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Coax-fed Dipole-type Applicator for Hepatic Cancer RF Ablation

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Abstract

Cancer is the third leading cause of mortality in the world and is one of the most difficult diseases to detect and cure. This fact motivates us to investigate a treatment method by using radiofrequency (RF) ablation. RF ablation therapy kills cancer cells by electromagnetically heating them up. The treatment uses an applicator that is inserted into the body to heat the cells. The cancer cells are exposed to a temperature of more than 60 °C in short duration (a few seconds to a few minutes), thereby causing cell destruction locally. To ensure effective treatment, a minimally invasive method is selected so that good local temperature distribution inside the cancer cells can be achieved. In this paper, a coax-fed dipole-type applicator is proposed for interstitial irradiation technique in hepatic cell treatment. The applicator design is conducted by simulation in CST Microwave Studio to obtain an appropriate size at operating frequency of 2.45 GHz. We also consider localizing the ablation area by designing the tip of the applicator such that the main electromagnetic radiation locally exists around it. The proposed applicator is inserted into a simple phantom model of an adult human body with normal and cancerous liver cells. Both simulation and measured results show that the proposed applicator is able to operate at center frequency of 2.45 GHz in a blood droplet-type ablation zone. A temperature of 60 °C around the cancer cell can be achieved by simulation. Moreover, a square four-array applicator is analyzed to increase the ablation zone for a larger tumor cell. The simulation results show that a reasonably wider local ablation area can be achieved.

Abstrak

Aplikator Dipole Catu Koaksial untuk *RF Ablation* pada Kanker Hati. Sekarang ini, kanker merupakan penyebab kematian utama nomor tiga di dunia. Kanker menjadi masalah kesehatan yang serius dimana sangat sulit untuk dideteksi dan diobati. Oleh karena itu kami melakukan studi metode pengobatan sel kanker menggunakan metode *RF ablation*. Terapi *RF ablation* merupakan metode membunuh kanker dengan cara pemanasan sel kanker secara elektromagnetik. Pengobatan ini menggunakan aplikator yang dimasukkan ke dalam tubuh agar dapat memanaskan sel kanker. Sel kanker dikenai suhu lebih dari 60 derajat Celsius dalam waktu yang singkat sehingga terjadi kerusakan sel kanker secara lokal. Untuk mendapatkan teknik pengobatan yang baik, kami memilih metode invasif secara minimal sehingga tercapai distribusi yang optimal di dalam sel kanker. Pada makalah ini, sebuah aplikator dipole catu koaksial diusulkan dengan teknik radiasi secara interstisial (injeksi) untuk pengobatan kanker hati. Aplikator dirancang secara simulasi dengan *CST Microwave Studio* untuk mendapatkan dimensi yang cocok di frekuensi kerja 2,45 GHz. Area ablasi juga dipertimbangkan dalam rancangan dimana radiasi elektromagnetik dapat terjadi di sekitar ujung aplikator secara lokal. Aplikator yang diusulkan dimasukkan ke model phantom sederhana yang merepresentasikan tubuh manusia sel normal dan sel kanker. Baik hasil simulasi dan pengukuran menunjukkan bahwa aplikator yang diusulkan dapat beroperasi di frekuensi tengah 2,45 GHz dengan zona ablasi berbentuk tetes darah. Suhu di sekitar sel kanker dapat mencapai lebih dari 60 derajat Celsius berdasarkan hasil simulasi. Selain itu, untuk memperluas zona ablasi terhadap sel tumor target, sebuah aplikator empat-susun bentuk bujur sangkar diusulkan untuk dianalisis. Hasil-hasil simulasi menunjukkan luas zona ablasi yang lebih lebar.

Keywords: Ablation zone, applicator, coax-fed dipole applicator, hepatic cancer, RF ablation.

1. Introduction

Radiofrequency (RF) or microwave ablation (MWA) is one of the few technologies being used in cancer or tumor treatment. Some MWA methods use an applicator to deliver microwave energy into the target tissue and raise its temperature to a level that results in immediate cell death. Above 60 °C, nearly instantaneous protein coagulation is induced, thereby leading to cell death [1]. Thus, applicators have to generate a "tip-heating" beam in a specified region. Through tip heating, sufficient and localized heat occurs near the tip of interstitial applicators without damage to the surrounding normal tissue, and the hot spot is an undesirable high-temperature region [2].

In most cases of MWA, the applicator is fed by a coaxial cable and its feed structure is optimized to achieve the desired heating pattern while choking the currents that flow on the outer surface of the outer conductor of the feeding coaxial cable [3]. In most MWA procedures, the antenna is inserted into the center of the targeted tissue and the ablation zone grows radially outward [4]. Performing MWA must consider precluding thermal damage to non-targeted tissues while ensuring complete thermal coverage of the targeted tissue.

According to most MWA studies, the applicator is excited by coaxial feeding technique in which both the antenna/radiator configuration and the feed structure are optimized to achieve the desired heating (beam) pattern. The configuration is basically perturbed to allow the currents to flow on the outer surface of the outer conductor of the feeding cable. Some examples of such designs include floating sleeve dipole [5], choke [6], triaxial [7], and cap choke [8].

In this paper, we propose a coax-fed dipole-type applicator that offers the desired performance characteristics for MWA, such as specific absorption rate (SAR) pattern at a working frequency of 2.45 GHz. The proposed applicator is numerically simulated on a liver organ by emulating it within a numerical phantom in CST Microwave Studio, a finite difference time domain-based simulator. Once the optimum simulation results are obtained, validation is conducted by measurement in a simple phantom model.

The rest of this paper is organized as follows. The methodology and details of the proposed applicator are described in section 2. The simulation results are reported in section 3. The basic validation results are discussed in section 4 and compared with the simulation results. Finally, concluding remarks are provided in section 5.

2. Design of Applicator

Figure 1 shows a schematic representation of the proposed applicator. The applicator is a coax-fed dipole antenna. The poles have two slots, each having a width of 1 mm. The length of the proposed applicator is 120 mm.

The slot dipole applicator is designed by connecting three coaxial chokes with different sizes to the outer conductor and separating them with a 1 mm gap. The end tip of the center conductor is shorted with the lower part of the pole. The coaxial choke matches the antenna to the coaxial transmission line to improve the efficiency. The dimension of the chokes mounted on a semi-rigid coaxial cable is depicted in Figure 2. The poles have different lengths of 3, 3, and 10 mm with the same diameter of 3.58 mm. We consider that such a dimension setting for intercavitary microwave endometrial thermal ablation can be achieved. To simulate the ablation process, we assume that a cancer cell has a diameter of 20 mm and is located at 3 mm from the lower pole of the applicator. To ensure good resonance frequency with the liver and cancer cells, the proposed applicator is designed with the dimensions shown in Figure 2.

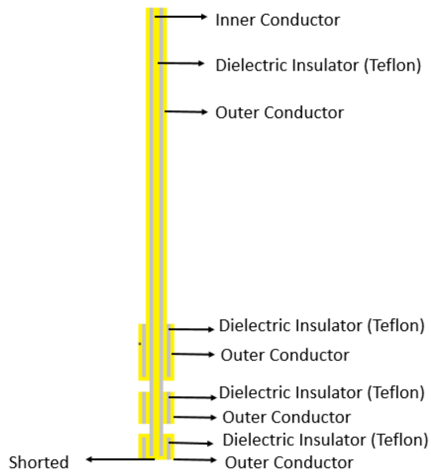


Figure 1. Schematic Representation of the Proposed Applicator

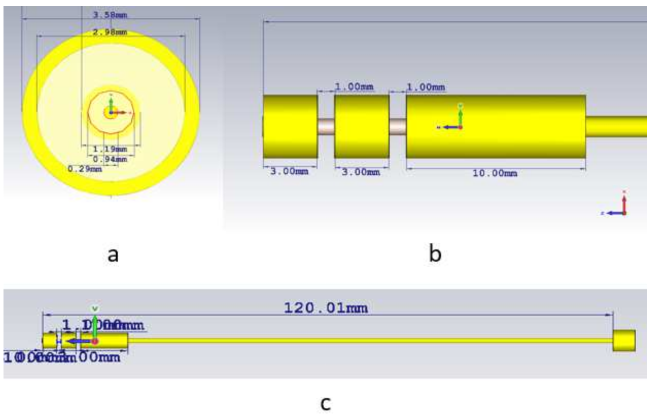


Figure 2. Features of Proposed Applicator (a) Cross Sectional View, (b) Each Pole Size at Applicator Tip, and (c) Side View

$$\lambda_{eff} = \frac{3x10^8}{2450.10^6\sqrt{62.44[9]}} \quad (1)$$

$$\lambda_{eff} = 0.0155\ m = 15.5\ mm \quad (2)$$

The proposed applicator is calculated by CST Microwave Studio and MPhysics Studio using a simple phantom model that emulates a human body. The numerical phantom model, as shown in Figure 3, consists of three layers (skin, fat, and muscle, respectively) from exterior to interior. Inside the phantom, a simple liver and cancer model is added, as shown in Figure 4. The cancer cell model is spherical and located on the liver cell, in which the size is larger than the applicator's diameter, as depicted in Figure 5. The electrical properties of the numerical phantom model and applicator are summarized in Table 1. The liver phantom and cancer model (divided into malignant and cirrhotic types of cancer) are described in Table 2.

When the phantom model is built, the proposed applicator is applied by calculating the input reflection coefficient (S_{11}) on CST Microwave Studio. In addition, we consider calculating SAR, which is defined as the power dissipated per unit volume (W/m³) normalized by the tissue mass density (kg/m³). SAR is a measure of the amount of microwave energy absorbed by the tissue. SAR in the region of tissue surrounding the applicator is calculated by using full-wave computational electromagnetic simulation in CST Microwave Studio.

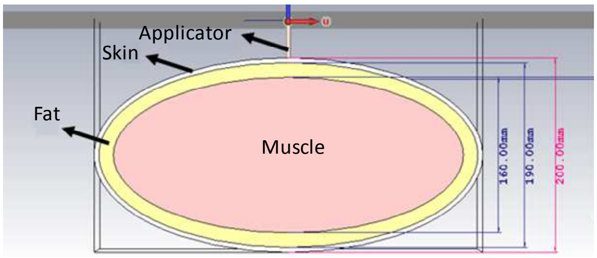


Figure 3. Cross Sectional View of Body Phantom Model for Simulation Setup

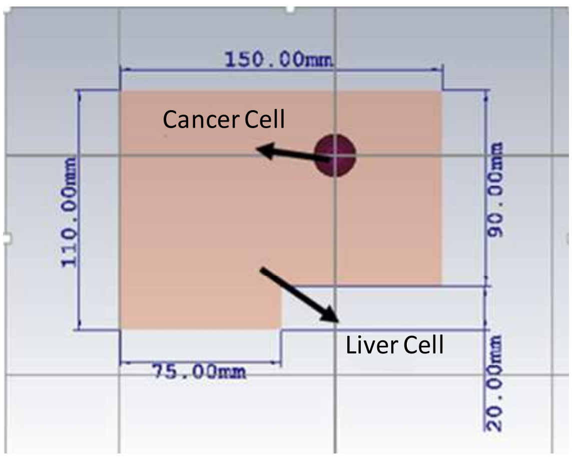


Figure 4. Liver Phantom with Hepatic Cancer Cell Model

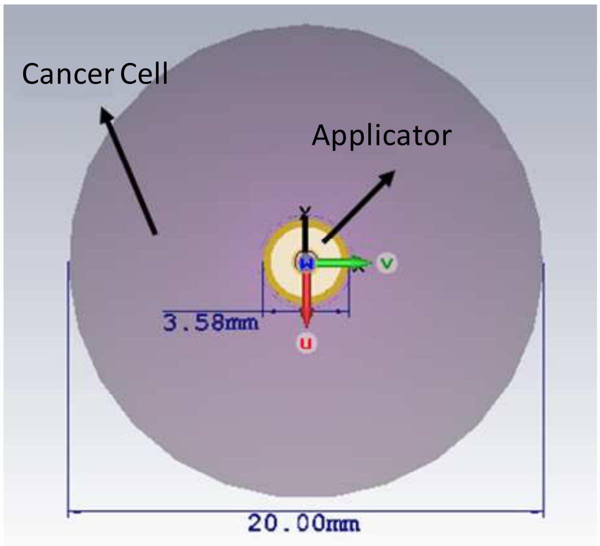


Figure 5. Dimensional Comparison between Hepatic Cancer Cell Model and Proposed Applicator

Table 1. Electrical Properties of Numerical Body Phantom Model in Simulation

Tissues	Material density	Heat capacity	Thermal Conductivity
	kg/m³	kJ/K/kg	W/K/m
Skin	1100	3.5	0.293
Fat	910	2.5	0.201
Muscle	1041	3.546	0.53
Liver	1020	3.6	0.469
Cancer	1040	3.5	0.642
Copper	8930	0.385	401
Dielectric (Teflon)	2200	1	0.2

Table 2. Electrical Properties of Liver and Cancer Model [9] used in Simulation

	Normal		Malignant		Cirrhotic	
	ε_r	σ(S/m)	ε_r	σ(S/m)	ε_r	σ(S/m)
In vivo	57.55 ±3.05	1.95 ±0.18	62.44 ±3.18	2.18 ±0.13	61.26 ±2.70	2.21
Ex vivo	45.79 ±7.53	1.68 ±0.27	54.88 ±3.10	1.99 ±0.11	50.16 ±2.36	1.83 ±0.11

3. Results and Discussion

Simulated Results. Once the simulation model is established by using CST Microwave Studio and MPhysics Studio, several essential parameters are obtained. Figure 6 shows the reflection coefficient characteristics (S_{11}) of the proposed applicator. The applicator is able to resonate at a frequency of 2.448 GHz with S_{11} value of −24.86 dB. Although a slight difference of 2 MHz exists with the desired frequency at 2.45 GHz due to energy absorption, the phantom still works at 2.45 GHz. To evaluate the thermal characteristics, we have to observe the SAR, which is usually averaged either over the whole body or over a small sample volume (typically 1 g or 10 g of tissue) [10]. The cited value is the maximum level measured in the body part studied over the stated volume or mass. Figure 7 shows the 10 g averaged SAR, which is the peak value at 10.6 W/kg. The result is good for a sufficient RF–MWA method.

In Figure 8, we simulate the RF MWA method to kill a cancer cell by applying input microwave power at 10 Watts on a cell with 20 mm diameter. According to Figure 8(a), the highest simulated temperature is achieved at 111 °C, encompassing all areas of the cancer cell. Figure 8(b) presents a cross-sectional view of the temperature distribution and shows that the heat covers all areas of the cancer cell, where a temperature of more than 60 °C is obtained.

Measurement Results. The following simulation is conducted on Microwave Studio and MPhysics Studio. The proposed applicator is fabricated to validate the simulation by measuring the main parameter, namely, the operating frequency of the applicator.

Figure 9 depicts the fabricated applicator to be evaluated in measurement. Its length is approximately 132 mm, including the feeding port installed at the end of the coaxial cable. The size of the applicator itself is 121 mm (with a difference of 1 mm from the simulation model) without the feeding port.

Prior to validation by measurement, a physical phantom model should be fabricated so we can evaluate the proposed applicator correctly. In this case, we use an agar-based physical phantom model. This phantom model is a simple block shape that emulates a liver tissue in a plastic container, as shown in Figure 10. The

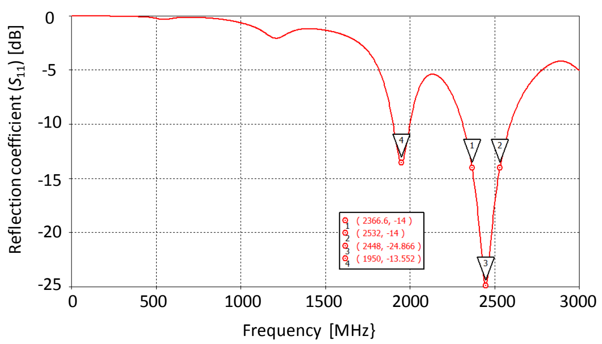


Figure 6. Reflection Coeffcient (S_{11}) of Proposed Applicator

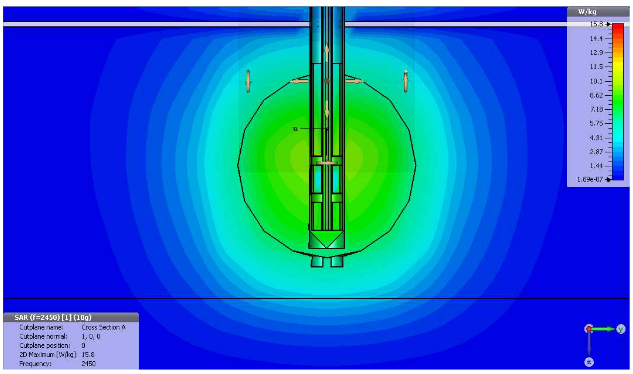
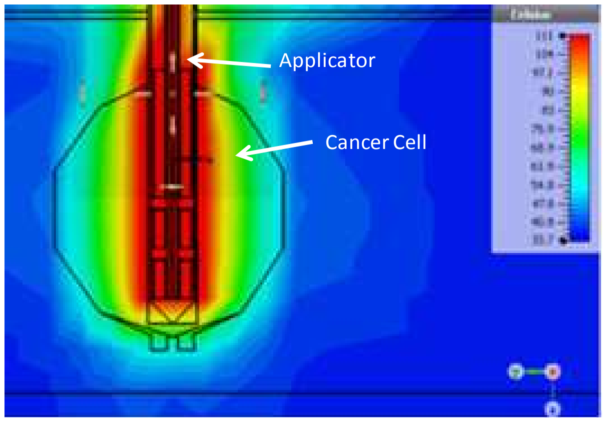
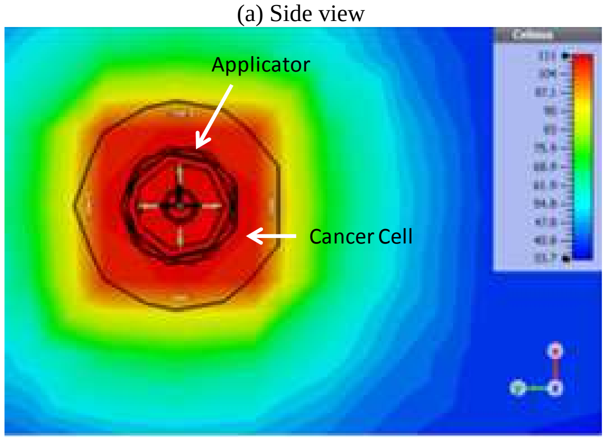


Figure 7. Simulated SAR of Single Proposed Applicator



(a) Side view



(b) Cross-sectional view

Figure 8. Simulated Thermal Distribution by Applying 10 Watts of Input Microwave Power: (a) Side View Thermal Distribution and (b) Cross-sectional Thermal Distribution

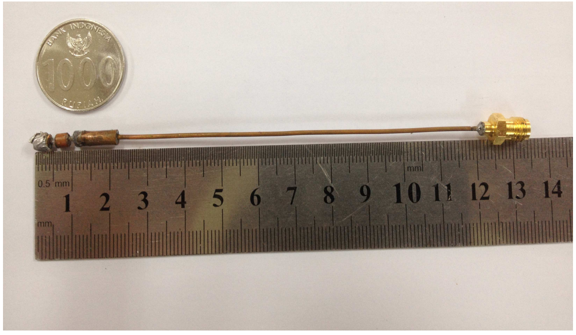


Figure 9. Fabricated Applicator

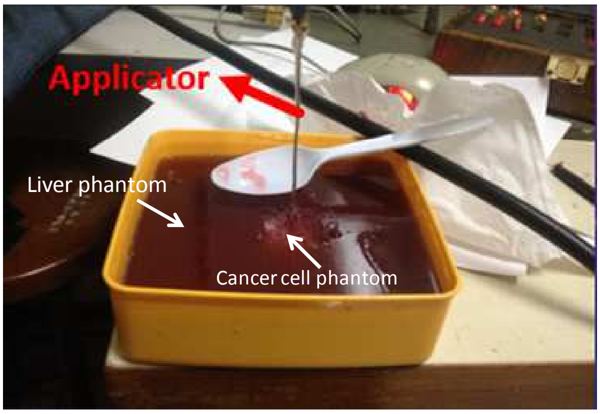


Figure 10. Measurement View of the Applicator with Liver Physical Phantom and Cancel Cell Phantom Models

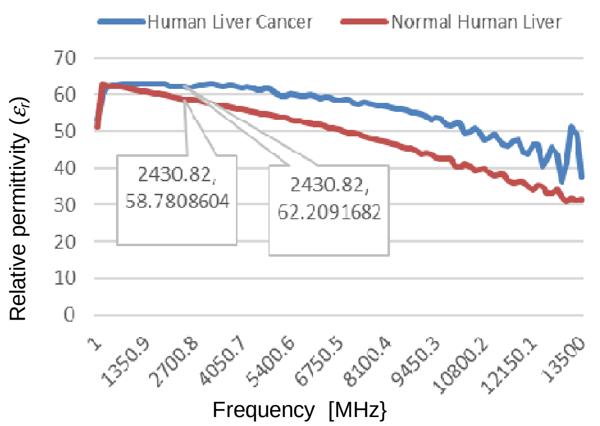


Figure 11. Electrical Property (i.e. Relative Permittivity) of Agar-based Physical Liver Phantom and Cancer Cell Phantom

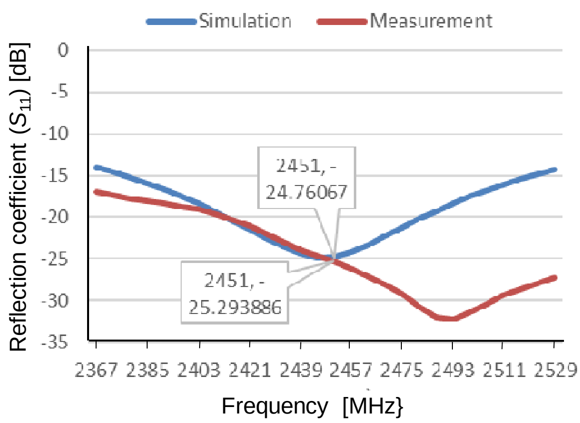
size of the phantom is 15 mm × 14 mm × 4 mm (L×W×H). In the middle of the liver phantom, a cube-shaped cancer cell model with diameter of 2 mm is inserted. The fabricated applicator is then injected into the middle of the cancer cell phantom through the liver phantom to emulate cancer thermal treatment by the applicator.

Figure 11 shows the electrical property, i.e., measured relative permittivity (ε_r) of the agar-based physical liver phantom and cancer cell model. The measured values show that the relative permittivity of the cancer cell phantom is 62.21 (the target value is 62.44) at 2.45 GHz. In addition, the measured relative permittivity of the liver phantom is 58.78 (the target value is 57.55). These values are acceptable because the difference is less than 3% as described in Table 3.

Table 3. Electrical Properties (Relative Permittivity) of Liver and Cancer Physical Phantom Model

Physical phantom	Parameter (@2.45 GHz)	Target	Measured value	Error percentage (%)
Liver	Relative permittivity (ε_r)	57.55	58.78	2.14
Cancer cell	Relative permittivity (ε_r)	62.44	62.21	0.37

(a)



(b)

Figure 12. Reflection Coefficient Measurement of Proposed Applicator with Physical Liver Phantom Model: (a) Measurement View on Vector Network Analyzer Display (b) Measurement Versus Simulation Comparison

Following the measurement setup after the physical phantom model is established, the reflection coefficient parameter is measured. Figure 12 shows the measured reflection coefficient parameter (S_{11}) of the proposed applicator when it is inserted into the physical phantom model. The magnitude of S_{11} by −25.79 dB is obtained at a frequency of 2.45 GHz. As shown by the difference between measurement and simulation, the measured result tends to agree with the simulation result. At the same frequency of 2.451 GHz, the magnitude of S_{11} by −25.29 dB is obtained and 0.5 dB is different from the simulation. The discrepancy in the peak value occurs at 2.493 GHz on −32.26 dB due to manual fabrication of the applicator, which results in a slight difference in the construction.

Array Investigation. To increase the performance and efficiency of the applicator in treating large cancer cells, an array configuration has to be investigated. In this configuration, each single applicator is placed at the end of plus (+) configuration. The distance between each applicator on the opposite side is 15 mm. Based on the same numerical liver phantom model, the size of the cancer cell is set at a diameter of 30 mm (10 mm larger than the previous cancer model), as shown in Figure 13.

Figure 14 shows the simulated thermal distribution when the arrayed applicator is applied on the cancer cell phantom. Each applicator is applied with 5 Watts of input microwave power. The simulation shows effective thermal distribution because most of the cancer cell area exceeds 60 ºC for microwave coagulation. When viewed on a cross-sectional plane, each distribution area for each single applicator heats the cancer cell at more than 60 ºC, which is the lowest temperature is at 64.4 ºC.

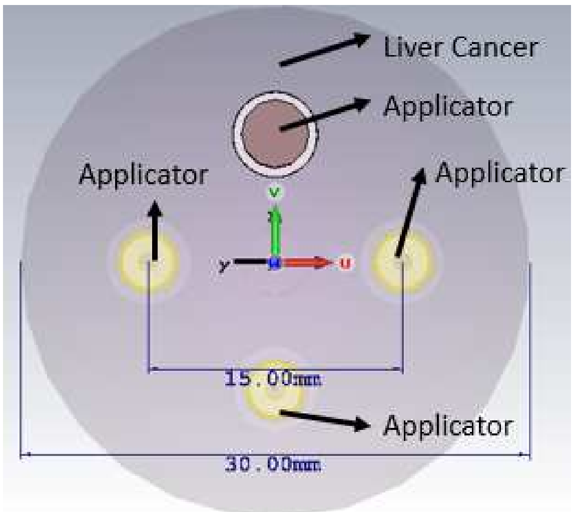
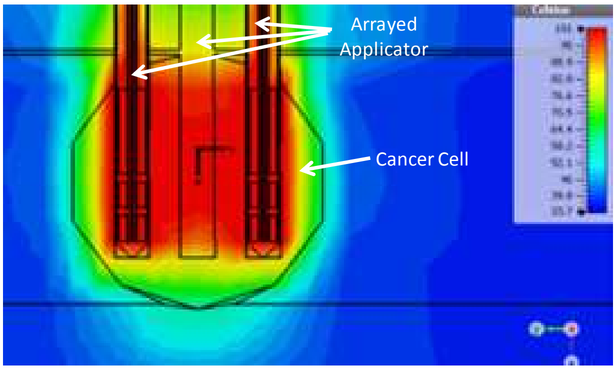
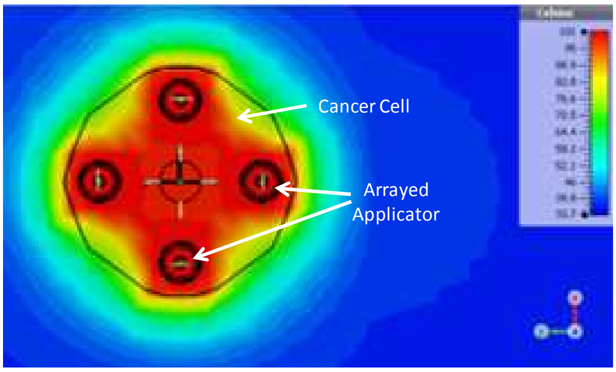


Figure 13. Array Configuration of Applicators on Relatively Large Cancer Cell



(a)



(b)

Figure 14. Effectiveness of Thermal Distribution when the Array Configuration is Applied on Large Cancer Cell: (a) Side View and (b) Cross-sectional View

4. Conclusions

In this paper, a coax-fed dipole-type applicator is proposed for interstitial irradiation technique in hepatic cell treatment. The applicator design is conducted by simulation on CST Microwave Studio to obtain a suitable size at an operating frequency of 2.45 GHz. Localization of the ablation area is achieved by designing the tip of the applicator such that the main electromagnetic radiation locally exists around it. The proposed applicator is inserted into a simple cancerous liver phantom model. Both simulation and measured results show that the proposed applicator is able to operate at a center frequency of 2.45 GHz with a blood droplet-type ablation zone. A temperature of more than 60 °C around the cancer cell can be achieved by simulation. In addition, to increase the ablation zone for a larger tumor cell, a square four-array applicator with plus (+) configuration is analyzed. The simulation results show that a reasonably wide local ablation area can be achieved to kill a large cancer cell. Thus, the proposed applicator design is promising for application in thermal therapy in future research.

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