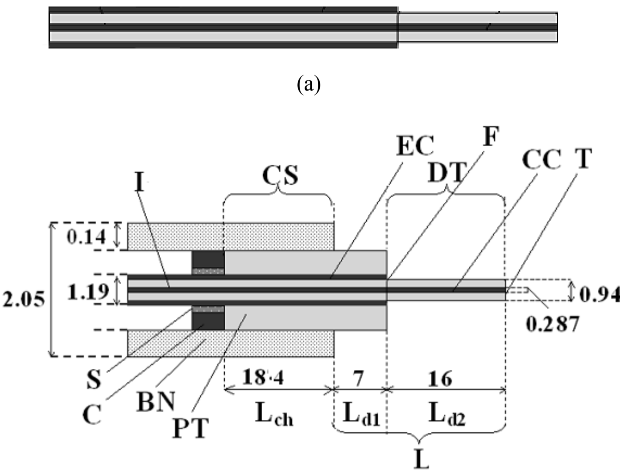
$$r\,(f) = 10\,\mathrm{Log}_{10}\,\frac{P_r(f)}{P_{in}}\ [\mathrm{dB}] \qquad (3)$$

B. Antenna Design

Fig. 1 shows the design of unchoked antenna, and choked antenna respectively, both being operated at the frequency of 2.45 GHz. The choked antenna, considered in present problem, has the choke section of quarter wavelength, short-circuited coaxial line behaving as an open circuit at its input. Choke antenna is made up from coaxial cable in which a small ring slot is cut close to the tip of the antenna to allow electromagnetic wave propagation into the tissue. The width of the slot (Ls=1mm.) is usually chosen to be smaller than the wavelength. Antenna geometry parameters, the choke section, choke offset, choke length, etc., were chosen based on the effective wavelength in bovine liver tissue at 2.45 GHz, which calculated as [19]:

$$\lambda_{eff} = \frac{c}{f\sqrt{\epsilon_r}}\ [\mathrm{m}] \qquad (4)$$

where c is the speed of light in free space (m/s), f is the operating frequency of the microwave generator (2.45 GHz), and ε_r = 44.4 is the relative permittivity of bovine liver tissue at the operating frequency; thus yielding 18.4 mm length of the choke for the effective wavelength. Because the thickness of catheter also affect the optimal geometry as well as performance of the antenna, hence (4) only provides a very crude approximation for the tip length of the antenna [4]. Tip length and catheter thickness were adjusted to achieve resonance. Except choke section, all the dimensions of both the antennas are same.



(a)

(b)

Fig. 1 (a) Cross section of a conventional unchoked antenna (b) Cross section of a conventional choked antenna of Legend: EC=CC = external/central coaxial conductor (copper), I = insulator (P.T.F.E.), PC = plastic catheter (e.g., silicone), CS = choke section, F = antenna feed, T = antenna tip, DT =dielectric tip, BN = biopsy needle, C = copper collar, S = solder, PT = plastic tubing (P.T.F.E.), L = length of CS, L = distance between CS input and T, L = distance between CS input and F, L = length of DT; all sizes are in mm

TABLE I
ELECTROMAGNETIC PROPERTIES AT 2.45 GHZ

Name	Expression	Values
Relative permittivity, dielectric	eps_diel	2.03
Relative permittivity, catheter	eps_cat	2.6
Relative permittivity, liver	eps_liver	43.03
Electrical conductivity, liver	sig_liver	1.69 [S/m]
Relative permeability	(ε_r)	1

TABLE II
THERMAL PROPERTIES FOR THERMAL ANALYSIS

Expressions	Name	Values
Thermal Conductivity, liver	K_liver	0.56 [W/(kg*K)]
Density, blood	Rho_blood	1000[kg/m^3)
Specific heat, blood	C_blood	3639 [J/(kg*k)]
Blood perfusion rate	Omega_blood	3.6 e-3[1/s]
Blood Temperature	T_blood	37 [degC]

The thermal modeling of hepatic MWA is based on the Pennes bioheat equation and dependent on both the electromagnetic simulations and thermal properties of tissue. The material properties required for antennas, liver tissue at 2.45GHz. Tables I and II summarize the material properties included in the FEM model [20], [21]. The electromagnetic models used to simulate the response of both applicators are strictly based on the geometry and material information included in Fig 1.

III. RESULTS

Fig. 2 and 3 show the axisymmetric finite element mesh of unchoked antenna and choked antenna respectively, and the convergence study was conducted by FEMLAB. It was done by gradually increasing mesh resolution along the effective source, catheter, and outer conductor boundaries of the antenna, as well as within the coaxial cable dielectric.

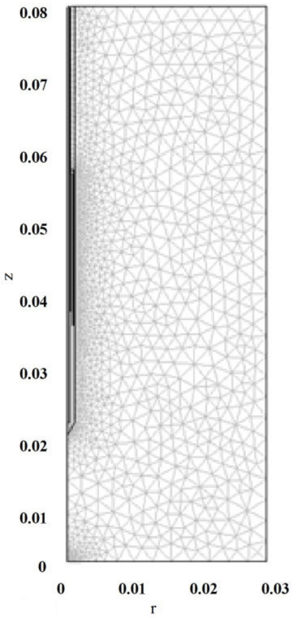


Fig. 2 Meshing for Unchoked antenna

Resolution in each region was adjusted individually and numerical convergence resulted when a uniform change of a less than 0.1% in the reflected power and normalized SAR was reached. The mesh for unchoked antenna consists of 7142 triangular elements and choked antenna consists of 9236 triangular elements.

Figs. 4 and 5 depict the surface heating plots for unchoked and choked antennas respectively. It is clear from Fig. 4 that unchoked antenna does not produce localized heat lesion and also produce backward heating which causes detrimental tissue heating along the antenna insertion region. Fig. 5 shows that for the choked antenna the surface heat is well distributed near the tip. 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. It is 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 for a hot spot in the temperature distribution inside the tissue.

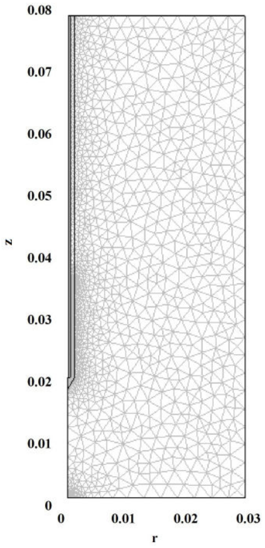


Fig. 3 Meshing for Choked antenna

Figs. 6 and 7 plot the variation of antenna reflection coefficient in liver, expressed logarithmically as a function of frequency with the dashed line indicating the commonly used MWA frequency of 2.45 GHz. It can be observed that the reflection coefficient shoots to peak minima of -21dB at resonant frequency of 2.45 GHz for choked antenna as compared to -17 dB for unchoked antenna. Hence the antenna return loss was highly affected when the choke contact was removed indicating that the choke not only prevents the reflected current from flowing along the antenna feeding line, but also influences the antenna matching. However, the obtained reflection coefficient was hardly affected by the antenna insertion depth into the tissue, due to the presence of the choke.

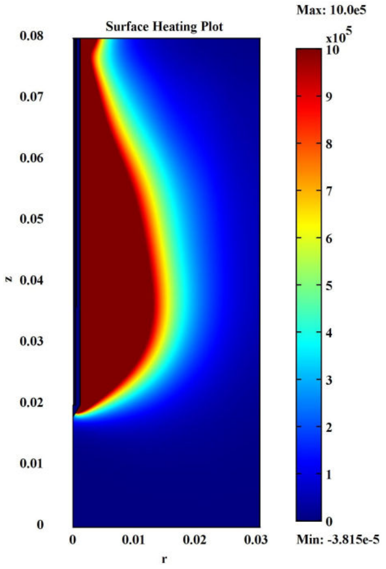


Fig. 4 Surface heating plot of Unchoked antenna in the tissue, 2D mode

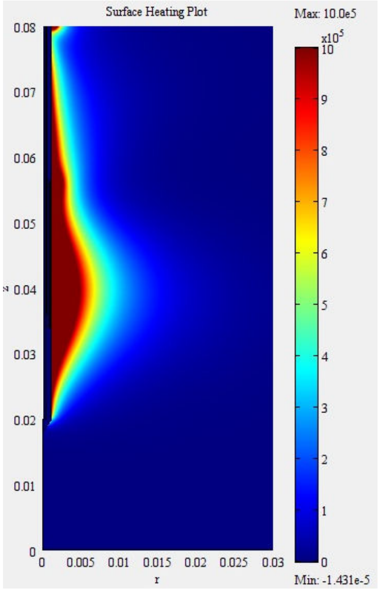


Fig. 5 Surface heating plot of choked antenna in the tissue, 2D mode

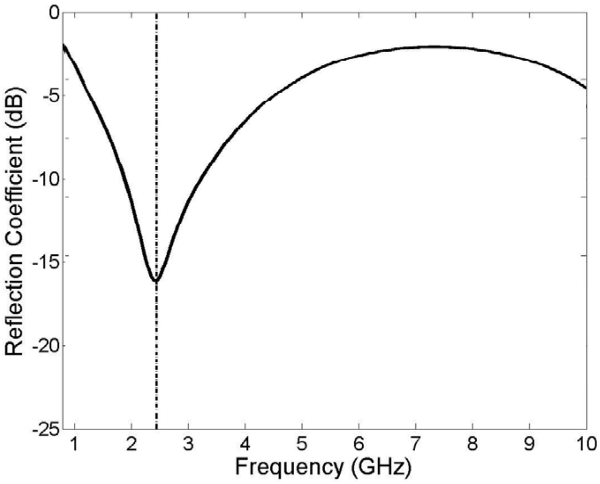


Fig. 6 The simulated reflection coefficient of the Unchoked antenna, expressed logarithmically. The dashed line represents the commonly used MWA frequency of 2.45 GHz

IV. Conclusions

The design of microwave antennas used in percutaneous ablation therapies takes into account not only electromagnetic constraints but also biological constraints, as well as physical ones. Choke antenna for hepatic MWA has been designed, modeled and simulated using an axisymmetric electromagnetic model implemented in FEMLAB™ 3.0. Numerical characterization and effectiveness of choked antenna has been verified in comparison with an unchoked antenna of the same type and a good agreement was observed between surface heating and input reflection coefficient measurements. This antenna is ideal for analyzing the surface heat and reflection coefficient of antennas used in hepatic MWA. The performance was evaluated both in terms of reflection coefficient and thermal lesion geometry, It was analyzed that reflection coefficient was not critically dependent on the choke section length and on the depth of insertion into the heated tissue. The antenna return loss was highly affected when the choke contact was removed indicating that the choke not only prevents the reflected current from flowing along the antenna feeding line, but also influences the antenna matching. The work successfully demonstrates that coaxial choked antenna has localized heat lesion near the tip, low reflection coefficient of the order of -21 dB and reduced detrimental backward heating.

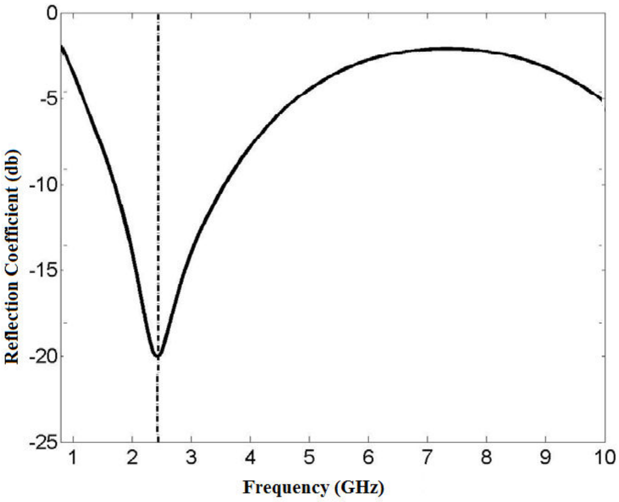


Fig. 7 The simulated reflection coefficient of the choked antenna, expressed logarithmically. The dashed line represents the commonly used MWA frequency of 2.45 GHz.

References

[1] R. Murakami, S. Yoshimatsu, Y. Yamashita, T. Matsukawa, M. Takahashi, and K. Sagara, "Treatment of hepatocellular carcinoma: value of percutaneous microwave coagulation," AJR Am J Roentgenol, vol. 164, pp. 1159-64, 1995.

[2] L. X. Liu, W. H. Zhang, and H. C. Jiang, "Current treatment for liver metastases from colorectal cancer," World J Gastroenterol, vol. 9, pp. 193-200, 2003.

[3] C. Erce and R. W. Parks, "Interstitial ablative techniques for hepatic tumours," Br J Surg, vol. 90, pp. 272-289, 2003.

[4] G. D. Dodd, M. C. Soulen, R. A. Kane, T. Livraghi, W. R. Lees, Y. Yamashita, A. R. Gillams, O. I. Karahan, and H. Rhim, "Minimally invasive treatment of malignant hepatic tumors: At the threshold of a major breakthrough," Radiographics, vol. 20, pp. 9-27, 2000

[5] Lu M-d, Chen J-w, Xie X-y, et al. Hepatocellular Carcinoma: US-guided Percutaneous Microwave Coagulation Therapy. Radiology 2001; 221(1): 167-172.

[6] Shibata T, Niinobu T, Ogata N, Takami M. Microwave coagulation therapy for multiple hepatic metastases from colorectal carcinoma. Cancer 2000; 89(2): 276-284.

[7] Su DWF, Wu LK. Input impedance characteristics of coaxial slot antennas for in-terstitial microwave hyperthermia. IEEE Trans Microwave Theory Tech. 1999; 47: 302–7.

[8] K. Saito, Y. Hayashi, H. Yoshmura, and K. Ito, "Numerical analysis of thin coaxial antennas for microwave coagulation therapy," IEEE Antennas Propagation Soc. Int. Symp., vol. 2, pp.

[9] S. L. Broschat, C.-K. Chou, K. H. Luk, A. W. Guy, and A. Ishimaru, “An insulated dipole applicator for intracavitary hyperthermia,” IEEE Trans. Biomed. Eng., vol. 35, 173-177, 1988.

[10] S. Labonte, A. Blais, S. R. Legault, H. O. Ali, and L. Roy, "Monopole antennas for microwave catheter ablation," IEEE Trans. Microwave Theory Tech, vol. 44, 1832-1840, 1996.

[11] S. Pisa, M. Cavagnaro, P. Bernardi, and J. C. Lin, "A 915-MHz antenna for microwave thermal ablation treatment: physical design, computer modeling and experimental measurement," IEEE Trans. Biomed. Eng., vol. 48, pp. 599–601, 2001.

[12] Yin XY, Xie XY, Xu HX et al "Percutaneous thermal ablation of medium and large hepatocellular carcinoma" Cancer 115:1914–1923(2009)

[13] Martin RC, Scoggins CR, McMasters KM et al "Microwave hepatic ablation: initial experience of safety and efficacy" J Surg Oncol 96:481–486, 2007.

[14] P. Liang, "Computer-aided dynamic simulation of microwave-induced thermal distribution in coagulation of liver cancer," IEEE Trans Biomed Eng, vol. 48, pp.821-9, 2001.

[15] Electromagnetics Module Model Library., COMSOL Multiphysics 3.4; 2009

[16] S. A. Sapareto and W. C. Dewey, "Thermal dose determination in cancer therapy," Int. J. Radiat. Oncol. Biol. Phys., vol. 10, pp. 787–800, 1984.

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

[18] Nevels RD, Arndt GD, Raffoul GW, Carl JR, Pacifico A: Microwave catheter design. IEEE Trans Biomed Eng 1998, 45:885-890.

[19] Iginio Longo, Guido Biffi Gentili, Matteo Cerretelli, and Nevio Tosoratti JANUARY (2003): 'A Coaxial Antenna with Miniaturized Choke for Minimally Invasive Interstitial Heating' IEEE Transactions on Biomedical Engineering, vol. 50, no. 1, pp 82-88

[20] Saito, K., Hayashi, Y., Yoshimura, H., and Ito, K., (2000): 'Heating characteristics of array applicator composed of two coaxial-slot antennas for microwave coagulation therapy', *IEEE Trans. Microwave Theory and Tech.*, 48, pp.1800–1806

[21] Haemmerich, D., Staelin, S T., Tsai, J Z., Tungjitkusolm- Un, S., Mahvi, D.M., and Webster J. G. (2003): 'In vivo electrical conductivity of hepatic tumours,' *Physiol.meas*., 24, pp.251-260

Surita Maini born on July 1972 at Pathankot. Surita Maini is Associate Professor in Electrical and Instrumentatiuon Engineering, SLIET, Longowal, Sangrur, 148106 Punjab, India. Completed her B.E in Instrumentation Engineering from B.R Ambedker Marathwada University in 1994, M.E in Instrumentation and Control from Thapar Institute on Engineering and technology (TIET) in 2001. She is annual member of ISTE, IEI and nnual member for IEEE and Institution of Engineers (India). She also has published 30 papers in National and International journals and conferences of repute. Her area of interest is implementation of Finite Element methods for hyperthermia for cancer treatment, antenna design and EEG signal processing.