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Coaxial Helix Antenna for Microwave Coagulation Therapy in Liver Tissue Simulations

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***Abstract*—**This paper is concerned with microwave (MW) ablation for a liver cancer tissue by using helix antenna. The antenna structure supports the propagation of microwave energy at 2.45 GHz. A 1½ turn spiral catheter-based microwave antenna applicator has been developed. We utilize the three-dimensional finite element method (3D FEM) simulation to analyze where the tissue heat flux, lesion pattern and volume destruction during MW ablation. The configurations of helix antenna where Helix air-core antenna and Helix Dielectric-core antenna. The 3D FEMs solutions were based on Maxwell and bio-heat equations. The simulation protocol was power control (10 W, 300s). Our simulation result, both helix antennas have heat flux occurred around the helix antenna and that can be induced the temperature distribution similar (teardrop). The region where the temperature exceeds 50°C the microwave ablation was successful (i.e. complete destruction). The Helix air-core antenna and Helix Dielectric-core antenna, ablation zone or axial ratios (Widest/length) were respectively 0.82 and 0.85; the complete destructions were respectively 4.18 cm^3 and 5.64 cm^3

***Keywords*—**Liver cancer, Helix antenna, Finite element, Microwave ablation.

I. Introduction

GENERALLY, liver cancer can be classified into two primary categories, namely those that originate from liver cells or other structures within the liver, the most common being hepatic cancer, and those that spread from other primary sites in the body, referred to as metastatic tumors. [1].

Percutaneous ablation is an important alternative to surgical resection, the most commonly used curative treatment. Microwave ablation (MWA) is a new ablation technique. MWA operates in the microwave range (0.3 GHz - 300 GHz) to excite the oscillation of water molecules, alternating electric field which causes water molecule rotation and creation of heat. This results in thermal coagulation and localized tissue necrosis. MWA provides larger and faster ablated volumes than radio frequency ablation (RFA) [2].

In MWA, a single microwave antenna connects to a generator are inserted directly into the tissue or tumor to be ablated. The microwave energy from the antennas generates friction and heat. The region of liver cancer where the temperature exceeds 50°C the microwave ablation was successful [3]. Several types of coaxial-based antennas, including the coaxial slot antenna [4], coaxial dipole antenna [5], coaxial monopole antenna [6], coaxial cap-choke antennas [7], and others have been designed for MWA or microwave hyperthermia therapies in an attempt to prevent this backward heating while creating as large an ablation radius as possible.

The purpose of this effort is to design the helix antenna. We studied and compared the heat flux, heating pattern or lesion pattern and the volume of liver cancer had been destruction of heat. The geometries of helix antennas of this study shown in Fig. 1, they are: (a) Helix air-core antenna (HAC) and (b) Helix Dielectric-core antenna (HDC).

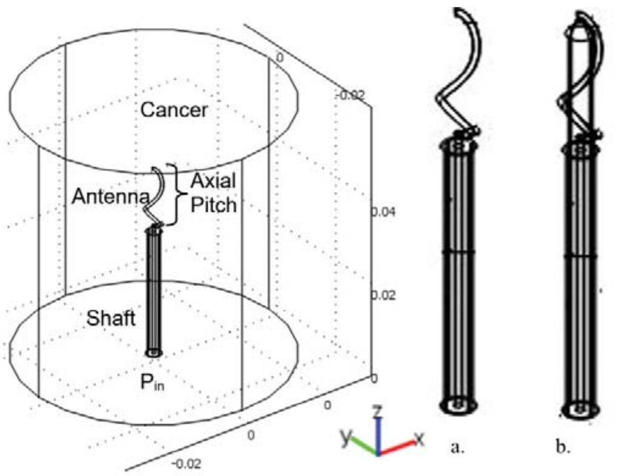

Fig. 1 Configurations of the Helix antennas: (a) Helix air-core antenna (HAC) and (b) Helix Dielectric-core antenna (HDC)

II. Materials and Methods

In this work, a numerical study is presented to simulate the temperature increase produced by ablation in different antennas cases. First, the electromagnetic field produced by a thin Helix antenna in liver tissue excited at a MW frequency is analyzed permitting the calculation of the specific absorption rate (SAR). Then, the temperature increase is calculated by the BHE in a biological tissue. The calculations for the different cases have been carried out by using the finite element method for the analysis of multiphysical three-dimensional (3D) problem.

A. Governing Equations

The time-harmonic electromagnetic field in a source-free region is governed by the electric field vector wave equation:

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$$\nabla \times \frac{1}{j\omega\mu} \nabla \times E - (\sigma + j\omega\varepsilon) E = 0 \quad (1)$$

where E is the electric field, ε the permittivity, μ the permeability, σ the electric conductivity, and ω the angular frequency. Equation (1) can be solved by the finite element method (FEM), and the SAR [W/kg] in tissue is calculated as a function of position as:

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

where ρ is the density (kg/m^3), E is the Electric field intensity (V/m). The resistive heating which is calculated from Maxwell's equations is used as an input to thermal model. Pennes bio-heat equation has been used to model the heat transfer during MWA [8].

$$\rho c \frac{\partial T}{\partial t} = \nabla . k \nabla T + \rho SAR - h_{b1}(T - T_{b1}) + Q_m \quad (3)$$

$$h_{bl} = \rho_{bl} c_{bl} \omega_{bl}$$

where c is the Specific heat (J/kg·K), k is the Thermal conductivity (W/m·K), T_{b1} is the temperature of the blood (i.e. 37 °C), ρ_{bl} is the blood density (kg/m^3), c_{bl} is the Specific heat of the blood (J/kg·K), ω_{bl} is blood perfusion (1/s) and the h_{bl} is the convective heat transfer coefficient accounting for blood perfusion in the model. The energy generated by the metabolic processes Q_m, (W/m^3). The metabolic heat generation rate of 33 800 W/m^3 is used [9].

B. Geometries Model

For the simulation of the proposed Helix Antenna, we utilized numerical modeling to solve 3D FE analyses in order to obtain temperature distributions during MW ablation. We solved our FE models using COMSOL Multiphysics 3.5a (COMSOL, Inc., Burlington, MA). The software allows specifying the geometry of antenna design. The Geometries models for analysis consist of the helix antenna interstitial into the liver cancer. The creation of the helix antenna is a sample coaxial cable. For the HAC antenna, the inner conductor was wound on the air-core, while the HDC antenna its was wound on the outer-dielectric of the coaxial cable (Fig. 1). We design the dimensions of the geometric model for analyses were: the liver cancer was cylindrical shape (diameter= 60 mm and length=60mm), we use the Multiflex_141 coaxial cable to design the helix antenna, the helix antenna has the number of turn was 1.172, the axial pitch was 13 mm and the shafts connect with the helix antenna has 29 mm.

After creating the geometric model as well as assigned material properties and necessary boundary conditions, while its the electromagnetic and thermal material properties are shown in Tables I and II, respectively [10], [11].

The boundary conditions assigned to FEMs in this study complied with the following [12]:

- We assumed the propagation mode for the microwave was TEM mode, where the feeding source was launched inside the cable. The total field was computed by the technique of the scattering problem
- All the conductors in the coaxial cable assume as perfect conducting boundaries, the tangential electric field is zero.
- The boundary of the coaxial input port is a hard feeding source aperture. For this type of source aperture, the port is treated as a hard source, launching an incident wave, but not allowing any reflected wave to be absorbed.
- The microwave power of 10 W and assigns the time of simulation for microwave ablation to be duration was 300s.

Then, we performed non-uniform meshing of the geometries using tetrahedral elements. The numbers of elements and nodes for simulation used in HAC antenna and the HDC antenna model were 380 000 and 420 000, respectively. Fig. 2 shows meshed models of the helix antenna model.

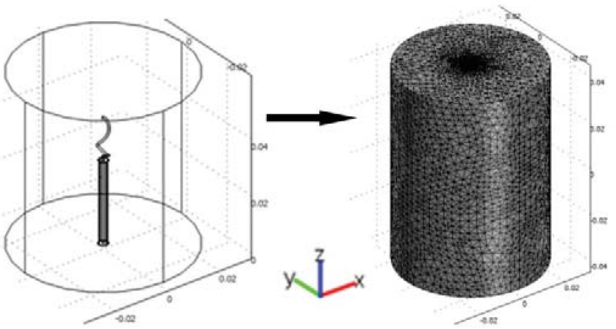


Fig. 2 The cross-section of the meshed model

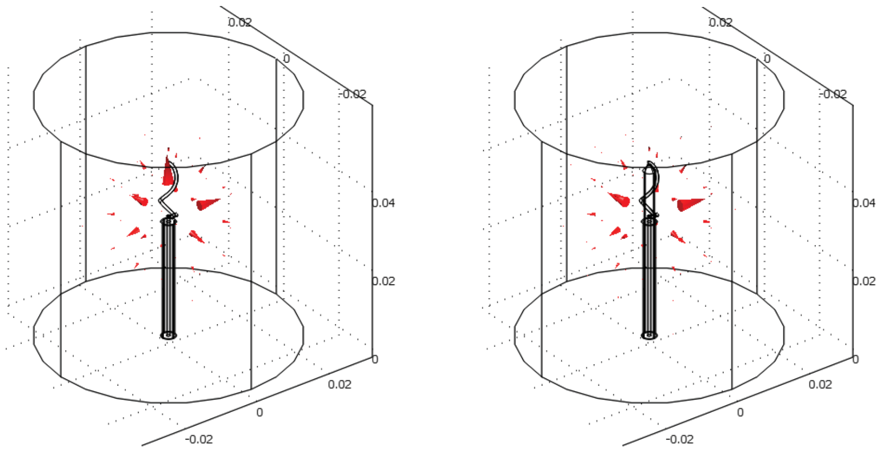
TABLE I
MATERIAL PROPERTIES FOR ELECTROMAGNETIC ANALYSIS AT 2.45GHZ

Properties	Liver cancer	Dielectric	Conductor
Relative permittivity (ε_r)	43.03	2.03	
Relative permeability (μ_r)	1	1	PEC*
Conductivity (σ) [s/m]	1.79	10^{-5}	

*PEC (Perfect electric conductor)

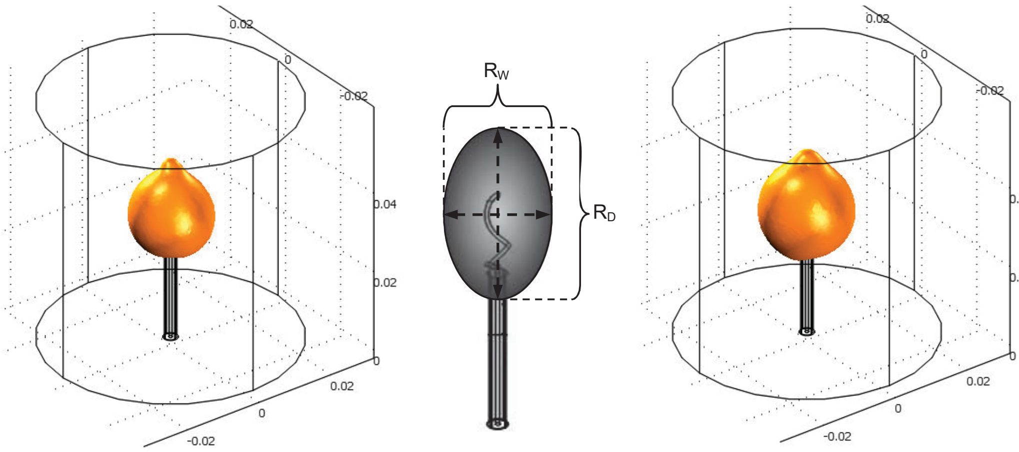
TABLE II
MATERIAL PROPERTIES FOR THERMAL ANALYSIS

Material	ρ [kg/m^3]	c[J/kg.K]	k[W/m.K]	σ [S/m]
Conductor	6450	840	18	10^8
Liver cancer	1060	3600	0.512	1.79
Dielectric	70	1045	0.026	10^{-5}
Shaft	70	1045	0.026	10^{-5}



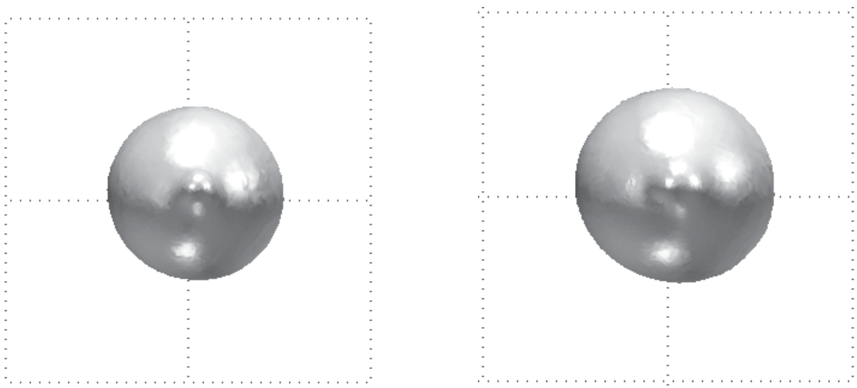
(a) HAC antenna (b) HDC antenna

Fig. 3 The heat flux of Helix antenna at power of 10W, duration was 300s



(a) HAC antenna (b) HDC antenna

Fig. 4 The lesion profile of Helix antenna at power of 10W, duration was 300s



(a) HAC antenna (b) HDC antenna

Fig. 5 Lesion profile on x-y plane, which considered the region temperature exceeds 50 °C (destruction complete region)

TABLE III
THE SIMULATION RESULTS OF HELIX ANTENNAS FOR MW ABLATION

Parameter	Antenna type	
	HAC	HDC
Max temperature (°C)	196.41	145.78
Thickness (mm)	9.8	11
Lateral (mm)	9.8	11
Longitudinal (mm)	12	13
Axial ratio (RW/RD)	0.82	0.85
Ablated volume (cm^3)	4.18	5.64

III. SIMULATION RESULTS

After we created the geometrical model, generated finite element mesh, and assigned all the material properties and boundary conditions, we ran the coupled electromagnetic-thermal simulations using Comsol. We then performed post-processing to obtain the heat flux and lesion profile for different antennas (Figs. 3-5). Lesion width is defined as regions where the tissue temperature is 50°C or above.

Fig. 4 showed the heat flux, both antennas have heat flux and heating pattern was similar, which its distribute at the region around of the helix antennas. In addition, we found that the HDC antenna can be induced the maximum temperature within the cancer and its create the lesion bigger than the HAC antenna. The dielectric at the core of the antenna was absorbing the microwave power more than the air core. Thus the HAC and HDC antenna can be induced microwave power for destruction, liver cancer cell was 4.18 cm^3 and 5.64 cm^3 respectively.

We consider the lesion profile from axial ratio. The axial ratio equal one (i.e. the shape of ablation zone was a sphere). When the ablated with the HAC and HDC antenna, an ablation zone shape closer to a spherical one (i.e. 0.82 and 0.85 respectively) (see Table III).

IV. CONCLUSIONS

In this paper, a tool for the numerical evaluation of the corresponding temperature increase induced in liver cancer through a MW catheter ablation technique. Various designs for Helix antennas were simulated using FEM. We analyzed the heat flux, heating pattern, lesion of the size and ablated volume of each antenna. All the antennas have a potential to create lesions. In the future, we shall simulate by performing temperature controlled ablation of 90°C. In addition, we also plan to perform *in vitro* experiments to verify our results from FE analyses.

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