Development and Analysis of Coaxial Slot Antenna in Comparision with Coaxial Dipole Antenna for Interstitial Microwave Ablation

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Abstract: - Hepatocellular carcinoma (HCC) is the most common malignant tumors to affect the liver. Microwave ablation is efficiently used for treatment of liver cancer. Although surgical resection remains the gold standard for treatment of liver cancer, but only 5-10% patients are the candidates for surgical resection due to numbers of limitations. Because most patients with HCC can not be treated with surgery or transplantation, thermal ablative treatments have started to become viable alternative methods to treat those patients. Microwave ablation (MWA) has shown great promise for the treatment of unresectable liver tumor and exhibits many perceived advantages. This attraction has driven the researchers to develop innovative antennas to effectively treat the deep seated hepatic tumors. In this paper, a two dimensional Finite Element Method (FEM) is used to measure and simulate the results of the coaxial slot antenna and coaxial dipole antenna. These two antennas are compared and discussed, while noting the similarities and differences between the heating patterns near the tip of the antenna. It was found that dipole coaxial antenna is more prone to backward heating and causes detrimental tissue heating along the antenna insertion region with respect to coaxial slot antenna.

Key-Words: - Microwave ablation (MWA), tumor, Finite Element Method (FEM), Coaxial slot antenna, coaxial dipole antenna.

1 Introduction

Hepatocellular carcinoma (HCC), or primary liver cancer, is the 6th most common cancer worldwide and third most common cause of death from cancer. When these tumors are left untreated is disastrous, with 100% mortality rate within 5 years [1]. Conventional therapies such as systemic chemotherapy or radiation have proven ineffective. Liver transplantation is best option for liver cancer and critical shortage of size matched liver donor limits its applicability [2]. 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 cannot be surgically removed, or too many tumor spots to be removed, which is again a big difficulty. Because most patients with HCC are not the candidates for resection or transplantation, the thermal ablative treatments have started to become viable alternative methods to treat patients who cannot be treated by surgery. Thermal ablation is direct application of heat to a specific tumor in order to achieve complete eradication of tumor. The primary methods used to produce thermal ablation are : radiofrequency ablation (RFA), microwave ablation (MWA). Although RF ablation (RWA) devices are more technically developed than MW ablation (MWA), but RFA is fundamentally restricted by the need to conduct electric energy into the body [3]. MWA now a days may not be commercially available in, but have potential to become the superior treatment modality. The main advantage of microwave technology, when compared with existing thermoablative technologies, promises higher intramural temperature, larger tumor ablation volume, faster ablation time and improved convection profile [4].

The basic principle of microwave hepatic ablation is to apply microwave power to the liver tissue through the microwave applicator i.e antenna. The power of the EM wave is absorbed by the liver tissue and heats the tissue. Liver tissue is destroyed when it is heated to a high temperature for a long duration of time [5]. Many perceived advantages of MWA have driven researchers to develop innovative antennas to effectively treat deep-seated, nonresectable hepatic tumors.

Many different antenna designs have been proposed, optimized and verified. Coaxial-based antennas are extremely important for MWA application because of their low cost and small dimensions. Coaxial antennas differ in many ways: the allowed power level, thermal lesion size, lesion shape, antenna dimension etc. Detrimental backward heating is one of the major problems for MWA, refers to the undesired heating that occurs along the coaxial feedline of the antenna. This detrimental backward heating causes damage to the liver outside the desired treatment region which may lead to burning of the skin during percutaneous treatment.

Several types of coaxial-based antennas, including the coaxial slot antenna [6, 7], coaxial dipole antenna [8, 9], coaxial cap-choke antennas [10], and others, have been designed for MWA. Many researchers are doing effort to develop the less invasive interstitial antennas for microwave ablation for treating the liver cancer. These antennas are that are capable of producing highly localized patterns of electromagnetic power deposition in tissue [11, 12, 13]. In this paper heating characteristics of coaxial dipole antenna and coaxial slot antenna has been studied using computer simulation. COMSOL Multiphysics [14] version 3.4 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) and can be used standalone [15].

Finite Element Method (FEM), has been extensively used in simulations of microwave interstitial antennas because, the computer simulations determine the optimal antenna design, optimal probe geometry, optimal placement of inner temperature sensors for the purpose of efficient temperature-controlled ablation and optimal power application and ablation procedure duration
In section II the design of coaxial dipole antenna and coaxial slot antenna is described. In section III heating characteristics of both the antennas has been investigated using FEM. Finally, conclusions are presented in section IV.

2 Design of Antennas

The authors have been studying coaxial antennas for minimal invasive microwave thermal therapies. Fig. 1 and 2 shows the design of dipole coaxial antenna and coaxial slot antenna; both the antennas operate on the frequency of 2.45 GHz. Table I lists values of liver tissues with parameters for both of the antennas. Although the basic structure of the coaxial slot antenna appears very similar to that of the interstitial coaxial dipole antenna, important differences exist between the two designs. Unlike the dipole, the physical structure of the coaxial cable is preserved for the entire length of the slot antenna, except for the ring slot and short-circuited tip. The tip of the dipole antenna is a whole piece of metal, while the inside of the tip of a slot antenna is still the dielectric of the coaxial cable. Like all other antennas, a slot antenna is usually sealed in its catheter to be used in MWA procedure. For frequency at 2.45 GHz, a slot antenna works very similarly to a dipole antenna having very low power reflection of -16 dB as shown in Fig. 3.

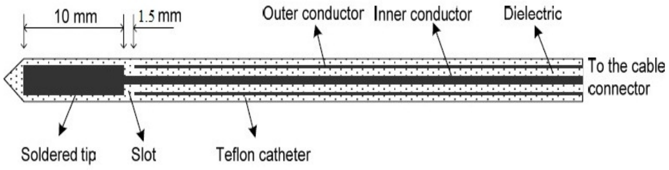

Fig. 1 : Schematic of the coaxial dipole antenna

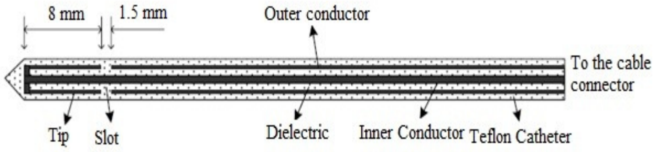

Fig. 2: Schematic of the coaxial slot antenna

Table I: Liver Properties

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 [degC]	Blood Temperature
P_in	10 [W]	Input power
Nu	2.45 [GHz]	Microwave freq.
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

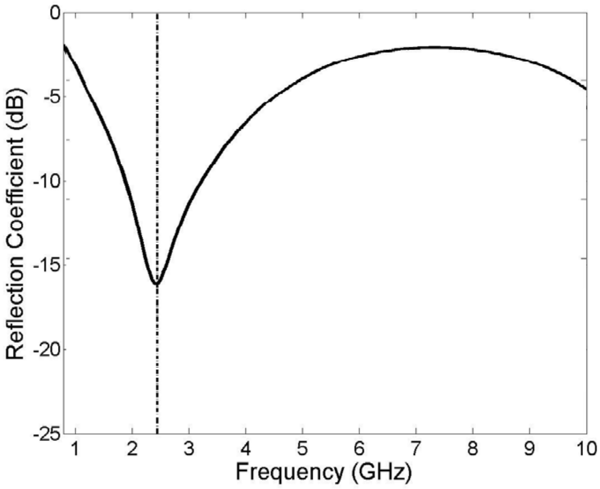

Fig. 3 : The simulated reflection coefficient, expressed logarithmically. The dashed line represents the commonly used MWA frequency of 2.45 GHz.

3 Results

After creating the geometrical models, assigning all the material properties and boundary conditions, surface temperature distributions and finite element mesh has been generated. Figs. 4 and 5 shows the surface temperature 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. From the temperature distribution patterns 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 of a hot spot in the temperature distribution inside the tissue. Basically coaxial dipole antenna is an unbalanced dipole structure. The antenna tip is one pole and the long outer conductor of the coaxial cable is the second pole. The length of the tip is usually short and the outer conductor tail of the antenna is much longer. The unequal lengths of both poles make the EM fields of the antenna unbalanced between the two poles. Moreover from the surface temperature distribution Fig.s it is clear that coaxial dipole antenna has a long tail which referred to as backward heating which causes detrimental tissue heating along the antenna insertion region. The backward heating can cause excess patient discomfort, induce necrosis in normal liver tissue, and lead to surgical complications.

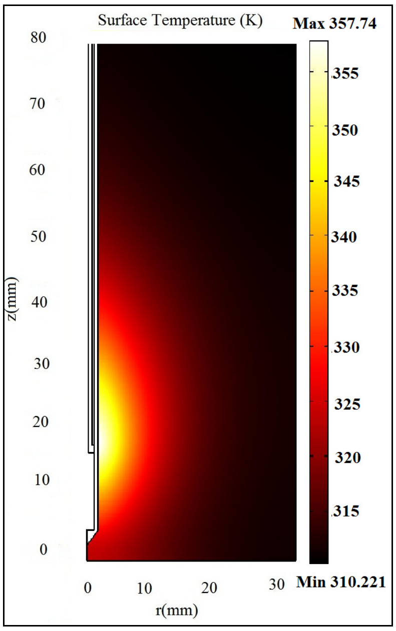

Fig. 4 : Temperature distribution of coaxial dipole antenna in the tissue, 2D model

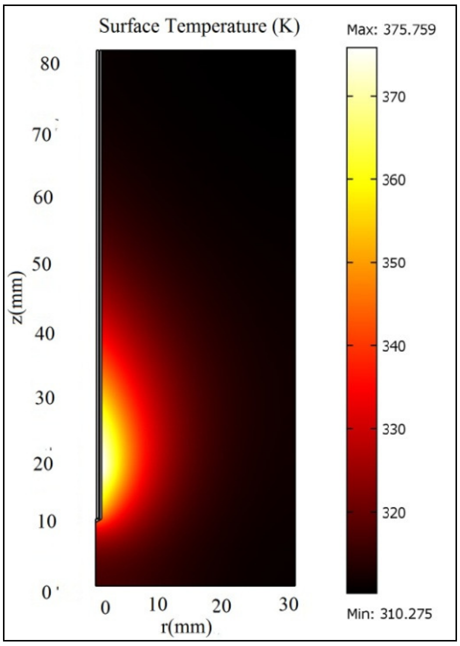

Fig. 5 : Temperature distribution of coaxial slot antenna in the tissue, 2D model

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. Fig.s 6 and 7 shows the axisymmetric finite element mesh, generated by FEMLAB using the free mesh parameters with the maximum element size 3e-3 mm, in order to achieve a best compromise between computational accuracy and optimized dimensionality of the model. A dense mesh generated near the vicinity of tip of antenna is observed, where the temperature is high and having variable distribution. The mesh consists of 9627 triangular elements with 27911 degrees of freedom (D.O.F) for coaxial dipole antenna and 8495 triangular elements with 24552 degrees of freedom (D.O.F) for coaxial slot antenna. Comparison of mesh statistics is given in Table 2.

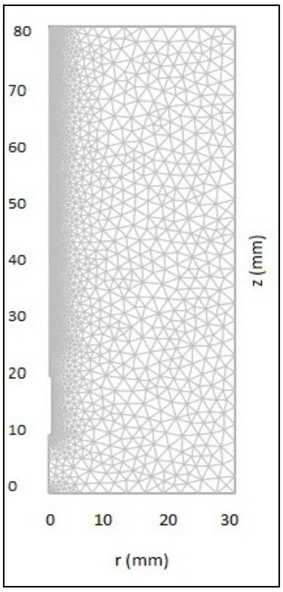

Fig. 6 : Meshing for coaxial dipole antenna

Table 2. Mesh Statistics

Mesh Parameters	Coaxial Slot	Coaxial dipole
Number of D.O.F	24552	27911
Number of mesh points	4838	5011
Number of elements	8495	9627
Triangular	8495	9627
Quadrilateral	0	0
Number of boundary elements	1380	1429
Number of vertex elements	18	18
Minimum element quality	0.697	0.619
Element area ratio	0.001	0

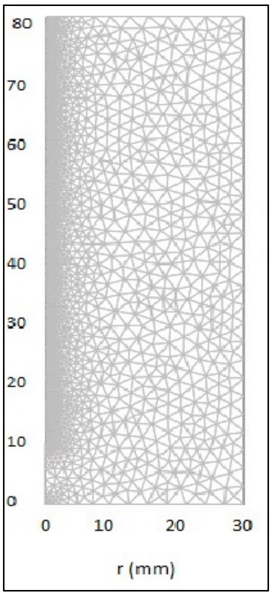

Fig. 7: Meshing for coaxial slot coaxial antenna

The Thermal lesion produced by coaxial slot antenna is of tear-drop shape. The lesion produced depend upon the power supplied to the antennas, when the input power is increased, lesions produced will be large, but backward heating problem causes burning of healthy tissues which poses a huge challenge for microwave antenna designs [16].

4 Conclusion

The Finite Element Method (FEM) has been used for simulating Coaxial dipole antenna and coaxial slot antenna with 2D modeling, in a longitudinal plane. Surface temperature distribution of both the coaxial antennas for the MCT has been studied. The work successfully demonstrates that coaxial dipole antenna has much longer long tail with respect to coaxial slot antenna; referred to backward heating problem refers to the undesired heating that occurs along the coaxial feedline of the antenna. This detrimental heating causes damage to the liver outside the desired treatment region and can lead to burning of the skin during percutaneous treatment.

The backward heating problem posts a huge challenge for MWA antenna designs. Most antennas used in MWA are unbalanced coaxial-based antennas, which transmit the microwave power out of their tips. The backward heating problem will become more serious when power levels and application durations are increased in order to achieve larger lesions.

The surface temperature distribution and calculations using FEM can play an important role in clinic planning of heat treatments using microwave interstitial antennas. Specific tumor geometries may be modeled and other physiological parameters may be measured and based upon the type of antenna, clinical heat planning may be chalked out.

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