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RESEARCH ARTICLE

THEORETICAL INVESTIGATON AND PERFORMANCE ANALYSIS OF DIFFERENT ANTENNAS FOR MICROWAVE ABLATION

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ABSTRACT

Microwave ablation is a treatment method that effects malignant tissue area directly without damaging surrounding healthy area. Microwave energy lead to rise tissue temperature instantly and coagıulation occurs. Micro coaxial slot antennas ere employed to apply ablation process. The main objective of this work determine the efficiency of antenna geometry on the ablation process. Three different slot coaxial antenna models (single slot, double slot and sleeved) are employed to comparison and exposed to power of 10w, 20w and 30w during 10 minute. The COMSOL MULTIPHYSICS (ver 4.3, COMSOL Group) software is employed to design and simulate antennas. Eventually ablation length, ablation diameter, temperature, special absorption rate and power dissipation are obtained with finite element method from the electromagnetic simulations using COMSOL. Experimental validations were designed to evaluate the proposed antenna. Model verification and simulation results have been evaluated in effective antenna geometry.

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INTRODUCTION

In recent years, diagnosis and treatment methods which play an active role in the fight against cancer, prioritize patient comfort with technological advances. There are various treatment methods for malignant (cancer-malignant) tumors. These methods can be listed as surgery, chemotherapy and radiotherapy applications. Often, these methods are applied after the tumor of patient has no chance of surgical removal. Nowadays, routine treatment methods surgery and chemotherapy are not effective enough. Therefore new methods of treatment are needed. In addition to the classical methods of treatment of malignant tumors in lung, liver and kidney , ablation (removal, separation) techniques gain importance increasingly. Microwave ablation is thermal therapy that expose of tissue the high temperature for treatment of malignant tissues. Variety of medical devices used for microwave ablation has increased significantly. In microwave coagulation therapy, in which a thin slot coaxial antenna operating at 2.45 GHz is inserted in the tumorous area. The probe is made of a thin coaxial cable with a ring-shaped slot. In the outer surface a catheter surrounds the antenna. Main problems of the designing a medical antenna are biocompability, impedance matching, security of patient [1]. A slot coaxial antenna is placed into the malignant (target) zone to radiate at mwa frequency during application. Microwave frequency bands approved for ISM and 2.45GHz most widespread value for microwave application [2].

Electromagnetic energy radiated from the antenna is deposited in the lossy tissue leading to heating via dielectric hysteresis. Microwave ablation can shrink tumors through damaging of protein and intercellular structures. However because of the impedance mismatch between antenna and surrounding zone lead to damage healthy tissues along the coaxial feed line [3]. Such cases limits the current, time period and ablation area. Microwave ablation therapy leads to temperature increasing within a short period of time in the malignant tissue area. In this way coagulation of malignant tissues occurs instantly without damaging surrounding healthy tissues. Polar molecules inside the tissue cause increasing kinetic energy and temperature accordingly microwave ablation performance depends on that amount of water inside the tissues [4]. Specific absorption rate (SAR) and frequency dependent reflection coefficient is important for microwave ablation antenna optimization [5]. Microwave ablation is common treatment technique used for also atrial fibrillation by cutting cardiac tissue. Heating diseased tissue disrupts the electrical conduction that leads to cardiac rhythm disease.In microwave antenna specific power deposition patterns can be arranged with polarization and phase effects [6]. Theoretical modelling is crucial in the optimization of antennas to evaluate the performance and efficiency. Because of especially small dimensions, slot coaxial antennas are common antenna types for mwa process. Coaxial antennas can be modelled as monopole, dipole, choked ,sleeved and double slot etc.In this paper we will investigate efficiency single, double slot and sleeved antennas. Both simulation and verification of the model were performed to analyze the effect of geometry on the antenna efficiency.

MATERIALS AND METHODS

In this work we have investigated effect of different antenna types on ablation performance.Three different,(single slot, double slot and sleeved) antenna types were used to simulation of heat transfer into malignant tissue.

Material	Permittivity	Conductivity
Slot	1	0 S/m
Liver	43	1.69 S/m
Dielectric	2.03	0 S/m
PTFE	2.1	0 S/m

Inner conductor diameter of these antennas should be notably thin to increase interstitial treatment effect therefore it is selected as 0.27 mm. Silver plated copper wire (SPCW) is used as material because of strong conductivity. Inner conductor enclosed coaxial dielectric made of low loss polytetrafluoroethylene (PTFE). Antennas are formed of inner conductor, dielectric, outer conductor and catheter. A circular cutout from the outer conductor is located at 5.5mm to the distal section of antenna which served as radiation structure. Slot wide was set in 1 mm that optimizes amount of radiation. In double slot antenna second slot is located at 4.2 mm to the first slot. Slot spacing was chosen one-quarter of the wavelength in tissue at frequency of 2.45GHz.The single slot antennas generate extended ablation area. Slots in multi slot antenna shaft is a set of multiple periodic slots that are transmit micro waves [7]. Figure 1 illustrates the geometric structure of single slot, double slot and sleeved MCA (Microwave Coaxial Antenna).

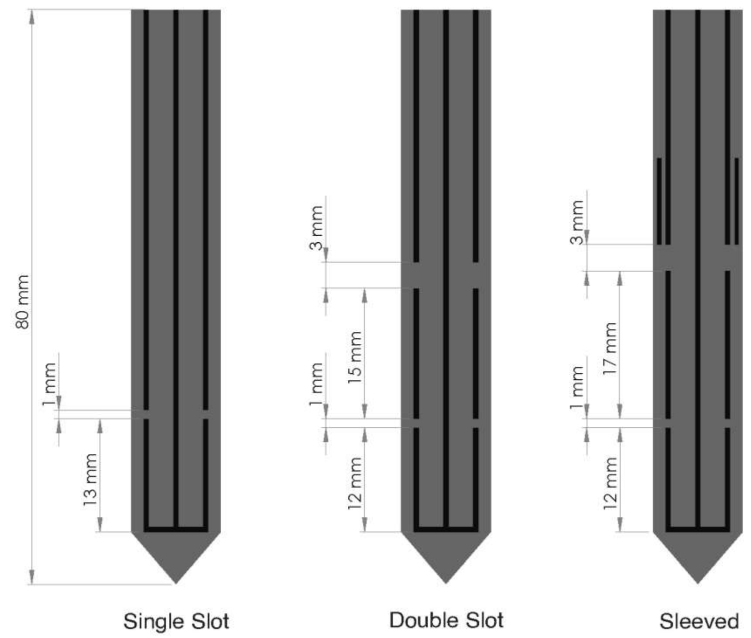


Fig. 1. Model geometry of single slot, double slot and sleeved antennas

This study uses liver tissue to simulate the influence of antenna geometry on the ablation performance. We modelled a cylinder in 30mm radius and 80mm length with properties of liver tissue. The biological properties of liver tissue was assumed to be homogeneous. Table 1 lists electromagnetic properties of all materials used this work. In order to model radiation of EM waves and microwave power absorbed from liver tissue COMSOL Multiphysics was employed. Transverse Electromagnetic Field(TEM) characterized electromagnetic wave propagation in slot coaxial antenna and solved time and temperature distribution in tissue by COMSOL application. An electromagnetic wave propagating in a coaxial cable is characterized by transverse electromagnetic fields (TEM). The equations are expressed as, provided that time-harmonic fields with complex amplitudes containing the phase data ;

$$E = e_r \frac{C}{r} e^j (\omega t - kz) \quad (1)$$

$$H = e_\varphi \frac{C}{rZ} e^j (\omega t - kz) \quad (2)$$

$$P_{av} = \int_{r_{inner}}^{r_{outer}} R_e \left(\frac{1}{2} ExH^*\right) 2\,\pi r dr \quad (3)$$

z : Propagation Direction
r, ϕ, z : Cylindrical coordinates
P_{av} : Power flow in the cable
Z : Wave impedance
rinner; router : DielectricRadius

Antenna model can be express via axisymmetric transverse magnetic formula:

$$\nabla x\left(\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)^{-1} \nabla x H_\phi\right) - \mu_r k_0^2 H_\phi = 0 \tag{4}$$

In the equation(4) magnetic field in tissue is only in azimuthal direction. Electric field has component in axial direction. Deposited energy by the antenna was calculated using the electromagnetic field distribution:

$$Q = \frac{1}{2}\sigma|E|^2 \tag{5}$$

SAR is an amount of electromagnetic energy per unit mass absorbed by the body and is represented by mathematical equation as follows:

$$SAR = \frac{\sigma}{2\rho}|E^2| \tag{6}$$

σrepresents the conductivity of tissue exposed electromagnetic energy (S/m) at the desired frequency, ρ is the density of tissue and finally E represent the time dependent electric field. The microwave energy absorbed from the tissue, is transformed to internal heat generation. Penne's Bioheat Equation is widely used bioheat equation to solve temperature transfer in tissue and it generates conspicuous exact results. It provides both analysis rate of temperature change and heat transfer. The equation is expressed as:

$$\rho C\frac{\partial T}{\partial t} = \nabla.(k_{t} \nabla T) + \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \tag{7}$$

We applied scattering boundary condition to the outer surface of simulated liver region that is exactly non-reflecting condition. The antenna wall and metallic regions were assumed as perfect electric conductor and we get following boundary condition assuming $H_{\varphi 0}$ as input field:

$$nx\sqrt{\varepsilon}E - \sqrt{\mu}H_\varphi = -2\sqrt{\mu}H_{\varphi 0} \tag{8}$$

$$H\phi_0 = \frac{1}{r}\sqrt{\frac{P_{av}Z}{\pi r \ln\left(\frac{r_{outer}}{r_{inner}}\right)}} \tag{9}$$

A microwave source is set at top of the cylinder to provide the desired forward power of 10, 20 and 30 watts and duration in 10 minute for each antenna. The microwave coaxial antennas are analyzed in electromagnetic wave propagation, special absorption rate(SAR), power dissipation, maximum power distribution density and ablation diameter. These simulation results of MCA is compared experimental results of studies in literature in order to certify accuracy.

SIMULATION AND RESULT

Experimental Verification: Simulating in COMSOL antenna with variable geometries enables objectively assessment of performance for each antenna design.The verification of slot coaxial antennas is essential to make consistent evaluation. The liver tissue temperatures are compared regardless of the geometry, to verify micro coaxial antenna's output. In 2.45GHz operating frequency and 75W during 150s, a single slot micro coaxial antenna results are compared with experimental result of an equivalent antenna from study of Yang et. al.[9] Sensor positions are determined 4.5mm and 9mm away from the antenna and mca placed 20mm depth of the liver tissue. Results in the Figure.2 represent the combined curves exported from present study's temperature data in Comsol and results that are found compatible. The slighlty differences between the temperature curve, originates from the ignorance in Bioheat Equation used in our simulation as mentioned in detail at Yang et al. [9].

Antenna Simulation: Figure 3 shows the simulation results of liver tissue in micro coaxial antenna. Figure 3(a), (b),(c) represents the absorbed microwave power by the liver tissue under single slot, double slot, sleeved antennas and 10W, 20W, 30W. The figures shows how a liver tissues absorbs a radiated wave from an micro coaxial antenna and converts to heat by dielectric heating. In all antenna models, heating effect reaches highest value surrounding of slots and decreases when the further away. The main objective of ablation process is destroy the malignant tissues while providing safety of adjacent zone. In case of comparison single slot, double slot and sleeved antennas, the highest microwave energy deposited from liver tissue observed in sleeved antenna because sleeve make reducing effect of reflection microwave power along the antenna shaft. SAR value symbolizes deposited power amount per unit mass. It is dependent many parameters and widely employed for performance analysis of micro coaxial slot antenna. Figure 4 illustrates SAR distributions case of single slot, double slot and sleeved antennas. The liver tissue exposed to microwave energy in 2.45GHz frequency and power of 10W during 10 minute.

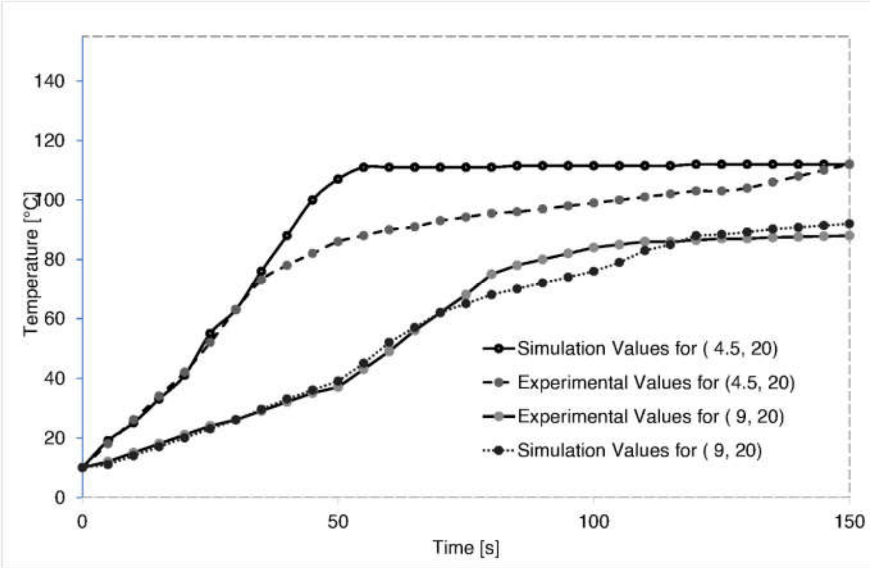
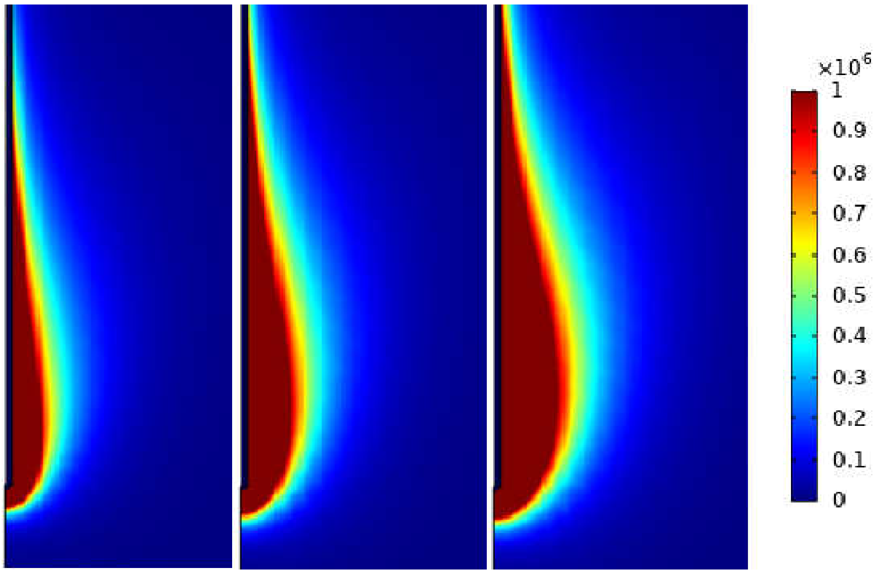
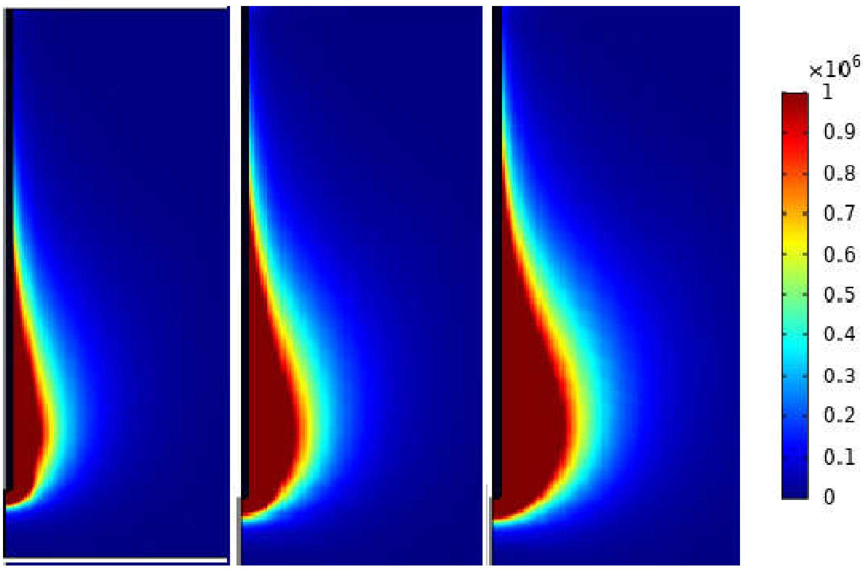


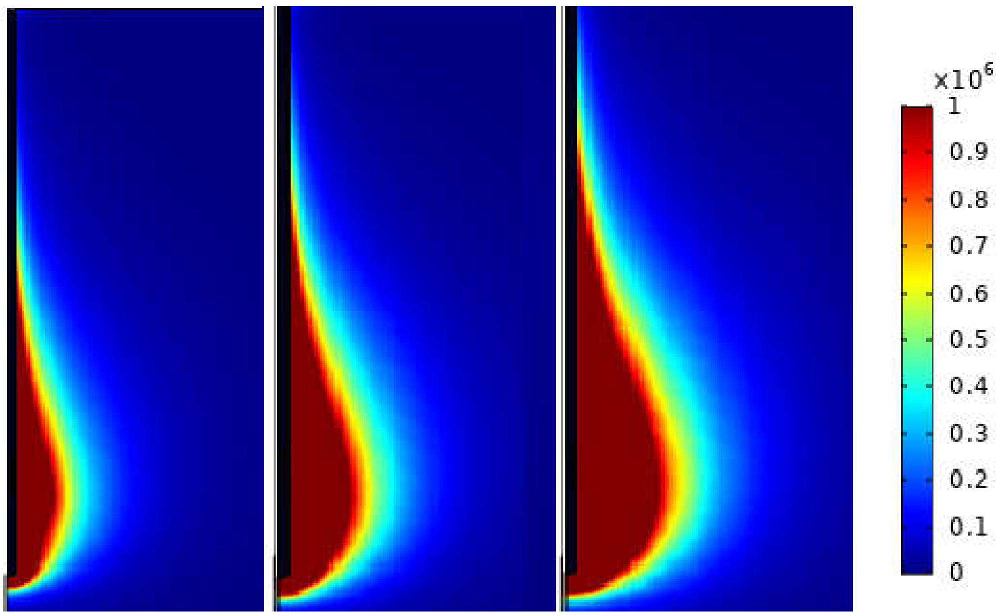
Fig. 2. Comparison simulation and experimental result of liver tissue temperature



(a)Single slot antenna

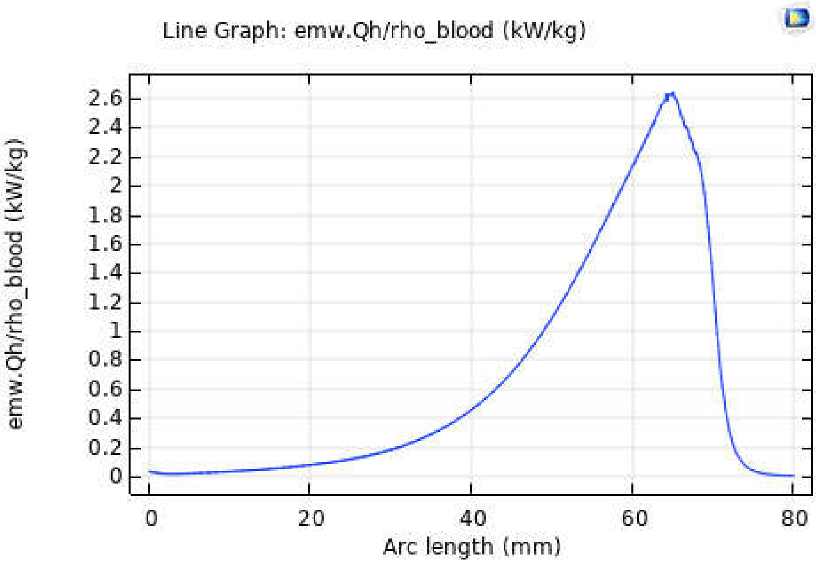


(b) Double slot antenna

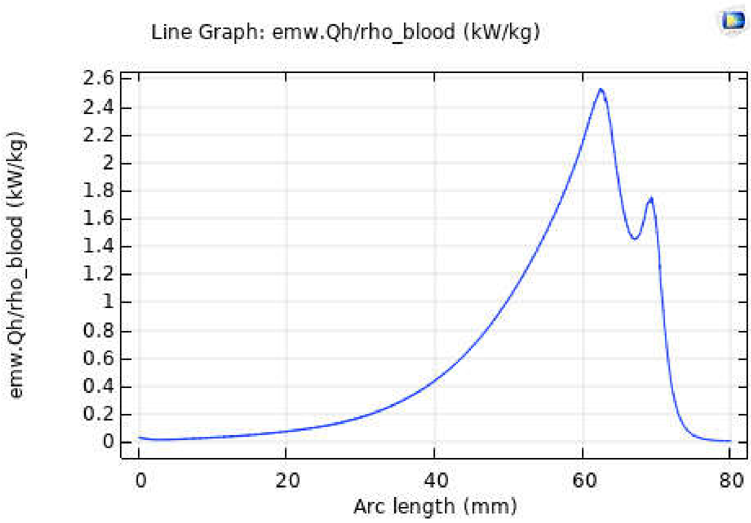


(c) Sleeved antenna

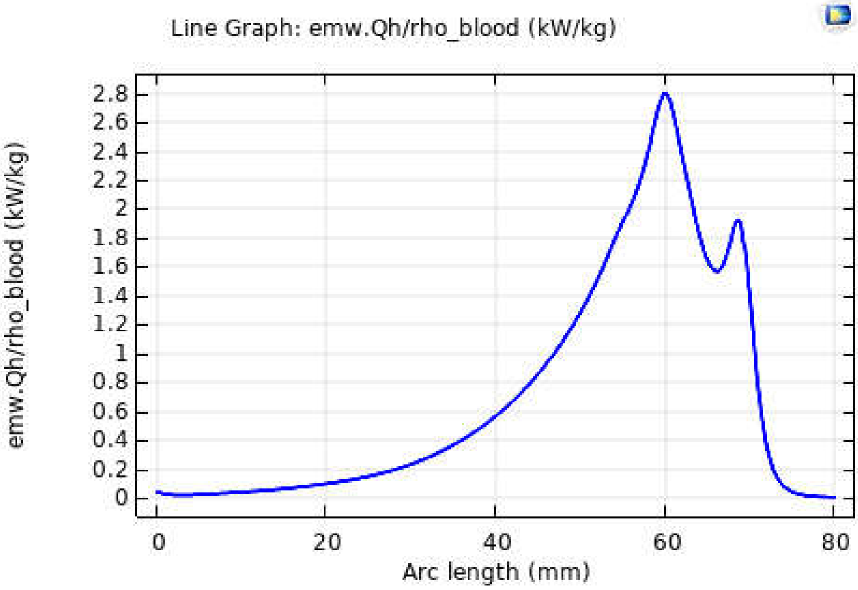
Fig. 3. The microwave power absorbed in liver tissue indifferent antennas of 10W, 20W and 30w



(a)Single slot antenna

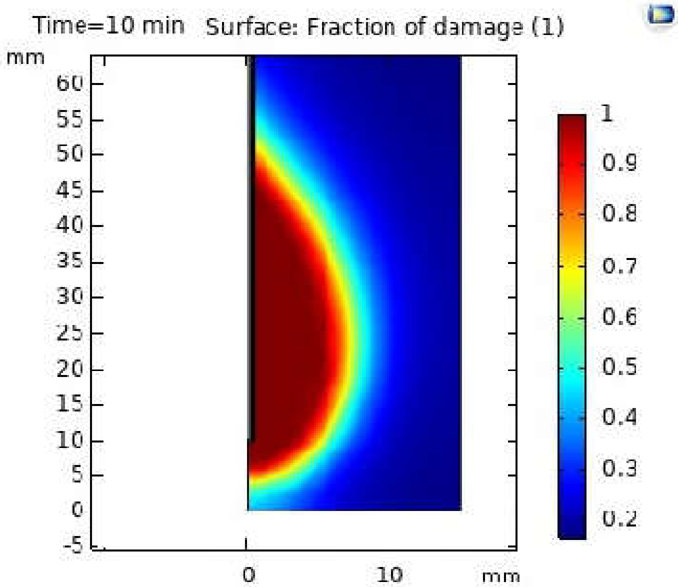


(b)Double slot antenna

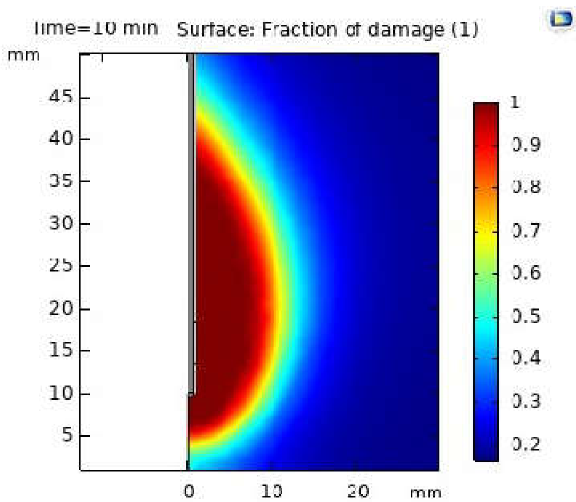


(c)Sleeved antenna

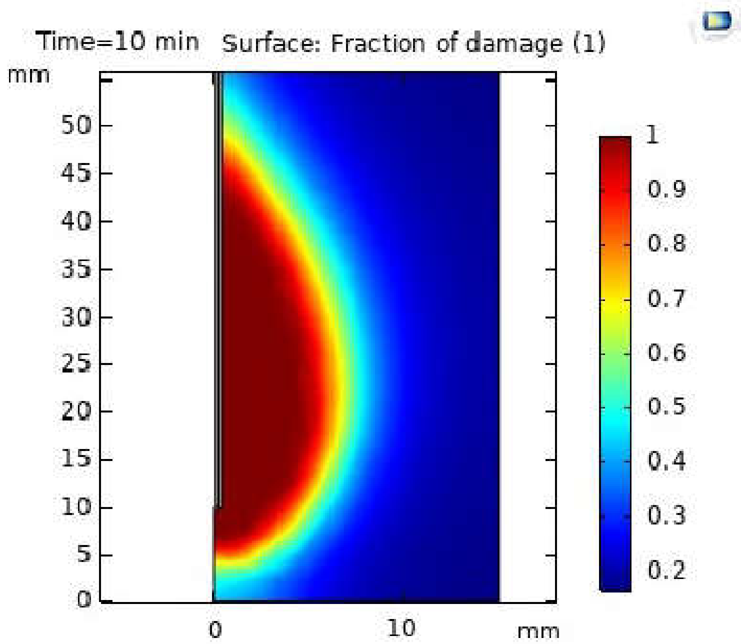
Fig. 4. SAR distribution three different geometry MCA at 10W power



(a) Single slot antenna



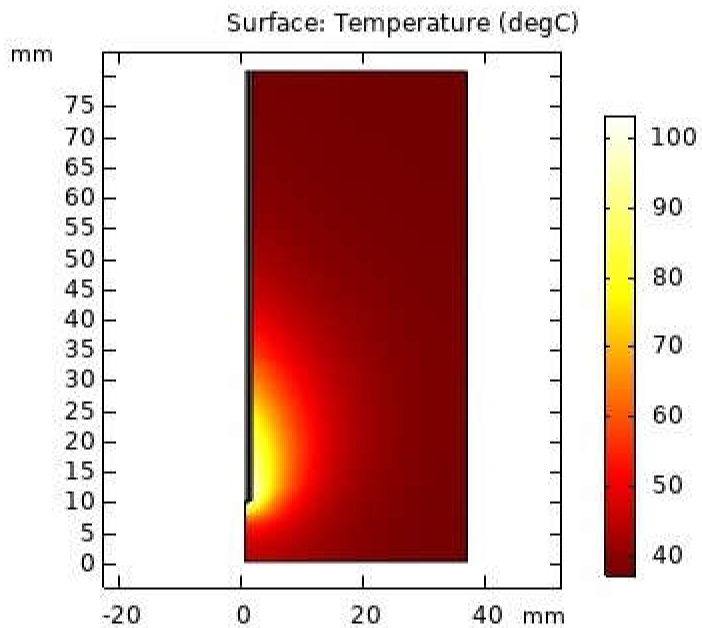
(b) Double slot antenna



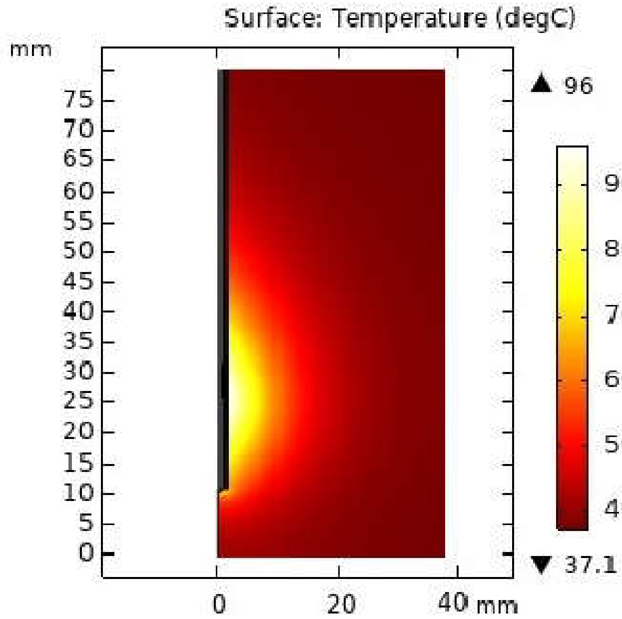
(c) Sleeved antenna

Fig. 5. Damaged tissue in single slot, double slot and sleeved antennas in 30W

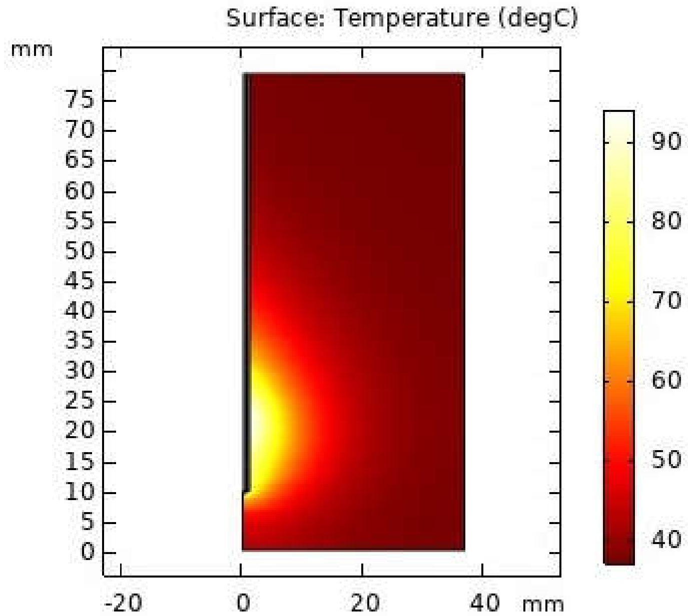
In all cases SAR distributions achieves maximum value at slot region and decreases along the longitudinal axis of antenna when the further away. SAR value measured from simulation result is 2.64kW/kg for single slot antenna at the 65mm depth of insertion. Double slot antenna reaches peak SAR values at 62.4mm insertion depth as 2.53kW/kg. The highest SAR value is measured in sleeved antenna as 2.804kW/kg at the 59.95mm insertion depth. Under specific temperature conditions can occurs damage or decease of living tissue. So that while simulating, determine the parameters are tissue specific (Fat, Skin, Prostate, and Liver) is crucial to get exact and verified result. These parameters are included in the material library in the Heat Transfer Module. The ablation length and ablation diameter of the ablated tissues were computed from the necrotic distribution patterns in Figure 5. Sleeved antenna presents the lowest ablation length and the highest ablation diameter. Comparison of the sleeved and the other antennas are listed in Table II. The all data in the table are measured in power of 10W and 2.45GHz operating frequency. According to the Penne's Bioheat Equation; heat is transferred from the antenna probe to the biological tissue andtemperature increases in regard of the heat absorption ratio of tissue. Figure 6. shows the temperature distribution for three different geometries antenna in liver tissue power of 30w. The result is similar to the necrotic tissue distribution. In all cases peak temperature value occurs near the slots and decreases with distance.



(a) Single slot antenna



(b) Double slot antenna



(c) Sleeved antenna

Fig. 6. Temperature distribution in power of 30w

Table 2. Simulation Results Comparison

Parameter	Single Slot	Double Slot	Sleeved
SAR	2.64kW/kg	2.53kW/kg	2.804kW/kg
Ablation Diameter	1.7cm	1.4cm	2.4cm
Ablation Length	5.2cm	4.9cm	4.3cm
Reflection Coefficient	-20.48dB	-18.11dB	-22.41dB

RESULT AND CONCLUSION

This paper presents a simulation based approach to evaluate the performance of single slot, double slot and sleeved geometry slot coaxial antennas. Electromagnetic wave propagation and heat transfer to liver tissue are main objectives to determine the the suitable applicator geometry. For duration 10 minute power of 10W, 20W and 30W, sleeved antenna deposited the highest power and absorption ratio observed power dependent. Ablation diameter, SAR value, ablation length and reflection coefficient are used to evaluation of performance. The highest temperature and SAR distribution value obtained from the sleeved antenna's result. In case of sleeved geometry the lowest ablation length is reported. Because it is reflected to the back microwave radiation in the upper part of the slot.

This is why the highest reflection coefficient observed in sleeved geometry, it cause low power dissipation. The major advantage of sleeved geometry is almost totally eliminated backward heating. In addition, presents high power localization. The main drawback of sleeved antenna is requirement of complicated fabrication process due to the it's feature of geometric structure. However high SAR value, backward heating eliminating and high amount of microwave energy make it optimal applicator geometry. Next step of research will need to be performed experimental approach varying input power, duration and enclosure structure to characterize and improve the applicator antenna
geometry.

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