

DIELECTRIC HEATING WITH HIGH-FREQUENCY CURVED PLATE APPLICATOR FOR BREAST CANCER TREATMENT

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Abstract

This paper presents the dielectric heating with high-frequency by using the straight and curved plate applicator to compare the electric field focusing on the tumor tissue in the breast phantom. The tumor tissue size provides 10, 20, and 30 mm was investigated heat distribution by using the bioheat transfer equation. The simulation result consists of return loss in dielectric materials, temperature treatment, and power loss density was analyzed in the tumor tissue on each coordinate. This applicator was stimulated by 2,450 MHz based on the electric field using the copper plate applicator. The tumor tissue in breast phantom was located at different coordinates in xy-plane and xz-plane. Simulation results show that the heating efficiency area could penetrate the internal tumor. The curved plate can be relocated and focused on tumor tissue. The rotation axis of the curved plate has been rotated in the vertical or horizontal axis of the breast phantom to heat up tumor tissue. The heat distribution area to the affected neighboring tissues has been decreased. The maximum heating area was close to the tumor tissue at the midpoint position between copper plates.

Keywords: Dielectric heating, curved plate applicator, breast cancer treatment

Introduction

Hyperthermia is pervasive in non-invasive cancer treatment. It is advantageous that hyperthermia treatment can be operated without a surgical process which causes pain. The high-frequencies with a particular effect on the tumor tissue can efficiently stimulate heat because of its appropriate electrical properties to absorb energy which is good for heat. The primary purpose of hyperthermia is to increase the tumor temperature approximately from 42-43°C for a sufficient time more than 30 to 60 min while keeping the surrounding tissue temperatures below 42°C (Nguyen *et al.*, 2016; Tang *et al.*, 2017). Typically, the dielectric properties of a malignant

tumor are significantly different than healthy tissues, and energy absorption is better than healthy tissue (Giering *et al.*, 1995). The electromagnetic energy selectively heats in tumor tissue, this is performed in the range of (ISM) band 433 MHz, 915 MHz, and 2,450 MHz. Nevertheless, the high-frequency configuration is insufficient to penetrate enough thermal energy to the tumor located in a particular area. (Converse *et al.*, 2004; Nguyen *et al.*, 2015; Fiser *et al.*, 2017). Hence, the study of the hyperthermia apparatus is focused on the electromagnetic energy on a specific region desired of the breast tissue and is to provide a means for

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protecting the nearby healthy tissues. In addition, the dielectric heating technique is also interesting since it uses an electric field instead of electromagnetic waves. From the study of the data, it was found that the 70 MHz capacitive applicator systems are significantly penetration depth. This frequency is suitable to heat up deep tumors (Kok *et al.*, 2010; van Stam *et al.*, 2017), while operating at 2450 MHz has insufficient penetration. But, there is a known that the dielectric behavior of tumor tissue is different. Furthermore, the capacitive heating of 70 MHz should get a high power level to generate a temperature between 39-42°C and suitable for large areas (van de Kamer *et al.*, 2001; van Wieringen *et al.*, 2009; Kok and Crezee, 2017). The applicator of 2,450 MHz is employing less an electric field power to generated heat up the tumor tissue was compared to 70 MHz, as follows in (2). As mentioned above, there are a number of researches proposing methods for effectively controlling thermal (Stang *et al.*, 2012; Iero *et al.*, 2014; Asili *et al.*, 2015; Nguyen *et al.*, 2017). The studied of the hyperthermia apparatus is focused on the electromagnetic energy on a specific region desired of the breast tissue and is to provide a means for protecting the nearby healthy tissues. However, penetration of electromagnetic waves and operating by a high-frequency antenna to thermal therapy within the breast tissue is delicate. (Correia *et al.*, 2009; Iero *et al.*, 2010; Fiser *et al.*, 2017). Breast cancer causes loss of tissues in the body and provides several effects on antennas used for medical applications (Elkayal *et al.*, 2015). Likewise, the dielectric heating technique is also interesting since it uses an electric field instead of electromagnetic waves.

In this research, we propose the high-frequency dielectric heating method with a curved plate applicator to improve the adequate heating to penetration depth. Especially, on the focal area of small tumors, to avoid overheating of the applicator that affects surrounding for breast cancer treatment. The straight and curved plate will be considered the frequency response capability, the ability to transfer maximum power in the dielectric load, especially power loss density given on the specific region.

Materials and Methods

Concept and Structure of Dielectric Curve Plates Applicator

The curved plate applicator was performed based on 2,450 MHz, includes a straight and curved plate as shown in Figure 1(a) and Figure 1(b). The curved plate is made to increase the ability of electric field focusing. The conductivity of copper

plates equals $5.8 \times 10^7 \text{ S} \cdot \text{m}^{-1}$. During the simulation, we suggested that the usability of curved plate applicators are able to focus the heating absorption position for a tumor inside the breast phantom. The investigation of the effect of the electric field was carried out in the study. To analyses the focus of the electric field of materials, we specify 50 Ω impedance of frequency source. The dimensions and schematic details of the curved plate applicator to analyzing the electric field focusing were shown in Figure 1(d) and Figure 1(e). The plates size includes include, plates length (L, 52 mm), copper thickness (1 mm), plates width (d, 20 mm), breast phantom width (D, 90 mm), and height (h, 4 mm) respectively. The characteristic of the dielectric material and was defined from breast phantom consisting of skin and fat are shown in Figure 1(c). In the simulation, the tumor tissue is placed in the breast phantom model at coordinates (0, 0, and 10 mm) with size 10, 20, and 30 mm. The dielectric property includes density ($\text{kg} \cdot \text{m}^{-3}$), relative permittivity (ϵ_r), and electric conductivity (σ , $\text{S} \cdot \text{m}^{-1}$) of various tissue are provided in Table 1 (Martellosio *et al.*, 2017).

The heating position can be relocated by the vertical or horizontal axis in breast phantom due to

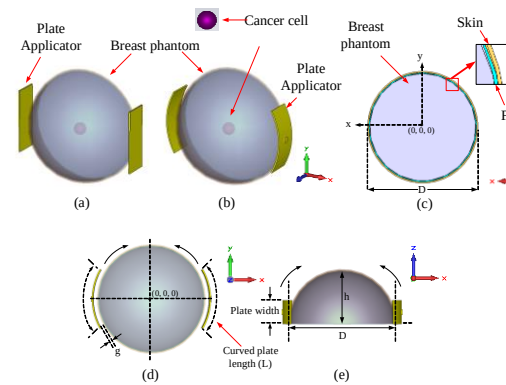


Figure 1. Analytical model of breast phantom with tumor tissue, (a) straight plate, (b) curved plate, (c) dielectric materials or breast phantom, (d) curved plate with xy-plane orientation, and (e) curved plate with xz-plane orientation

Table 1. Summary of Electrical properties of skin, fat, breast, and tumor tissue at 2.45 GHz

Material	Electrical property				
	permittivity (ϵ_r)			conductivity (σ , $\text{S} \cdot \text{m}^{-1}$)	density ($\text{kg} \cdot \text{m}^{-3}$)
	dielectric constant (ϵ')	loss factor (ϵ'')	loss Tangent ($\tan \delta$)		
Skin	46.7	5.06	0.11	0.69	1,130
Fat	5.6	0.29	0.05	0.04	920
Breast phantom	4.44	0.95	0.21	0.13	1,020
Tumor tissue	55.25	19.80	0.36	2.7	1,050

the curved plate applicator can be moved orientation in the xy-plane or xz-plane. Figure 1(d) and Figure 1(e) are illustrated the orientation axis of the curved plate. We have suggested the usability of curved plate applicators are able to focus the heating absorption for a tumor inside breast phantom by changing the orientation of the curved plates.

Analysis and Temperature Distribution

In this section, the power loss density was investigated in the form of heat distributions in the 3-D model by CST microwave studio program. The power loss density was observed by simulation and 2D cross-section of the phantom. The temperature distribution in the dielectric loss tissue was calculated from the electric field power and dielectric losses factor. The bioheat transfer equation can be used to calculate the temperature distribution in dielectric materials as a representative of human tissue or breast tissue (Jiao *et al.*, 2011; Wu *et al.*, 2015; Tang *et al.*, 2017). It can be expressed as follows.

$$\frac{\partial T}{\partial t} = R_T \nabla^2 T + \alpha P \quad (1)$$

$$P = 5.536 \times 10^{-11} f E^2 \epsilon'' \quad (2)$$

$$R_T = \frac{k_t}{\rho C_p} \quad (3)$$

Where T is the temperature ($^{\circ}\text{C}$), t is the heating time period (s), R_T is the distribution temperature (m^2s^{-1}), k_t is the thermal conductivity of tissue ($\text{W}\cdot\text{cm}^{-1}\text{C}^{-1}$), ρ is the local physical density of tissue (kgm^{-3}), C_p is the specific heat capacity of an object ($\text{J}\cdot\text{kg}^{-1}\text{C}^{-1}$), α is the correction coefficient: ($\alpha = 1/\rho C_p$), and P is the power loss density ($\text{W}\cdot\text{cm}^{-3}$). The power loss density was calculated from dielectric loss factor (ϵ''), E is the electric field $\text{V}\cdot\text{cm}^{-1}$, and f is the frequency (Hz). The simulation of dielectric heating was conducted by analyzing the power of loss density of the plate applicator. It is considered in the next section.

Results and Discussion

In this section, we investigate the power loss density, which can be controlled by the shape of the curved plates and varying a distance of applicator to resolve the problem of the focal treatment area and given heating. Moreover, the studies show that the coordinates of the treatment could be relocated by moving the orientation of the curved plates in the xy-plane and xz-plane direction. The construction of the curved plate applicator to verify the field distribution on the heating model, full-wave 3D

model simulation was performed using the finite difference time domain method by using CST.

Evaluate Electric Loss

The different plates are shown in Figure 1. In the simulation, the dielectric loss factors of breast phantom and tumor tissue were 0.95 and 19.8. The tumor tissue located (0, 0, and 10 mm), the dielectric loss factors of fat and skin were 0.29 and 5.06. The frequency range between 2.25-2.55GHz, Return loss in simulation results of each plate illustrated in Figure 2. The straight plates achieved bandwidth of operating frequency at -10 dB less than the curved plates about 0.94%. But, the simulation results of the power loss density of dielectric materials were not equal and depended on each varying a distance of applicator. The maximum power loss density of the curved plates more than straight plates about 20% at optimization distance by 11.6 cm are illustrated in Figure 3. For temperature in simulation

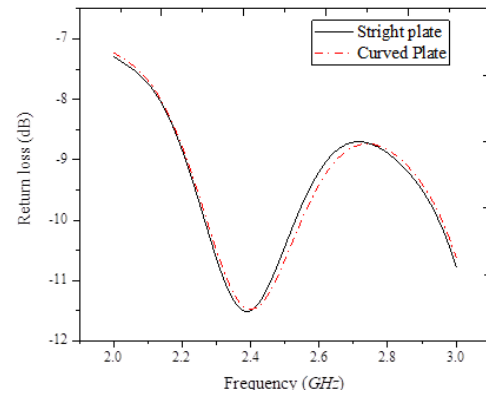


Figure 2. Return loss in dielectric materials between straight and curved plate between 2-3GHz

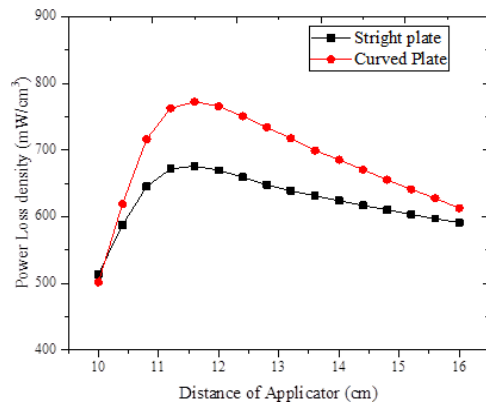


Figure 3. Power loss density in dielectric materials between straight and curved plates on each varying a distance of applicator

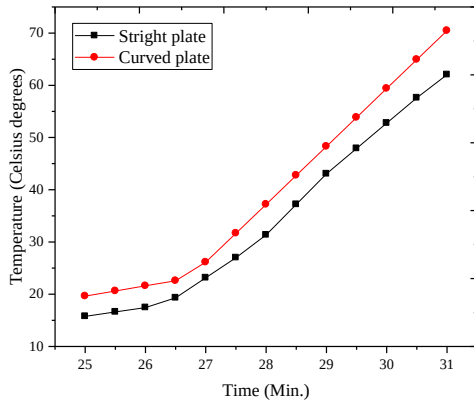


Figure 4. Temperature in the tumor tissue between straight and curved plate

results, there was a response to the curved plates more than straight plates. The duration time is required to heat the tumor tissue at least 30 min, it will be obtained the temperature around 40-60°C as shown in Figure 4. The tumor diameter size changed to 10, 20, and 30 mm. The power loss density was dependent on the size of the tumor tissue inside. Furthermore, the result of the curved plate also functioned in reducing heat distribution in healthy tissues of breast phantom, but midpoint heating increased. The simulation results uncovered the investigation of 2D maximum power loss density $784 \text{ mW} \cdot \text{cm}^{-3}$ as shown in Figure 5. According to the result of the tumor size from the simulation, it was found that the tumor size that responses to frequencies near 2,450 MHz performed well at the tumor size of 10 mm. The heat distribution results show that efficiency is related to the tumor tissue size, the maximum heating area was located in the tumor tissue. In this context, the temperature distribution for the curved plates is narrow than the straight plates.

Investigate the Heating Orientation

Investigated the heating coordinates by changing orientation in xy-plane. The plate applicator orientation angle with 180-degree, 150-degree, and 120-degree are studied shown in Figures 6, 7, and 8. The simulation results showed the heating efficiency, it will be noticed that the curved plates can able to focus the heat distribution better than the straight plates, and it also decreases the treatment region of tumor tissue at (0, 0, and 10 mm) with a curved plate angle 180-degree. The area of heat distribution for the temperature range of 19-27°C of the curved plates is less than that of the straight plates, the heat treatment of neighboring tissues is reduced, and the temperature range of 40-60°C the maximum heating area was nearby tumor

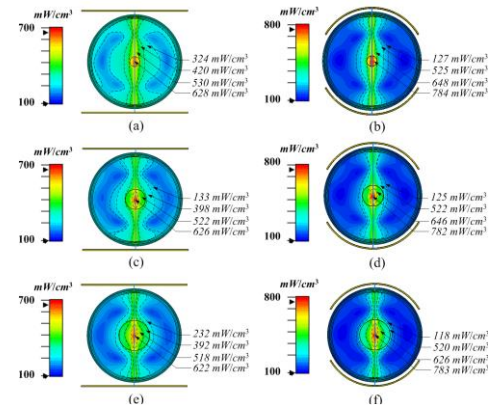


Figure 5. Power loss density of the heating model with each tumor size (a) straight plate with tumor size 10 mm, (b) curved plate with tumor size 10 mm, (c) straight plate with tumor size 20 mm, (d) curved plate with tumor size 20 mm, (e) straight plate with tumor size 30 mm, and (f) curved plate with tumor size 30 mm

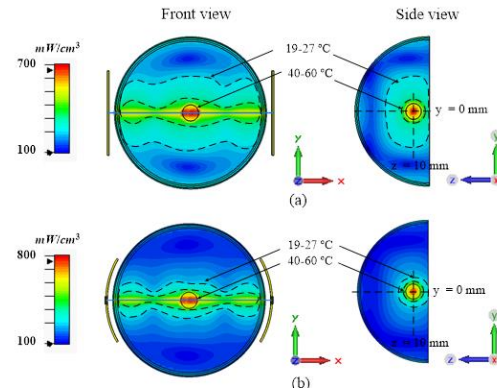


Figure 6. Power loss density in the breast phantom and tumor tissue size 10 mm at coordinates 0, 0, 10 mm with (a) straight plate angle 180-degree, and (b) curved plate angle 180-degree (b)

tissue as shown in Figure 6(a) and Figure 6(b). For investigated the heating location by changing plate orientation become to 150-degree and 120-degree, the maximum power loss density moved coordinates in the y-axis into 10 and 20 mm as same as tumor tissue, as shown in Figure 7(a) and Figure 7(b).

In the simulation results uncovered the investigation of 2D maximum power loss density, curved plates also have a role in focusing the heat distribution directly on the tumor tissue in a breast phantom. Likewise, the orientation of the curved plates angle can be rotated in xz-plane, tumor tissue coordinates are relocated along the z-axis as shown

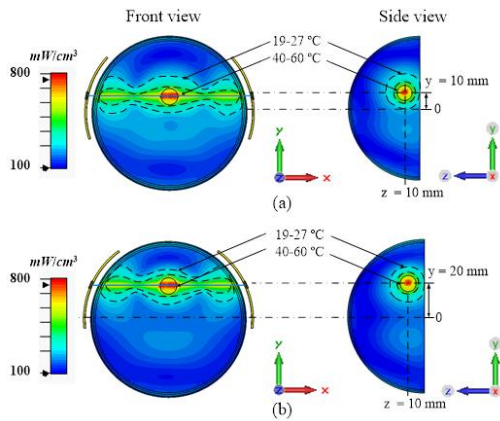


Figure 7. Power loss density in the breast phantom and tumor tissue size 10 mm, moved along y-axis, (a) the tumor tissue at coordinates 0, 10, 10 mm with curved plate angle 150-degree, and (b) the tumor tissue coordinates 0, 20, 10 mm with curved plate angle 120-degree

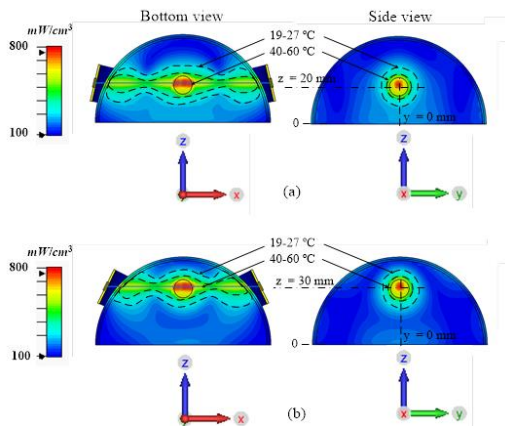


Figure 8. Power loss density in the breast phantom and tumor tissue diameter 10 mm with curved plates, moved along z-axis, (a) the tumor tissue coordinates 0, 0, 20 mm with curved plate angle 150-degree, and (b) the tumor tissue coordinates 0, 0, 30 mm with curved plate angle 120-degree

in Figure 8(a) and Figure 8(b). The results show that the temperature is related to the coordinates of the tumor tissue and the maximum power loss density has still appeared inside the tumor tissue. Therefore, the temperature distribution in the neighboring tissue is less than the tumor tissue.

Conclusions

The effect of the curved plate applicator was excited by 2,450 MHz and impedance 50 Ω of frequency

source. The simulation was conducted by using tumors sized 10, 20, and 30 mm. It was found that the maximum power loss density of curved plate was highest, and minimum heat distribution than the straight plate. The power loss density and dielectric in (2), directly proportional to the temperature interval of the breast phantom and tumor tissue model. Considering the ability to penetrate the dielectric tissues by using a curved plate, the results showed that the maximum power loss density is equal to 784 mW·cm⁻³ at plate distance 11.6 cm and the heat was seemingly not varying on each tumor size. Furthermore, it can control the orientation of the electric field more effectively. Also, the heating location can be varied by changing plate orientation. The results show that the heating location can be relocated in xy-plane and xz-plane of the breast phantom and that it takes at least 30 min to generate temperature about 43°C. Although the tumor tissue was located deeper than the outer breast phantom. But tumors tissue are able to arise better heat from dielectric properties with a higher loss factor.

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